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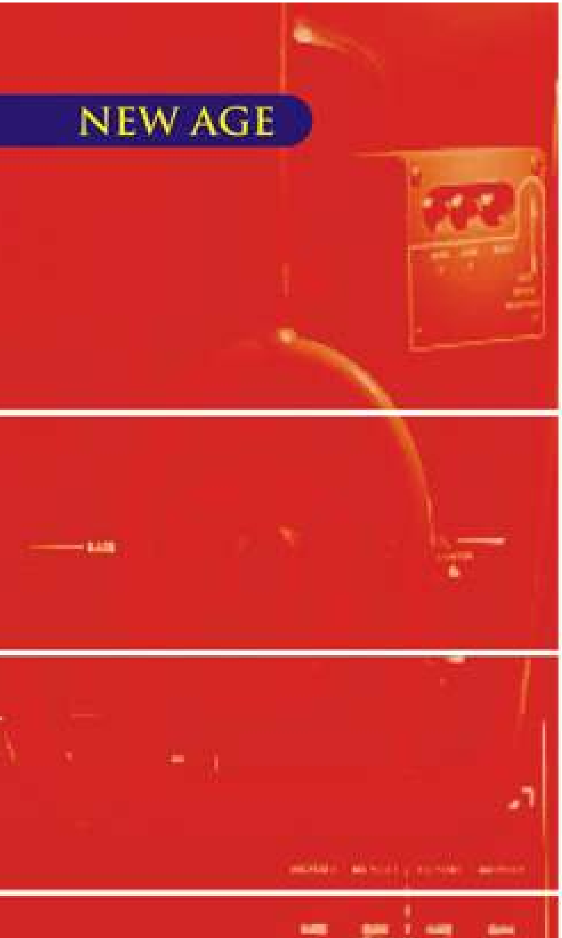
Control of Machines



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REVISED SECOND EDITION

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Preface

The purpose of this book is to present the subject of Control of Machines using electromagnetic relays, static switching devices and programmable logic controllers. The book has been designed for use as a text in diploma and degree courses. The content of this book may also be used effectively in conducting industrial training programmes. It will be of immense help to students who intend to join industry.

Electrical control of motors and other machinery started with the advent of relays, timers and contactors. In the 1960s, programmable controllers started being widely used in industry. In India, however, these technologies were introduced much later. Indian industries are now fast switching over to programmable controlled machines. All the three types of controls have been discussed in this book. However, more emphasis has been laid on magnetic control using relays. This is so because, inspite of the increasing popularity of solid state control and programmable controllers, relay logic control will continue to be used as far as single motor control or the control of a machine with few operations is concerned. Thus, study of relay logic becomes essential for an electrical engineer in order to gain proficiency in the design of control logic.

The first section of the book deals with motor control using relays and timers. Here construction and working of different types of components have been described in detail. It is recommended here that students support their study of components with catalogues published by various manufacturers. The symbols followed for control components are as recommended by the Bureau of Indian standards. Starters for different types of ac and dc motors have been covered in detail. The main highlight and interesting part of this section is the explanation of a large number of typical control circuits used in industry.

Description of machines, various control operations desired and the step by step working of control circuit have been discussed. Students will find these circuits very interesting. It is hoped that a careful study of these circuits will generate confidence in the students and enhance their confidence in handling such control circuitry employed in industry. Besides these there are chapters devoted to troubleshooting and protection of motors.

The second portion of the book deals with static control using digital devices. Modern control systems are designed using integrated circuit elements. These control systems are particularly useful in adverse environments for complex control situations, and applications where high speed operation is required. In this section, ladder logic diagram and USAUI symbols for digital devices have been used, as these are universally used in industry. To make students familiar, the alternate symbols, other than those specified by BIS, have also been used in the section for control components. Besides discussing the general approach to development of circuits, a number of industrial circuits have been discussed.

The last section of the book deals with use of programmable logic controllers for control of machines. PLC architecture and its programming in Ladder Logic Language has been discussed extensively.

We hope that this book will be useful to teachers and students of polytechnics and engineering colleges. Suggestions for the improvement of this book will be thankfully acknowledged.

Finally, we would like to thank our colleagues in the institute as well as teachers of various technical institutes who have encouraged us to make our best efforts in bringing forth this book. Thanks are also due to the publishers, M/s New Age International Pvt. Ltd. for bringing out this book in a very presentable manner.

Dr. S.K. Bhattacharya
Brijinder Singh

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Introduction to Control of Machines

1.1 GENERAL IDEA OF CONTROLS

A machine, as we know, is a device consisting of several interconnecting parts which by their motion, transform/transmit power to do some work. The motion of various parts of a machine can be obtained by using two types of devices, viz.

(*i*) an electrical motor

(*ii*) a solenoid valve and cylinder piston assembly operated by a compressor or a pump.

A constant rotational motion developed by a motor can be converted into linear mechanical movement through rack and pinion arrangement connected to the motor shaft.

In solenoid valve and cylinder piston assembly, fluid or air pressure is applied to cylinder piston through a solenoid valve. Solenoid valve consists of a mechanical valve operated through an electrical coil. Fig. 1.1 shows how a cylinder piston is used to get linear to and fro motion of a machine part. A spring returned solenoid valve is also shown in Fig. 1.1.

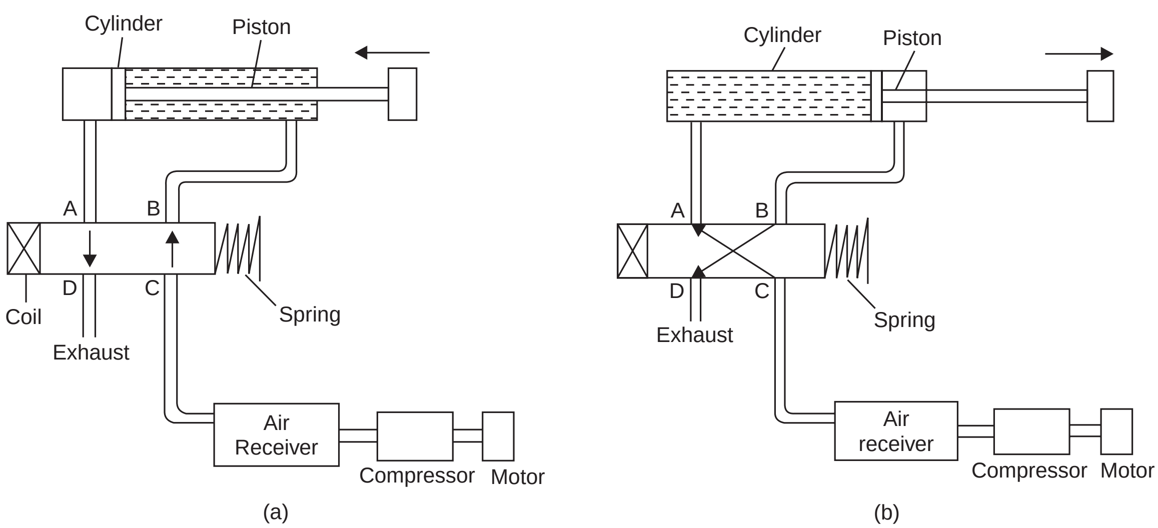


Fig. 1.1 Operation of a solenoid valve (*a*) solenoid coil de-energised (*b*) solenoid coil energised

In Fig. 1.1 (*a*) the solenoid coil is de-energised and ports of the valve are connected as shown by arrows. Port A is connected to exhaust while port B is connected to air receiver in which air is stored at a high pressure. The machine part connected to the piston will be in the position as shown. This is due to air pressure acting on the right-hand side of the piston.

When the solenoid coil is energised, a spool will get shifted in the valve and now the ports of the valve will get connected as shown by arrows in Fig. 1.1 (*b*). Port A gets connected to pressurised air while port B gets connected to exhaust. The piston will thus move forward to the extreme end due to air pressure on the left-hand side of the piston. In this arrangement also, of course a motor is used as drive for the air compressor or the pump (if fluid is used) to build up air or fluid pressure. Thus it is seen that a motor is the heart of all machinery whether its output is used directly or indirectly. In this text the main emphasis is on the study of control of motors. However some control circuits using solenoid valves will also be taken up. Now we will proceed to discuss methods of control of motors.

1.2 DISADVANTAGES OF MANUAL CONTROL

When electric motors were first introduced, simple manual switches were used to start and stop the motor. The only protective device used was the fuse. Progress was subsequently made along the lines of improving the reliability, flexibility and make-break performance of the manual switches. In those days one large motor was used to drive a line shaft through a belt pulley arrangement. Individual machines were then connected to the line shaft through belt and pulley arrangements. This system of driving a number of individual loads from a common line shaft and manual switching of motors had many disadvantages as listed below:

- Starting, stopping and speed control of motor had to be performed by hand every time. The operator had to move a manual switching device from one position to another.
- Switching of large motors required great physical effort.
- Operator had to remain continuously alert to watch indicators so as to adjust motor performance according to drive requirements.
- Sequence operations of number of motors could not be accomplished in common line shaft arrangement.
- The varied needs of individual machines like frequent starts and stops, periodic reversal of direction of rotation, high-starting torque requirement, constant speed, variable speed, etc., could not be accomplished in common line shaft arrangement.

1.3 INTRODUCTION TO MAGNETIC CONTROL

The disadvantages of common line shaft arrangement necessitated the use of small motors on individual machines instead of one large motor in line shaft arrangement. The use of individual motors on different machines made the machine shop or factory more flexible.

Introduction of electromagnetic CONTACTORS AND RELAYS, that is, devices actuated by electromagnets and requiring only a small power for actuation as compared to the power switched ON through their main contacts, led to the much desired control of machines possible. The word control means to govern or regulate. By control of a motor we mean regulation or governing of its various operations like starting, stopping, acceleration, reversal of direction of rotation, speed variation, protection etc. Fig. 1.2 shows the connections for manual and magnetic control of a small squirrel cage induction motor using push buttons.

In a simple manual control the motor starts when the main switch is closed by the operator. The motor is protected by fuses as shown in Fig. 1.2 (*a*). In Fig. 1.2 (*b*) an electromagnetic contactor is used to switch on the motor. Before we discuss the working of the circuit, it is essential to be familiar with the working principle of a contactor. Various types of contactors, however, will be discussed in detail in the next chapter.

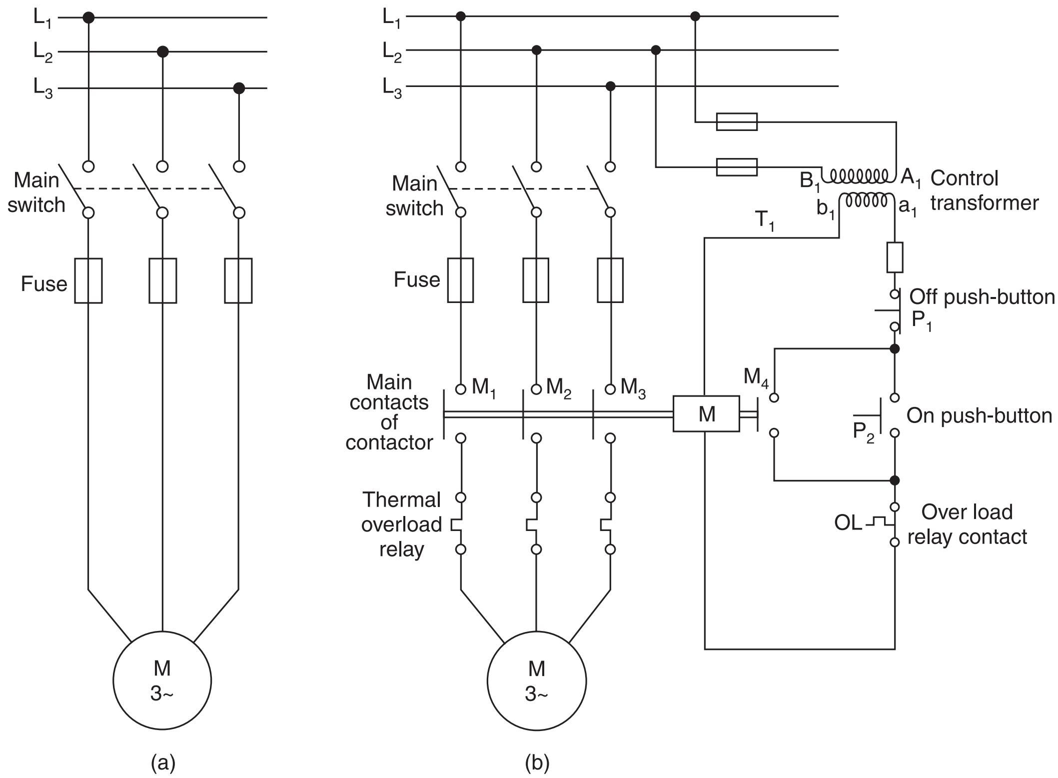


Fig. 1.2 Manual and Magnetic control of a small squirrel cage induction motor

In Fig. 1.3 it is seen that a coil is wound on the fixed core while the contacts are mounted on the moveable core, called the armature. The contacts remain in the normal position as shown in Fig. 1.3 (*a*) *i.e.*, when the coil remains de-energised. The spring (S) keeps the main and the auxiliary contacts in the position shown. In Fig. 1.3 (*b*) the contactor is shown with its coil in energised condition. As soon as the coil is energised, the armature *i.e.*, the movable core is attracted towards the fixed core against the pressure of spring (S). The contacts thus change their positions. The normally open main contacts close. Simultaneously auxiliary contacts also change their positions. The normally open contacts close and normally close contacts open. The main contacts are used for switching the power to the motor while auxiliary contacts are used in the control circuit. When the coil is again de-energised armature comes back to its original position due to the tension of the spring (S).

Now let us refer back again to the starting circuit of motor in Fig. 1.2 (*b*). In this figure there are two separate circuits, *i.e.*, the power circuit and the control circuit. Supply to the control circuit is isolated from the main supply using a control transformer T_1. Alternatively, a phase and neutral can also be used for providing supply to the control circuit. The motor can be switched ON and OFF with the help of push buttons. These push button switches require small force to actuate their contacts. These contacts remain operated as long as pressure is applied and they return to their normal position when pressure is released.

In this circuit when the ON-push button is pressed, contact P_2 closes. Supply from secondary terminal of the control transformer reaches the contactor coil through contacts, P_1 (OFF-push button), P_2, (ON-push button) and the over-load relay contact OL. The other terminal of the coil is connected directly to the terminal b_1 of the transformer. The coil is thus energised

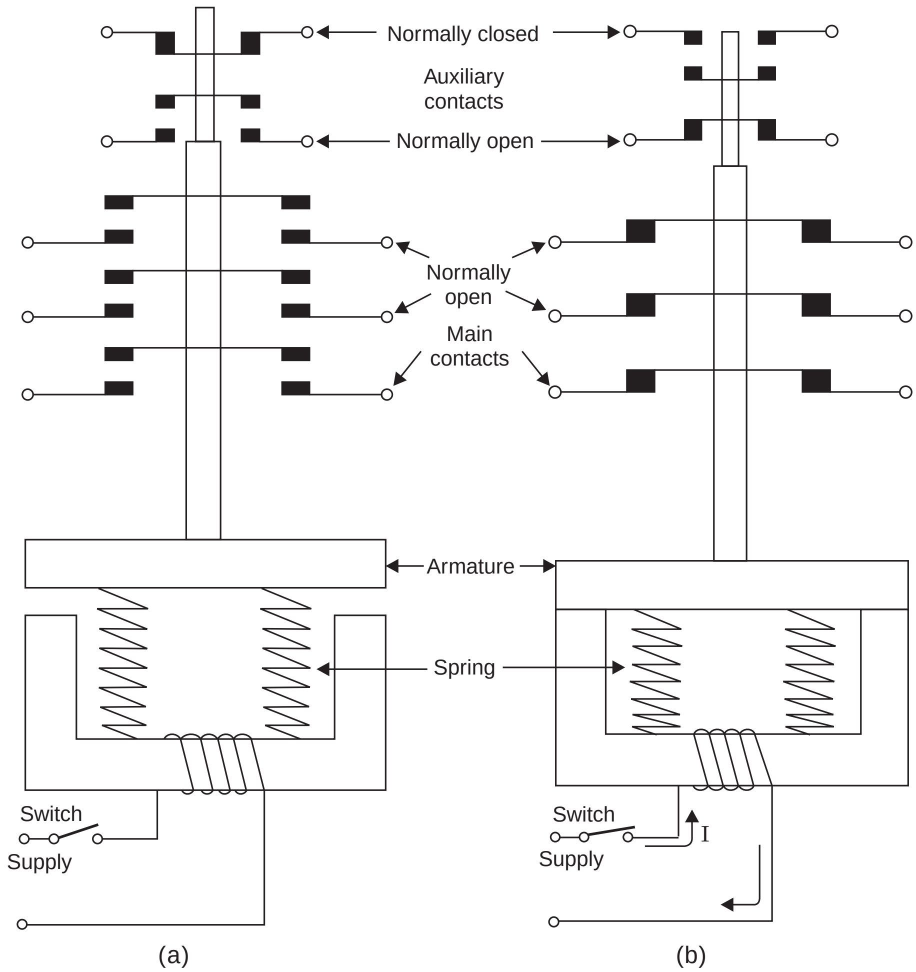


Fig. 1.3 Operation of an electromagnetic type contactor (*a*) coil de-energised (*b*) coil energised

and contactor closes its main contacts M_1, M_2, M_3 and the auxiliary contact M_4. Closing of contact M_4 bypasses ON-push button contact P_2. Now if pressure on the ON-push button is released contact P_2 will open but supply to contactor coil M would reach through closed contact M_4 connected in parallel with contact P_2. This contact M_4 is known as holding or sealing contact. A bimetallic thermal over-load is also shown connected in the power circuit. If motor draws more current than its rated value, thermal relay contact OL opens and de-energises coil M. De-energisation of coil opens the contacts M_1, M_2, M_3 and M_4. Supply to motor stops and holding of control supply through M_4 is also broken. Motor can also be stopped by pressing the OFF-push button. When OFF-push button contact P_1 opens, coil M is de-energised and thus holding of supply through contact M_4 is broken. Motor can be switched on again by pressing the ON-push button. This circuit that we have discussed is also known as direct-on-line starting of motors. This is the simplest control circuit in the field of industrial control.

1.4 ADVANTAGES OF MAGNETIC CONTROL

Having discussed the starting and stopping of a motor by using control devices like push buttons, contactors and over-load relays, we are in a position to discuss the advantages of magnetic control over the manual control. The various advantages are listed as follows:

- Magnetic control permits installation of power contacts close to motor whereas the actuating control device *i.e.*, a push button switch could be located away from the motor in a position most convenient to the operator.
- Magnetic control provides safety to the operator as remote operation described above minimises the danger to the operator of coming into accidental contact with live parts or being exposed to power arc and flashes at the main contacts.
- The most important advantage of magnetic control is the elimination of dependence on operators' skill for control of motor performance. Current and torque peaks could be limited thus resulting in less wear and less maintenance.
- Magnetic control also makes interlocking (to be discussed later) between various operations of a multi motor drive easy. The various operations can be performed in the desired sequence automatically.
- With the demand for more production in industry, it became necessary to automise the machinery to meet the challenge. Today in our industrial plants most of the machines are automatic. Once the machine is started most of the operations are carried out automatically.

1.5 SEMI-AUTOMATIC AND AUTOMATIC CONTROL OF MODERN MACHINERY

Control of a machine can be semi-automatic or fully automatic. There are probably more machines operated by semi-automatic control than by manual or fully automatic controls. Consider, for example, an over-head tank which supplies drinking water to a factory.

If we provide a manual switch near the pump motor and depute an operator to switch it ON when water level falls, then this is classified as manual control. Here, the operator has to go to the pump site to fill the tank. For the same pump if a magnetic starter is provided near the pump motor and for its starting, a switch is provided near foreman's desk it may be classified as a semi-automatic control. A lamp indication or a bell can also be provided near the desk to indicate if the tank is full. The foreman can switch ON the pump from his desk without going to the pump site. Over-flow can also be avoided by switching OFF the pump when the lamp glows or the bell rings. If a float switch is provided in the tank to switch ON the pump motor when water level falls below a certain lower limit, and switch it OFF when water level rises beyond a certain upper limit, then the control becomes fully automatic. The cost of installation of an automatic control system will be higher than the other two types of controls. However, an automatic control arrangement relieves the operator from the task of keeping an eye on the water level and operate the pump. Also there is no danger of over-flow from the tank. Thus it is seen that the basic difference in manual, semi-automatic and fully automatic control lies in the flexibility it provides to the system being controlled.

The study of control circuits involves study of the construction and principle of operation of various control components and learning the art of designing control circuits for various functions of machines. In this text, we have first discussed the various control components and then control schemes for ac and dc motors. Some important industrial control circuits have also been discussed.

Modern machines have large number of operations requiring extensive control circuits consisting of large number of relays. Thus the control panel occupies a lot of space and control circuit design also becomes tedious.

Static control is used for such machines as the control design is easy with static control devices. The static devices used for design of control circuits are the digital logic gates. With much advancement in the field of computers this static control is also becoming obsolete as more and more machines are now being controlled by programmable controllers. Inspite of all these developments as far as single motor control or a machine having few operations is concerned, the magnetic control using contactor and relay will continue to be in use because it is the simplest and cheapest method of control for such applications.

1.6 DEVELOPMENT OF CONTROL CIRCUIT

1.6.1 Development of Two-wire and Three-wire Control

In this section we will explain the various steps of developing a control circuit. A control circuit is to be drawn in a simple form between two horizontal lines designated by 1, which denotes a phase and by 0, which denotes the neutral wire. In this section also explained are some control functions like remote operation, inter-locking of drives etc.

As shown in Fig. 1.4 a motor is connected to supply through a switch fuse unit, a contactor, and an overload relay. For developing the control circuit, we take a phase say L_1 and neutral as shown in the figure. A control fuse is connected in phase L_1 and outgoing control supply wire is numbered 1 and neutral is numbered 0.

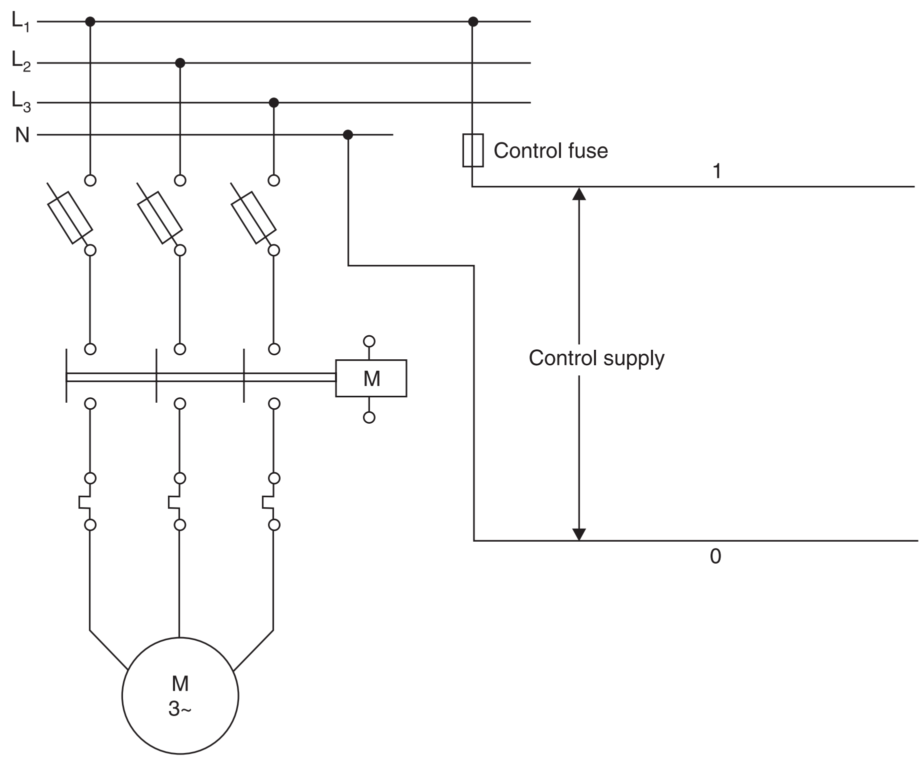


Fig. 1.4 Development of control circuit

Now we will study how the control circuit for energising a motor is developed. The motor is energised by closing the contactor and stopped due to opening of the contactor.

One method of designing of the control circuit is to connect a simple selector switch S and an overload relay control contact in series with control supply wire no. 1 and then connect it to contactor coil M as shown in Fig. 1.5. When switch S is open there is no supply at terminal 2 and, therefore, M remains de-energised. When the switch, S is closed supply reaches terminal 3 through the normally closed overload relay contact OL and thus the coil M is energised. The motor gets supply because of closing of the main contacts of the contactor (not shown in the figure). This control circuit just developed is known as two wire control. In this type of control circuit, however, the motor would automatically start when power supply to the motor is restored after a failure. This type of control is only useful for starting of motors at remote places, *e.g.,* starting of water pump for filling an over-head tank. Here the advantage is that the operator is not required to switch on the motor when power supply is restored after a failure. This type of control may however be dangerous in industries and can cause accidents due to sudden restarting of motors on restoration of power supply. Thus the control circuit of Fig. 1.5 has very limited application due to safety reasons.

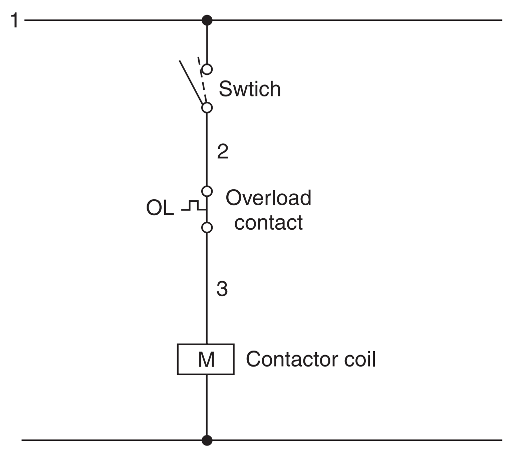


Fig. 1.5 Two wire control circuit

Now let us develop a control circuit using push button switches. The normally open contacts of these push buttons remain closed as long as the button is kept pressed by hand. Each push button has one normally open (NO) and one normally closed (NC) contact. To use a push button as stop (OFF) switch, the normally closed (NC) contact is generally used and for start (ON) operation the normally open contact (NO) is generally used. In Fig. 1.6 the stop and start push buttons and the over-load relay control contact have been connected in series with the contactor coil.

Under normal conditions as the STOP-push button contact is normally closed supply would reach upto terminal 2. When START-push button is pressed supply would reach the contactor coil and hence the contactor would get energised. The coil will remain energised as long as the START-push button is held pressed. As soon as the pressure on the START-push button is released, the supply is cut off at terminal 3 and the coil is de-energised. To develop the circuit further *i.e.*, to ensure that the coil remains energised permanently once the push button is pressed, we connect an auxiliary contact M_1 of contactor M in parallel with the push button as shown in Fig. 1.6 (*b*). When the coil M is energised, along with the main contacts the auxiliary contact M_1 also closes. The supply from terminal 2 now has two parallel paths *i.e.*, one through the closed contact of the START-push button and the other through the closed contact M_1. Thus even when the pressure on the START-push button is released, supply reaches coil M through closed contact M_1. Thus supply to coil M is held (or sealed) through its own

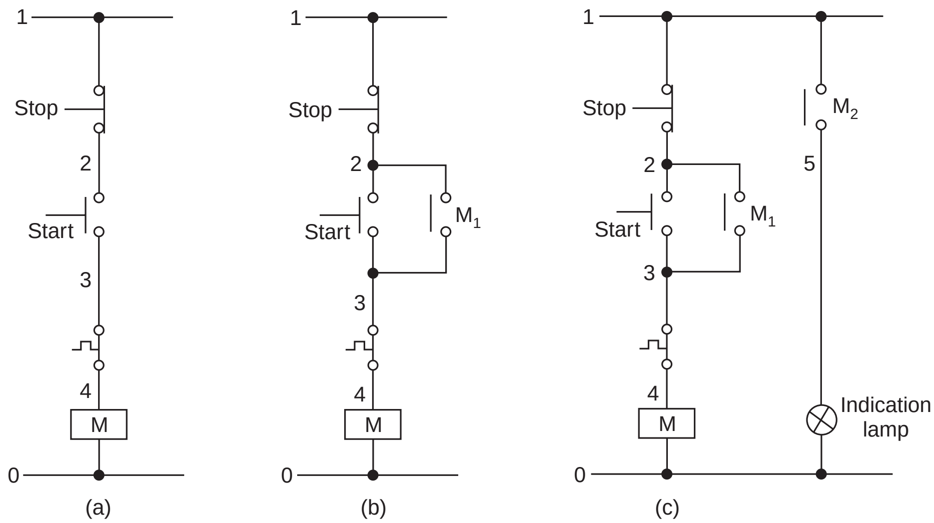


Fig. 1.6 Development of three wire control circuit

contact M_1. When it is desired to stop the motor, the STOP-push button is pressed and therefore its normally closed contact opens and the coil M gets de-energised. De-energisation of coil M also opens its sealing contact M_1. Thus when the pressure on the STOP-push button is released the coil does not get energised as both the parallel paths *i.e.*, of the START-push button and that of contact M_1 are open. To start the motor again the START-push button has to be pressed. It is therefore seen that unlike the control circuit of Fig. 1.5, here the control circuit does not get energised when the power supply gets restored after a failure. Thus the danger of motors getting restarted on restoration of power supply is eliminated. In case of over loading of the motor the over-load relay contact opens and supply is disconnected at terminal 4 thereby de-energising the contactor and subsequently stopping the motor. Even if the over-load protective device is of auto reset type *i.e.*, if its contact closes when the bimetallic elements cool down the motor would not start on its own. However, in the two wire control circuit as in Fig. 1.5, if the overload relay is of auto reset type the motor would restart automatically. Thus the motor may get damaged due to repeated on-off on over loading. The control, we have just discussed in Fig. 1.6, is known as three wire control. This designation is given because in this control circuit, three wires lead from a pilot device to the starter. The term two wire and three wires are used as they describe the simplest application of the two types. Actually in control circuits any number of wires can start from a pilot device in a three wire control. The control contact M_1 used in parallel with the START-push button is called the holding contact or sealing contact. The name is so because it holds/seals the contactor coil in the energised condition even when START-push button switch is released. The step in further development of the circuit is to have a 'motor ON' indication. An auxiliary contact M_2 of contactor M is connected in series with supply wire 1 to feed an indicator lamp terminal. Its other terminal being connected to the neutral as shown in Fig. 1.6 (*c*).

1.6.2 Remote Control Operation of a Motor

In further development of circuit of Fig. 1.6 (*c*) it may be desired that starting and stopping of the motor should also be possible from a distant place (remote place) while the starter being fixed near the motor. In this case, obviously, the control wire will have to be taken to the remote START and STOP-push buttons from the starter. Now, it is to be seen as to how the remote START-STOP push buttons should be connected to the circuit of Fig. 1.6 (*c*). The required connections for remote control have been shown in Fig. 1.7.

The remote STOP-push buttons have been connected in series with local STOP-push button and the remote START-push button has been connected in parallel with local START-push button. The motor can be started and stopped from any number of locations by making connections as above *i.e.*, by connecting all the STOP-push buttons in series and all the START-push buttons in parallel. If the motor is to be started by some other pilot device like pressure switch, thermostat etc., the same may be made by connecting such a device in parallel with START-push button. If such a device is to be used for stopping also it is to be connected in series with the STOP-push button.

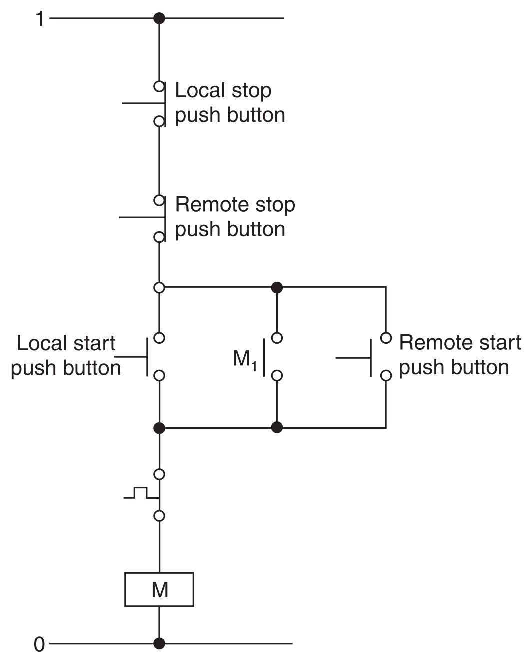


Fig. 1.7 Control circuit for remote operation of a motor

1.6.3 Interlocking of Drives

We well now see how the control function of interlocking of drives is incorporated into the circuits. Let us take motors *A* and *B*. It is required that motor *B* should start only after motor

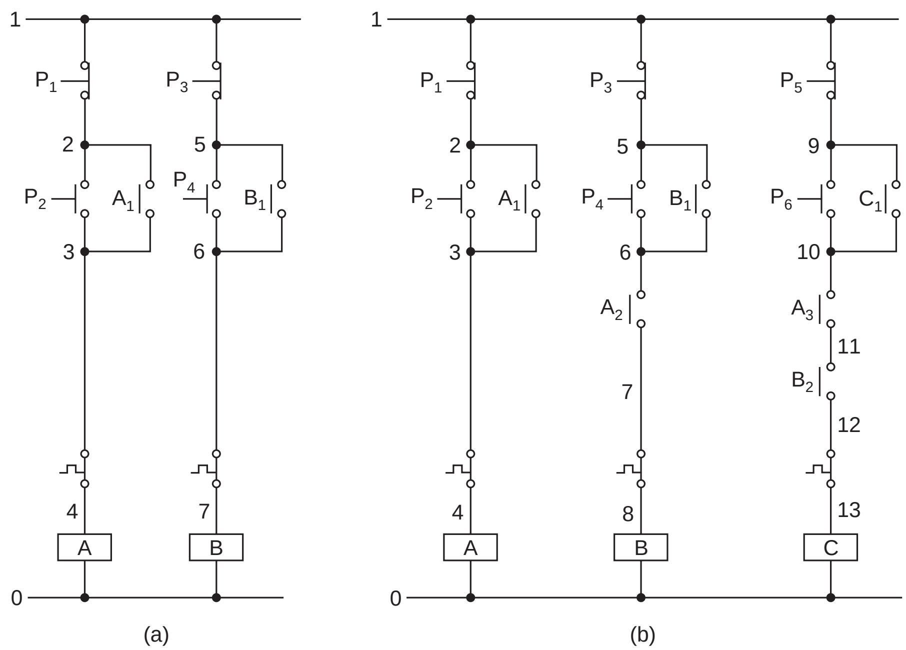


Fig. 1.8 Interlocking of drives

A has started. It should however be possible to stop the motor independently. The first step would be to develop the starters of motor *A* and motor *B* independently as shown in Fig. 1.8.

In order that contactor *B* should energise only when contactor *A* is energised we will have to insert a normally open contact of contactor *A* in series with the contactor coil *B* after terminal 6 as shown in Fig. 1.8 (*b*). As shown in the figure a normally open contact A_2 has been connected after wire No. 6. Thus when contactor *A* is not energised the contact A_2 will be open. If we press the push button P_4 the supply will reach upto terminal 6 only. The contactor coil *B* can be energised only when contactor *A* is energised *i.e.*, only when its contact A_2 is closed.

If in the above circuit it is further required that a motor *C* should run only if both motors *A* and *B* are running, we will be able to get this function by connecting normally open contacts of contactor *A* and *B* in series with the coil of contactor *C*. This development is also shown in Fig. 1.8 (*b*). When push button P_6 is pressed the supply will reach coil of contactor *C* at terminal 13, only if contacts A_3 and B_2 are closed *i.e.*, only when both contactors *A* and *B* are energised. When either of the two motors is not running motor *C* can not be started.

REVIEW QUESTIONS

1. State the disadvantages of using manual control for control operations of electrical motors.

2. Name the devices which led to the use of automatic control for motors.

3. State the advantages of magnetic control over manual control.

4. What is the difference between semi-automatic and automatic control?

5. What will happen if the plunger of a contactor is prevented from completing its stroke?

6. When will a contactor coil take maximum current and why?

7. Under what conditions static control is preferred against magnetic control?

8. Explain why magnetic control is used for control having few operations.

9. State the difference between a two wire and a three wire control.

10. When the plunger of a contactor is in closed position the coil current is:

(*a*) maximum

(*b*) minimum

(*c*) zero.

11. When the contactor coil is de-energised:

(*a*) the contacts remain closed

(*b*) are held closed by mechanical latch

(*c*) gravity and spring tension open the contacts.

12. The purpose of using over load protection in a motor is to protect the motor from:

(*a*) sustained overcurrent

(*b*) over voltage

(*c*) short circuit

(*d*) all the above.

2

Control Circuit Components

2.1 INTRODUCTION

All components used in motor control may be classified as either primary control devices or as pilot control devices. A primary control device is one which connects the load to the device, such as switch, fuse switch unit, circuit breaker, contactor, overload relay etc. Pilot devices are those which control the primary control devices. Pilot devices comprise items like selector switch, push button switch, float switch, pressure switch, limit switch, thermostat etc. Fig. 2.1 shows the control scheme in block diagram form of an induction motor for an air compressor.

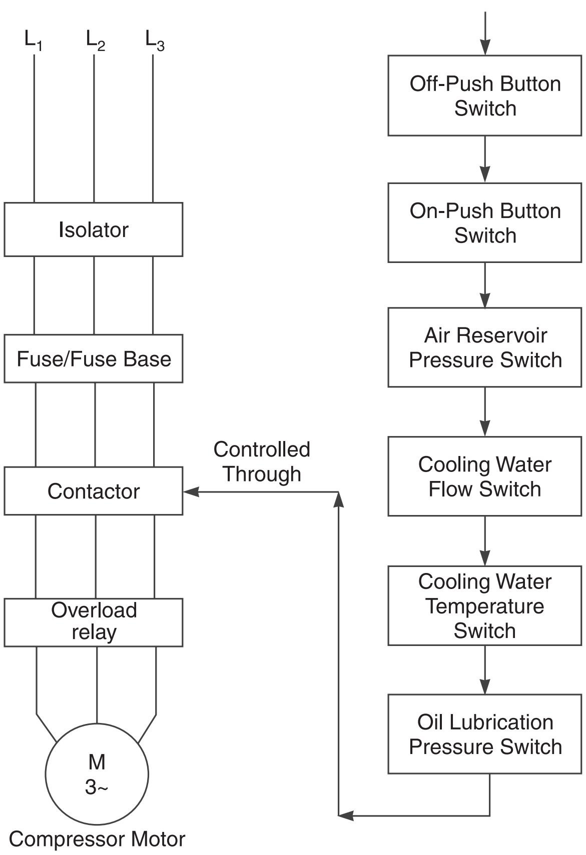


Fig. 2.1 Block diagram for automatic control of a compressor motor

As shown in Fig. 2.1 power to the compressor motor is controlled *i.e.*, switched ON or OFF through a contactor. Contactor closes its main contacts when its coil is energised. As shown in the block diagram the contactor coil is controlled through the following:

(*a*) Oil lubrication pressure switch: The contactor is switched off if oil lubrication pressure for compressor falls below a certain limit;

(*b*) Cooling water temperature switch: The contactor is switched off if the temperature of water being used for cooling the compressor rises above a certain limit;

(*c*) Cooling water flow switch: The contactor is switched off if flow of cooling water to the compressor stops;

(*d*) Air reservoir pressure switch: The contactor is switched off when air pressure in the reservoir becomes higher than the set limit;

(*e*) ON-push button: The contactor is energised initially through ON-push button when all the above mentioned conditions are favourable to run the compressor;

(*f*) OFF-push button: Pressing of the OFF-push button at any time will switch off the contactor due to the de-energisation of its coil.

From the block diagram it is clear that control of the compressor motor involves use of two separate circuits. One is the power circuit which consists of isolator switch, fuse, contactor and overload relay. The second circuit is control circuit which consists of ON and OFF push button switches, pressure switches for the lubricating oil of the compressor and for air in the reservoir, flow switch and temperature switch for cooling water of the compressor. All these components in the control circuit are pilot devices and provides a means for controlling the motor.

In the following sections all these primary control devices and pilot control devices have been discussed.

2.2 FUSES, SWITCHES AND FUSE SWITCH UNITS

Both the power circuit and the control circuit of a control scheme are protected against short circuit faults by means of fuses. Short circuit faults may occur due to mistakes made during wiring, fault within the motor winding, or due to mechanical injury to the cable and wires.

A fuse is a calibrated conductor which melts and breaks the circuit when current passing through it increase beyond its calibrated value. The fuse element melts due to generation of excessive heat under short circuit condition and thus isolates the circuit from the source of power supply.

Figure 2.2 shows the construction of a typical high rupturing capacity (HRC) fuse link.

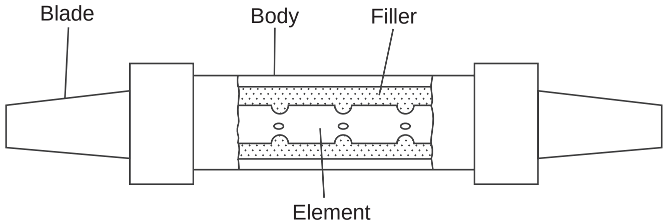


Fig. 2.2 Construction of a typical HRC fuse

The fuse element is surrounded by a filler material such as quartz sand which provides effective heat transfer. The fuse exhibits inverse time current characteristic to the heat transfer from the element. The fuse element can sustain small overloads for longer duration but in case of large overloads and short circuits the small cross-section of the fuse element melts quickly and opens the circuit. Fig. 2.3 shows the typical time characteristic of a HRC fuse.

Fuses are provided into the circuit through fuse base and fuse carriers generally made of bakelite material. Fuse is inserted in the fuse carrier which is then fixed into the fuse base.

Figure 2.4 (*a*) shows the power circuit for a motor. It includes four necessary elements for the control and protection of motor. None of the items used can be eliminated as they incorporate four basic functions very different in nature.

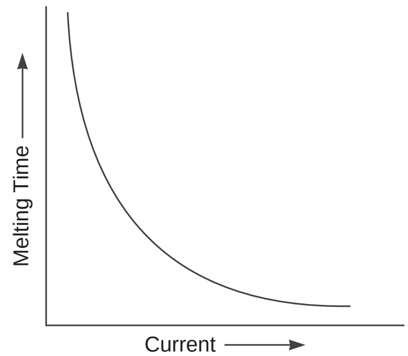


Fig. 2.3 Characteristic of a HRC fuse

Switch: To isolate the circuit for repairs and maintenance,

Fuse/Fuse base: To provide short circuit protection,

Contactor: To achieve automatic on-off of motor,

Overload relay: To protect the motor against overloading.

Development of a new type of switch gear, called fuse switch unit, has led to the use of a modified power circuit as shown in Fig. 2.4 (*b*). This fuse switch unit came into existence when the fuse base was integrated with switch.

The advantages of using fuse switch unit are that the number of electrical joints becomes less due to the elimination of one element from the circuit and hence requires less maintenance, and the space occupied is less as the combination fuse switch occupies less space than fuse/fuse base and switch when used separately.

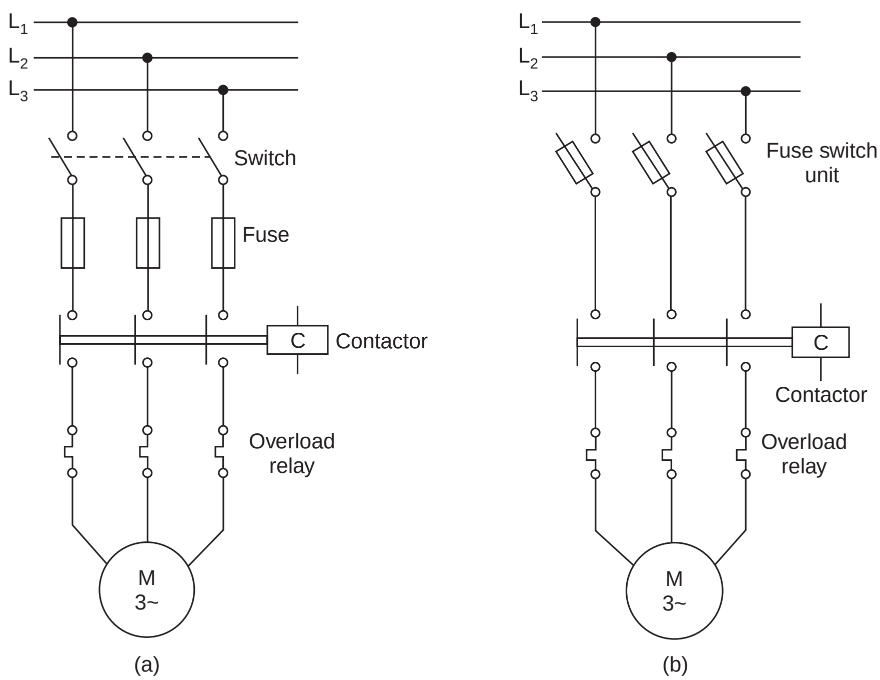


Fig. 2.4 Two types of power circuits for motor

Fuse switch units are of two types, namely, (*i*) where the fuse is stationary and (*ii*) where the fuse is mounted on the moving assembly. Both the above types are in use. However, the one having stationary fuse has the following advantages over the other type.

— The moving assembly weight is less as it does not carry the fuse, thus it is more reliable against mechanical failure.

— There is less deterioration of electrical joints between fuse and fuse switch.

Switches and fuse switch units are manufactured upto a rating of 1000 A, 415 V with breaking capacity of 50 KA. They are manufactured in standard ratings. For example Larsen & Toubro Ltd. manufacture these in the ratings of 63 A, 100 A, 250 A, 400 A, 630 A and 800 A while Siemens manufacture in standard ratings of 200 A, 400 A and 600 A. Switches and fuse switch units are available in three-pole (TP) type and three pole neutral (TPN) type.

2.3 MOULDED CASE CIRCUIT BREAKER AND MINIATURE CIRCUIT BREAKER (MCCB & MCB)

A slow and steady change to moulded case circuit breakers and miniature circuit breaker as an alternative protection system to fuse switch units and air circuit breakers is taking place in the Indian industry. As a result, distribution and control system without fuse are being designed today.

Miniature circuit breakers are manufactured in 1, 2, 3 and 4 pole versions upto fault levels of 10 KA. They find applications in protection of lighting circuits, sub-distribution and control circuits. Moulded case circuit breakers are available in higher ratings. L & T manufactures MCCBs of rating 100 A, 200 A, 250 A, 450 A, 630 A, 800 A, 500 V, 50 Hz with fault level withstanding capacity of 50 KA. They cover a wide range of applications in circuit protection in branch feeders, motor circuits, transformer secondaries, lighting distribution systems, capacitor switching and DC circuits.

Figure 2.5 shows a DTH 100 L & T make MCCB.

Fig. 2.5 Photographic view of a Moulded Case Circuit Breaker

An MCCB automatically isolates an electrical circuit under sustained overloads or short circuits. A thermal release consisting of bimetallic elements having inverse time current tripping characteristic trips the circuit breaker on sustained overload.

The breaker is opened by an electromagnetic release in case of short circuit faults. When the current is less than 10 times the setting of the thermal release the breaker trips due to thermal release and when current exceeds 10 times its value, the breaker is opened by magnetic release. The main features of a MCCB are:

- The breaker is switched on by a toggle type switch. The operating mechanism is "quick-make, quick-break" and is independent of manual operation. The breaker cannot be held closed under fault conditions.
- The housing is made of heat resistant insulating material. All parts are enclosed in the housing except terminals which are accessible for external connections. Terminals have large dimensions to accept links or cable lugs.
- All phases are disconnected even when a fault occurs on only one of them. The operating switch gives a clear trip indication. It assumes a position midway between ON (1) and OFF (0) on tripping.
- Arc chutes envelope each contact and draw the arc away from the contact tips thus quenching it rapidly. Silver alloy contacts having high arc resistance and long electrical life are used.

The magnetic thermal release has three bimetals to provide thermal overload protection and has an electromagnet for short circuit protection.

The magnetic thermal release is direct acting. The settings of thermal as well as magnetic release are adjusted over a wide range.

MCCBs offer a number of advantages over conventional breakers and fuse switch units. They are:

(*i*) Operating switch is easy to handle. There is no down time and need for replacement of fuse. After the breaker trips, it can be switched on again simply by resetting it. When the breaker trips, the operating switch occupies mid-position between ON (1) and OFF (0). To reset the trip mechanism the operating switch is to be moved to OFF-position.

(*ii*) In fuse switch units blowing of fuse on one of the phases results in single phasing. This problem is eliminated in MCCBs because a common trip bar ensures opening of all the phases even when a fault occurs on only one of them.

(*iii*) MCCBs are five to ten times smaller in size and weight as compared to conventional air circuit breakers and fuse switch units of similar ratings. This results in saving on panel space and supporting structures. Table 1 shows range of L & T make DTH type MCCBs.

Table 1 L & T make standard DTH type MCCBs

Standard rating	*Setting range of thermal relay*	*Short circuit rating*
DTH-100	12-100 A	700 A non-adjustable
DTH-250	80-150 A	375-2000 A adjustable
DTH-400	225-400 A	960-2560 A adjustable
DTH-630	360-630 A	1500-4500 A adjustable
DTH-800	600-800 A	2600-6400 A adjustable

2.4 CONTACTORS

A contactor can be best described as a magnetically closed switch. It is the basic unit upon which the motor starter is built. Contactors are also used for switching ON and OFF of heavy loads like furnaces, heaters, capacitors, etc. A contactor consists of an electromagnet, a movable core, sets of stationary and moving contacts and an arc quenching structure. Contactors can be broadly classified in to two general types:

(*a*) Solenoid type

(*b*) Clapper type

There are other contactors for specific applications such as lock-out type and inductive accelerating type used in dc motor controls.

2.4.1 Solenoid Type Contactor

In this type the movable contacts are attached to the movable core of a magnet. When the electromagnet coil is energised, the movable core is pulled to the stationary core, thus closing the contacts. Fig. 2.6 (*a*) shows a solenoid type contactor. For better understanding, the contacts have been shown mounted in vertical plane though actually the contacts are in horizontal plane.

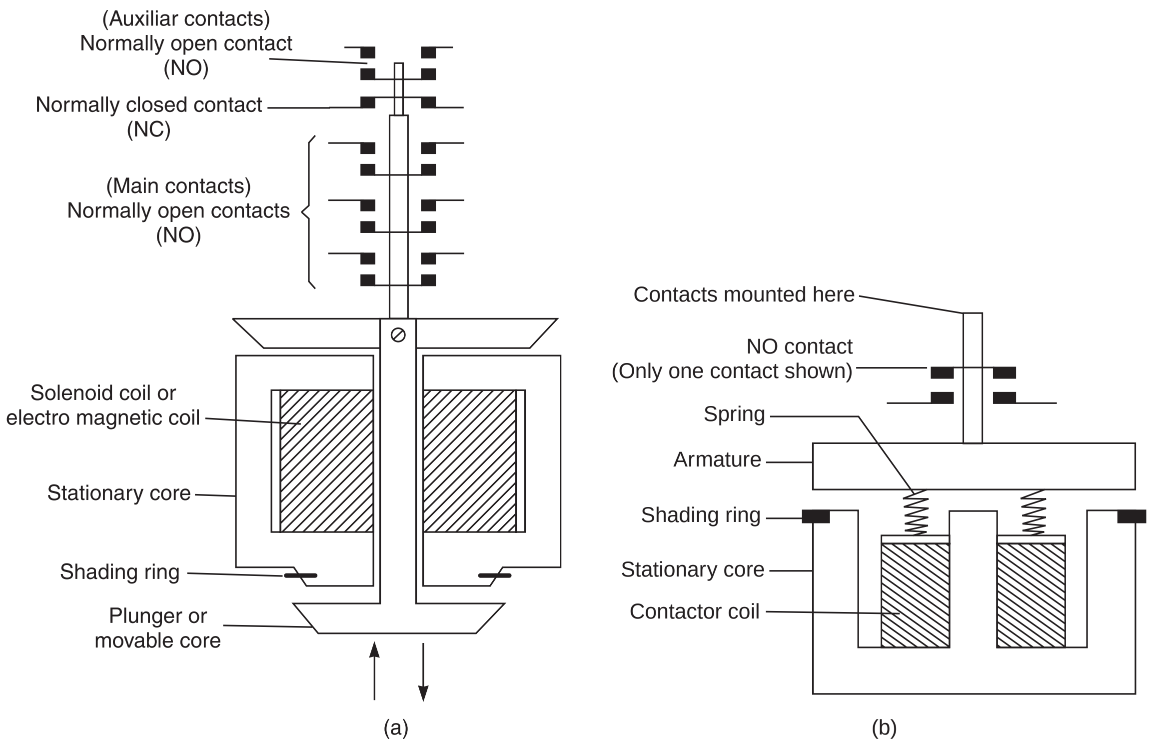


Fig. 2.6 (*a*) Solenoid type contactor (*b*) Contactor with E-type magnetic core

Mounting of contacts in horizontal plane reduces the size of the contactor. The position of plunger *i.e.,* movable core shown in the figure is for the coil in de-energised state. When the coil is energised, plunger moves up, moving contacts mounted on plunger also moves up and closes the normally open contacts. At the same time normally closed contacts open. When the coil is de-energised contacts are broken and they come back to their normal position by the pull of gravity.

The pole face of the magnet are provided with shading coil. This creates an out of phase flux to hold the magnet closed during the zero points of alternating current thus preventing chatter of the contactor. For contactors of higher ratings where chattering noise is to be avoided, dc coil is used. The solenoid type of contactors shown in Fig. 2.6 (*a*) are used for small ratings. For higher ratings *E* type construction for the magnetic core is used. A contactor with *E* type magnetic core is shown in Fig. 2.6 (*b*).

Symbols used for contactor coil, contactor with main and auxiliary contacts, and photographic view of a contactor have been shown in Fig. 2.7.

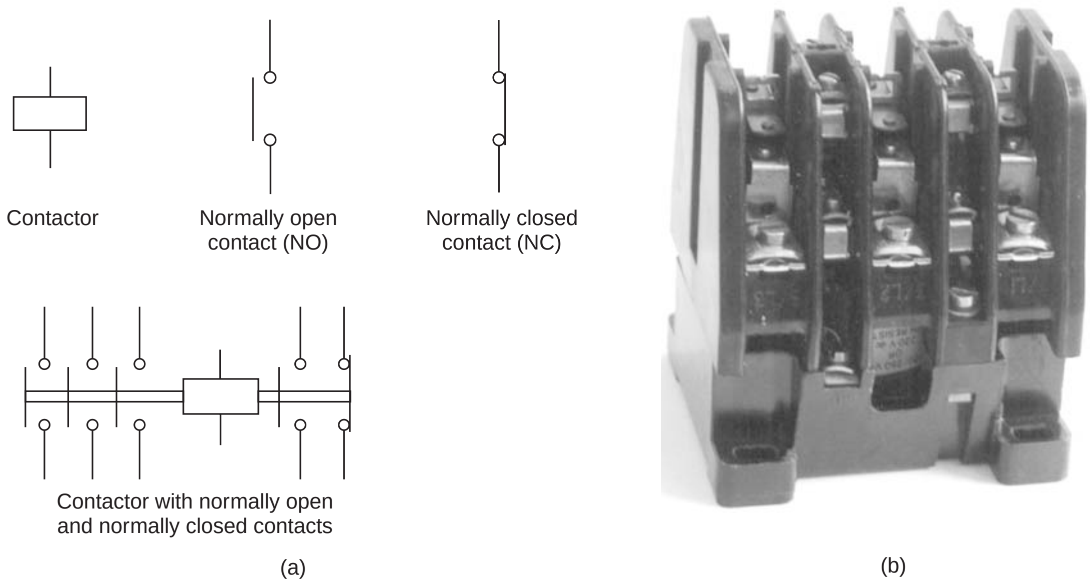


Fig. 2.7 (*a*) Symbols for contactor coil and contacts (*b*) Photographic view of a contactor

2.4.2 Clapper Type Contactor

In clapper type dc contactors the movable contacts are mounted on a hinged movable armature. The hinged armature when pulled by magnetic core moves the movable contact in more or less in the horizontal direction to make contact with the stationary contact mounted on the vertical back-plate of the contactor.

Figure 2.8 shows the general arrangement of the core, coil, contacts etc., of a clapper type dc contactor. The magnet is shown to consist of a round solid core on which the coil is mounted and a bent piece on which the moving armature is hinged. All parts of the magnetic circuit are made from a soft steel having high permeability. The moving armature carries the movable contacts. When the coil is energised the armature is attracted towards the core causing the movable contacts to close against the stationary contacts. A movable contact is not rigidly attached to the armature but is held in place by a spring and bolt. When the armature fully closes, a spring exerts a force on the movable contact. The amount of force to be applied on the moving contact can be varied with the help of a bolt on which the spring is fixed. Arcing horns are provided on both the fixed and movable contacts. Arc shifts towards the arcing horns during interruption thus saving the main contacts from damage. A blow out coil is also provided to extinguish the arc. The action of blow out coil is shown in Fig. 2.9.

A blow out coil is circular strip having an insulated solid core inside. Current flows from fixed contact through the circular strip to the outlet terminal.

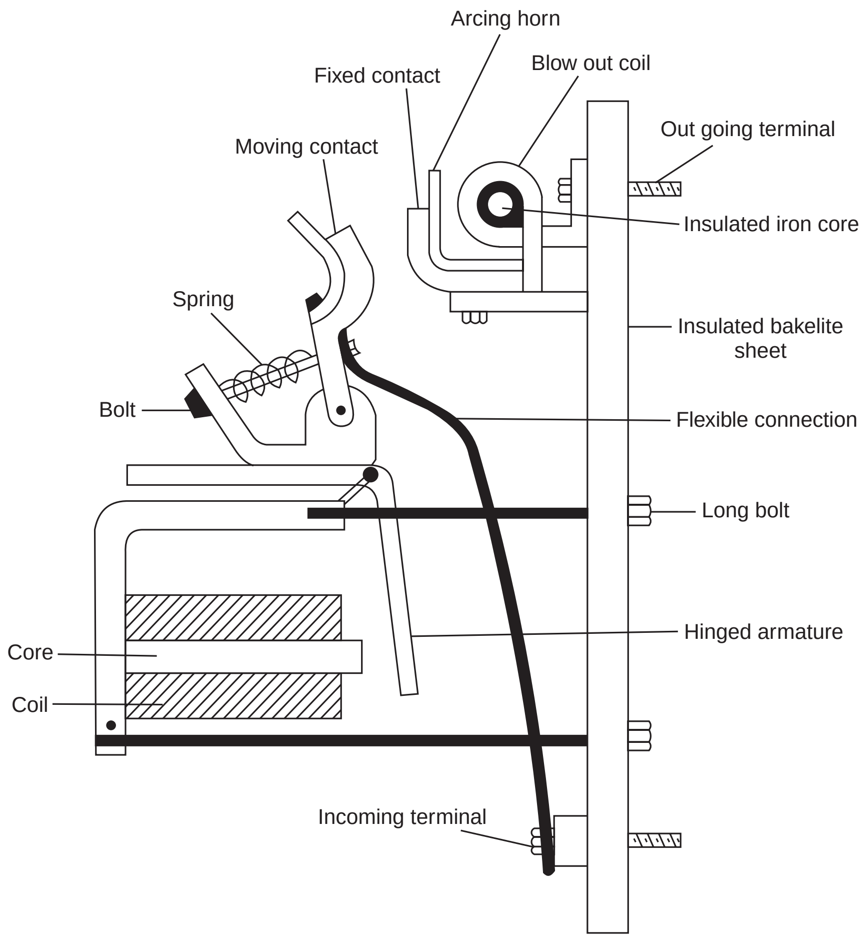


Fig. 2.8 Construction of a clapper type contactor

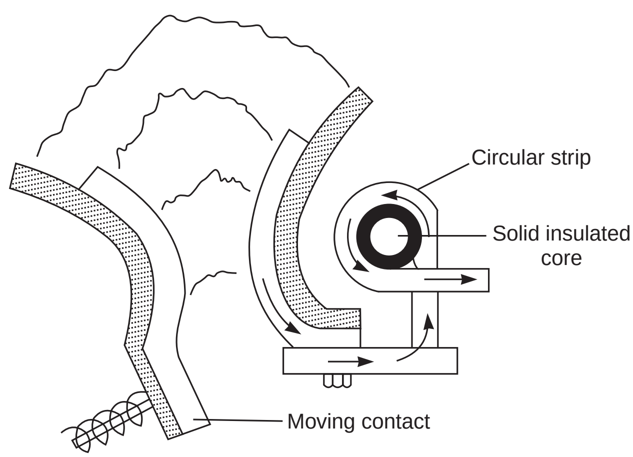


Fig. 2.9 Action of blow out coil

When the contacts separate, the magnetic field set up due to current flowing through the blow out coil exerts a force on the arc. Due to this force arc is elongated between the arcing horns. The arc chutes provided over the fixed and moving contacts also help in quenching the arc due to cooling action. Arc chutes also help to confine the arc and help avoid striking other structural parts. The force exerted by magnetic coil on the arc depends upon the current flowing through the coil. Force exerted is proportional to the square of the load current.

A shunt blow out coil is sometimes used in contactors when current to be interrupted is small. In this arrangment a constant blow out flux is obtained independent of the load current. A similar effect is sometimes obtained by the use of a permanent blowout magnet.

AC contactors of large rating are also built in clapper type with dc coil.

2.4.3 Lock-out Type Contactor

This type of contactor was primarily designed for the starting circuit of dc motors. Lock out contactors are used for cutting the resistance of the armature circuit of a motor in steps. The contactor is so designed that its contacts normally remain open. They also remain open during the inrush current on starting of motors. The contactor consists of two coils *i.e.,* a closing coil and a lock-out coil. The lock-out coil prevents the contactor from closing during the inrush current of the motor.

The magnetic circuit of closing coil (A) is made of such magnetic material which gets saturated easily. The magnetic circuit of the lock-out coil has air gaps and does not get saturated easily. The pull exerted by the lock-out coil, therefore, varies much more widely with changes in current than the pull of closing coil. The graph in Fig. 2.11 shows torque versus current characteristics of both coils.

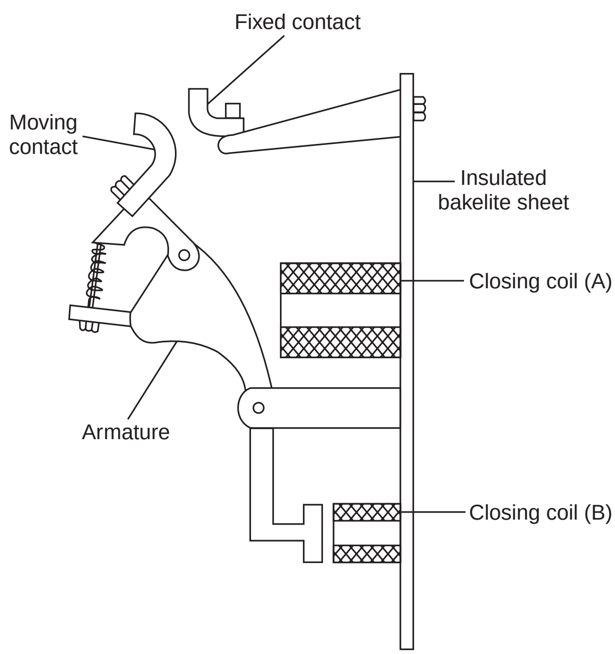


Fig. 2.10 Lock-out type contactor

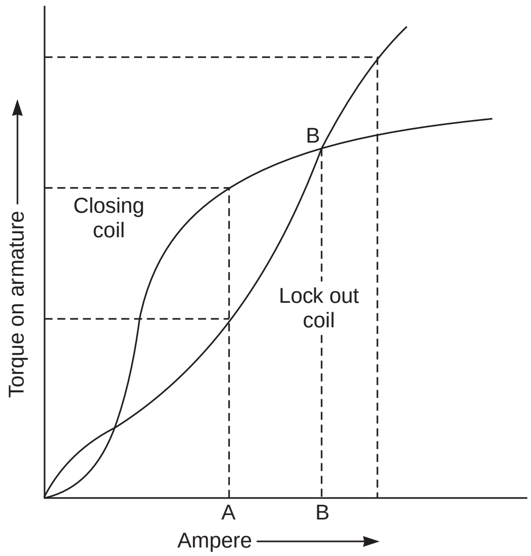


Fig. 2.11 Torque versus current characteristic of coils

Both the closing coil and the lock-out coil are connected in series with the motor circuit. During starting, high inrush current flows which is beyond point *B* (see graph). For point beyond *B* armature pull of lock-out coil is much greater than that of the closing coil (see graph), thus the contacts remain open due to armature being pulled by lock out coil. As the current drops below *B* the pull on armature increases for closing coil (refer point A on the graph) and therefore the armature is pulled by the closing coil and the contacts close. The closed contacts shorts the resistance in the armature circuit of the motor. The circuit is so arranged that when the contactor closes the lock out coil is short-circuited thereby preventing it from opening the contactor. This ensures that the contactor will remain closed after it has operated. In some contactors closing coil may be shunt wound connected directly across the line. This removes the disadvantage of possible opening of the series connected closing coil on low loads. However, any variations in line voltage would affect the setting at which the contactor would close.

At one time lock out accelerating contactors were very popular due to their simplicity. Now due to development of better and simpler accelerating means they are rarely used.

2.4.4 Inductive Accelerating Contactors

It is similar in appearance to the double coil lock out type contactor. However its lock out coil (also known as hold out coil) magnetic circuit is highly inductive. The magnetic circuit of the hold out coil is so designed that a certain fixed duration of time is required for the flux to die down to a value to permit the closing coil to close the contactor. This time may be varied by varying the air gap in the hold out magnetic circuit. The relative strengths of the closing coil and the hold out coil is so adjusted that the contactor remains open with full line voltage on closing coil and approximately 1 per cent of full line voltage on the holdout coil.

The closing coil and hold out coil are energised at the same time and then the hold out coil is short-circuited. The shor circuiting of holding coil will result in slow decay of flux in its magnetic circuit. The closing coil will close the contacts when flux of hold out coil falls to a certain low value. This type of contactors are also used in dc motor starting for cutting the armature resistances in steps.

2.5 CONTACTOR RATINGS

Table 2 shows the technical details of Larsen & Toubro make ML_2 type contactor.

A close look at these technical details shows that the contactor has different ratings for different types of duties designated as AC_1, AC_2, AC_3 and AC_4. Table 3 shows typical application of contactors for different types of duties. ML_2 contactor has a rating of 40 A for resistive loads and 32 A for motor loads (L & T) make.

Table 2 Technical details of L & T make ML_2 type contactor

MAIN CONTACTS NO. of contacts – 3 Nominal Rating – 32 A at 415 V, 50 Hz	*Economy Resister Kits*
AC RATINGS AT 415 V, 50 Hz AC_1 – 40 A AC_2 – 32 A AC_3 – 32 A/20 HP (15 KW) AC_4 – 32 A/20 HP (15 KW) Capacitor – 20 KVAR	*Permissible Switching Frequencies at Rated Current*
AUXILIARY CONTACTS No. of contacts – 2NO + 2NC Rating at 415 V – 6A 50 Hz	*Other Details* Mechanical life – 10 million operations Making capacity at 50 Hz – 384 A A at 0.35 P.F. & 500 V & 400 A at 0.35 P.F. & 457 V Breaking capacity 320 A at 0.35 P.F. Pick-up time 9 – 18 m secs Drop-off time 7 – 21 m secs Weight unpacked 0.95 kg
TERMINAL SIZE IN sq mm Lugs upto – 50 sq mm Wires upto – 2 × 2.5 mm	
COIL Standard coil – 110, 230/250, 360 Voltages 42, 400/440	
CONSUMPTION During closing 120 V A When closed 20 VA (8.5 W)	

Economy Resister Kits

Cat No.	To be used with standard coil rating.	Coil rating after addition of economy resistance
	230/250 V AC	220 V DC
	110 V AC	110 V DC
	42 AC	42 V DC

Permissible Switching Frequencies at Rated Current

Duty	Operation per hour/contact life at rated current
AC_1	750 –
AC_2	750 – 500, 000
AC_3	750 – 3000, 000
AC_4	250 – 100, 000

Table 3 Application of contactors/for different type of duties

Category		*Type of Duty*
AC	AC_1	Non Inductive or slightly inductive loads, resistance furnaces.
	AC_2	Starting of slip ring motors, Reverse current breaking
	AC_3	Starting of squirrel cage motors, switching off motors during running.
	AC_4	Starting of squirrel cage motors, plugging, inching.
DC	DC_1	Non inductive and slightly inductive loads, resistance furnaces.
	DC_2	Starting shunt motors, switching off shunt motors during running.
	DC_3	Starting shunt motors, plugging, inching
	DC_4	Starting series motors, switching of series motors during running.
	DC_5	Starting series motors, plugging, inching

From the technical details it is also seen that the same contactor can be used with a dc, control supply also. Resistors are connected in series with the ac standard rating coils for use on dc supply. The electromagnetic coil picks up positively between 85 and 110 per cent of the rated coil voltage. The drop off voltage for ac operated models is roughly between 65 and 45 per cent and for dc operated models it is between 45 and 20 per cent of the rated coil voltage.

The contact material used is silver alloy so as to avoid welding tendency of pure silver. Some of the common alloys used are:

— Silver Nickel

— Silver Cadmium Oxide

— Silver Tin Oxide

Silver Nickel is good for contactors of lower ratings upto about 100 A. For higher size of contactors, silver cadmium oxide is used as it has superior anti-weld property. The latest innovation is the use of Silver Tin Oxide ($AgSnO_2$) for contactors of higher ratings. Notable advantages of Silver Tin Oxide are:

- Erosion of contacts is very less
- No toxic effect because of absence of cadmium.

Table 4 gives standard ratings of contactors manufactured by Larsen & Toubro and Siemens India Ltd.

Table 4 Standard contactor ratings

L & T Make Type: Nominal Rating at 415 V, 50 Hz		*Siemens Make Type: Nominal Rating at 415 V, 50 Hz*	
MM_{00}	10 A	0	10 A
ML_0	12 A	1	16 A
ML_1	16 A	2	32 A
$ML_{1.5}$	16 A	4	70 A
ML_2	32 A	8	170 A
ML_3	40 A		
ML_6	110 A		
ML_7	125 A		
ML_{10}	200 A		
ML_{12}	300 A		

2.6 RELAYS

The literary meaning of the word relay is to transmit information. The function of relays in control circuit is also the same *i.e.*, to sense or accept information from some sensing device and feed it into control circuit at proper level. The sensing devices used in conjunction with relays are known as pilot devices. Pilot devices, as described earlier, can sense or detect variables like current, voltage, overload, frequency, temperature, pressure and many others. Besides accepting information from pilot devices relays are also used to multiply the contacts available on pilot devices. Timing relays may be used to count or to insert time delays in a control circuit. In big machines large number of pilot devices like limit switches, proximity switches, pressure switches etc., are used to control various operations. Relays are used to locate the complex wiring in the panel by eliminating interwiring between pilot devices. Though extra expenditure on account of using relays is involved, a lot of time is saved in trouble shooting *i.e.*, locating faults in the control circuit. Figs. 2.12 (*a*) and (*b*) show how an air compressor motor control circuit having four pilot devices can be wired with and without relays. The function of various pilot devices used for control of compressor motor has already been discussed in the beginning of the chapter (refer introduction to control components).

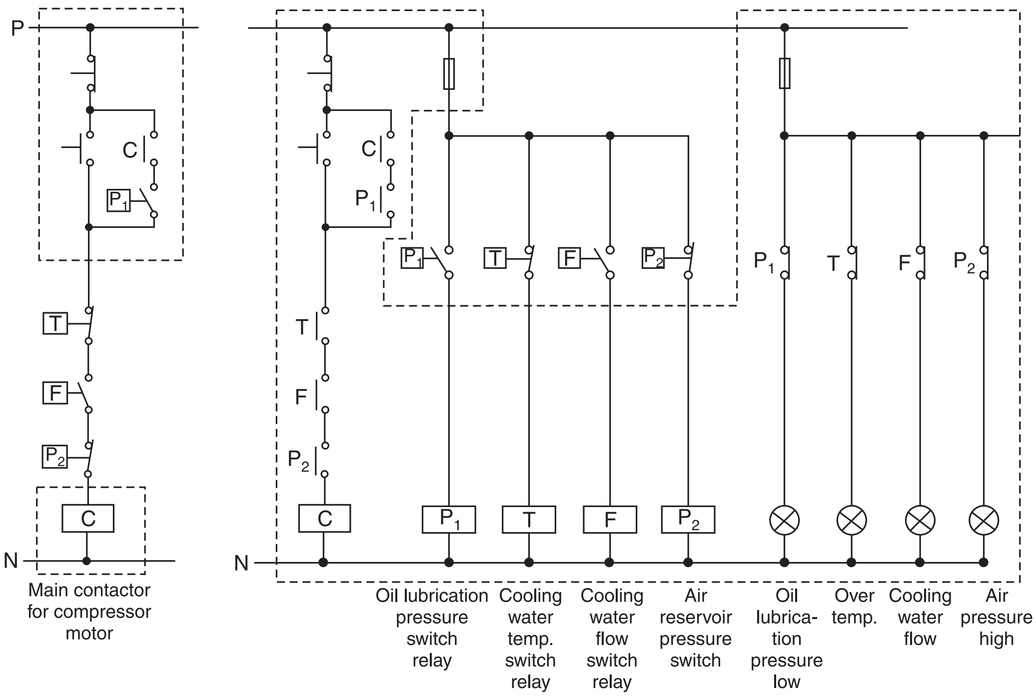


Fig. 2.12 Control diagram for a compressor motor

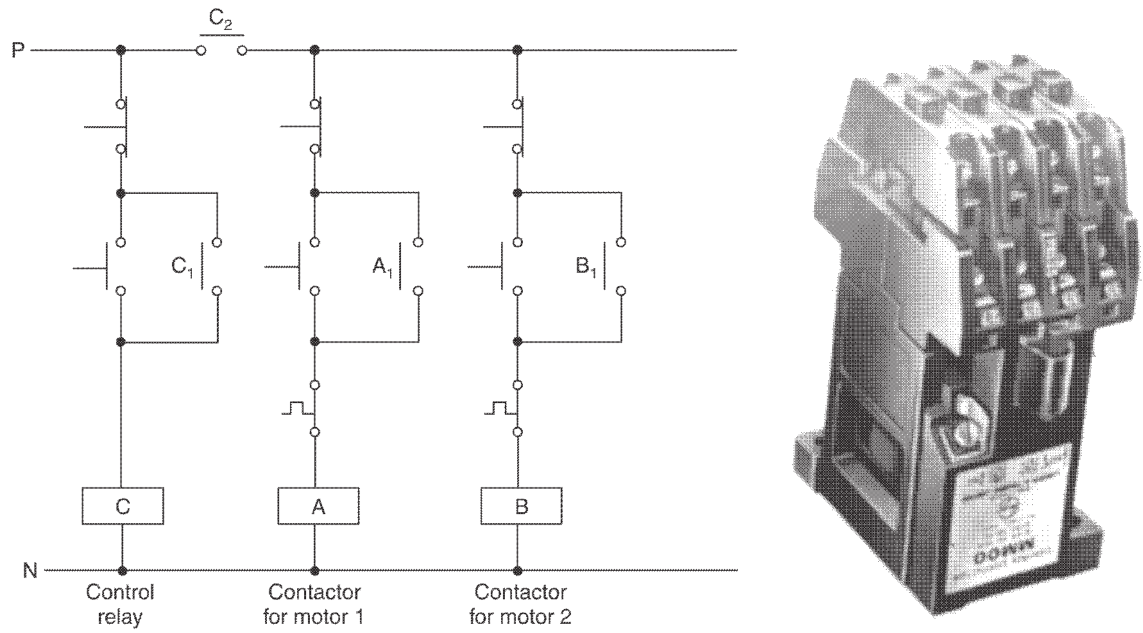
Control relays used are similar in construction to a contactor and therefore the same symbol of contactor coil is also used for ordinary voltage relays employed in control circuits.

The working of the above circuit will be discussed at a later stage. Here let us observe only the difference between the two circuits at (*a*) and (*b*) respectively. Note that the components and the wiring enclosed by dotted lines in the figure are located in the control panel. In case of any fault say, when the motor is not running, in the control circuit of Fig. 2.12 (*b*) the operator can find out the condition of any pilot device by inspecting its respective control relay. If indication lamps are also provided through relay contacts on the panel door he need not even have to open the panel, indication lamps will indicate the condition of pilot devices. However, in control circuit of Fig. 2.12 (*a*), although less number of components are used, it is difficult to detect which of the pilot devices is not working since they are all connected in series. Thus use of relays provides multiple contacts for indicating devices and makes fault analysis rather easy. Some of the important type of relays are discussed as follows:

2.6.1 Voltage Relays

This is just a small contactor which changes its contact positions from normally open to close and normally close to open when a proper voltage is applied across its coil. These relays come with as many normally open and close contacts as required.

The voltage level which when applied to the relay coil results in movement of relay contacts from their normal unoperated position to their operated position is called pick up voltage. The relay coil is generally designed to pick up at 85 % of its rated coil voltage. The voltage level at which the already operated relay contacts return to their unoperated position is called drop out voltage. Drop out voltage is generally less than 65 per cent of the rated coil voltage. This design characteristic of the relay can advantageously be utilized to provide under voltage protection. Under voltage protection for two direct-on-line starters of squirrel cage motors using a simple voltage relay is shown in Fig. 2.13.



(a) (b)

Fig. 2.13 (a) Control relay used for under voltage protection
(b) Photographic view of a control contactor

Whenever voltage level falls below the drop out voltage of the control relay, relay contact C_1 and C_2 open and supply to contactor coils A and B of motors gets disconnected. Thus contactors drop and motors also gets disconnected from the supply.

2.6.2 D.C. Series Current Relay

This relay changes its contact position in response to current change in its coil. The relay coil is connected in series with the circuit in which current change is to be sensed. The armature of the relay is light thereby making it very fast in action.

The armature is attracted when the current through the coil reaches a value high enough to produce the necessary magnetic flux for attraction. When the armature gets attracted, the closed auxiliary contacts will open. When current through the coil falls below a predertmined value the spring pulls the armature back and contacts close. The value at which the coil fails to hold back the attracted armature is determined by the setting of the spring. Some terms used in connection with a current relay are:

Pull in current. It is the minimum value of current to close or pull in the relay armature.

Drop out current. It is the value of current below which the relay no longer remains closed after having being pulled in.

Differential current. It is the difference in value of pull in and drop out currents. For example if a relay is energised or pulled in at 5 amps and drops out at 3 amps, then pull out current is 5 amps, drop out current is 3 amps and the differential current is 2 amps. For heavier current applications, a current transformer is used and its output is applied to the current relay coil.

One of the common applications of current relays is for timing acceleration of dc motors, which will be discussed at a later stage.

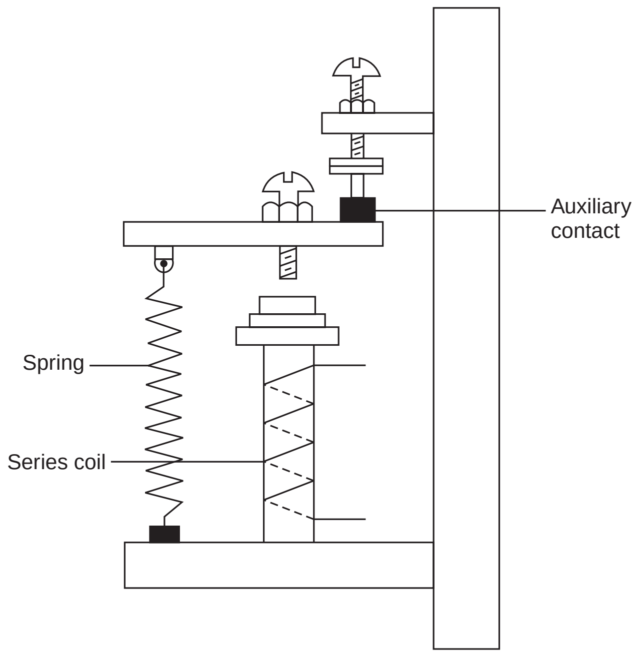


Fig. 2.14 Series type current relay

2.6.3 Frequency Responsive Relay

This type of relay changes its contact position when the frequency of applied voltage to the relay coil falls below a pre-determined value. The relays are designed differently for different applications. In one type of construction, voltage is applied to the relay coil with a capacitor in series through a potentiometer resistor as shown in Fig. 2.15.

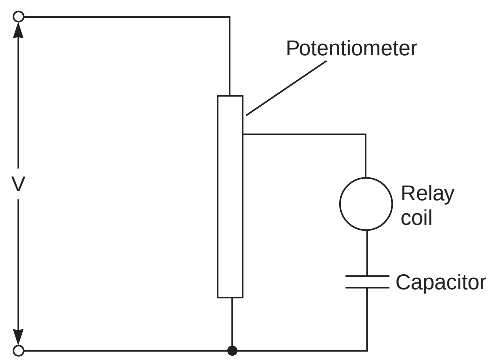


Fig. 2.15 Frequency responsive relay

The inductance of the relay coil and capacitor form a series resonant circuit through which a high current flows for a certain frequency range. The band width of the frequency range can be varied by changing the tapping of the potentiometer resistor. When the frequency falls below the resonant frequency range, current through the relay coil falls to a low value and the relay drops and its contacts open.

In another type of construction two similar coils are arranged for a common armature. One coil is energised from a reference frequency source and the other is energised from the one to be sensed. The relay is closed one way when the frequencies are the same or within a predetermined percentage and is closed the other way when the frequency differs by a given amount or more.

The frequency relays are used to apply field excitation to synchronous motors at the right instant and for acceleration control of wound rotor motors.

2.6.4 Latching Relays

The difference between a conventional voltage relay and latching relay is that the former drops to its de-energised position when the operating coil is de-energised, whereas a latching relay remains in energised position even when operating coil is de-energised.

Latching relay has two coils, an operating coil which is also referred to as latch coil and an unlatch coil. When the latch coil is energised the relay operates and is held in the energised position either by a mechanical latch or a permanent magnet. The relay remains in the energised position even when the latch coil is de-energised. The relay can be brought back to the de-energised position only when the unlatch coil is energised. The relay construction can be of two types depending on how the relay is held in the energised position when the latch coil is de-energised. The construction and working of the two types of latching relays *i.e.*, the mechnical latched type and the permanent magnet type are described as follows.

In a mechanical latched relay, when armature is pulled by the operating coil (latch coil) a mechanical latch engages the armature and holds it in place even when the coil voltage is removed. The relay can be brought back to the de-energised position when the mechanical latch is opened by energising the unlatch coil.

In permanent magnet type latch relay the magnetic circuit material gets permanently magnetised when current flows through the operating coil (latch coil). Both the latch coil and the unlatch coil are mounted on the same magnetic core. See Fig. 2.16.

When supply is given to terminals 1 and neutral, latch coil is energised and current flows in the direction shown. Relay is actuated and held closed due to magnetisation of the core even when supply is cut off. The supply to latch coil can also be cut off by using a normally closed contact of the relay in series with the coil. When relay closes, the contact opens and disconnects the coil (because the coil is not designed for continuous flow of current). Diodes are used to allow flow of dc current through the coil. When the relay is to be opened, supply is given between terminal 2 and neutral. Current in the unlatch coil flows through diode D_2 in a direction so as to demagnetise the core. The current direction is opposite to that of the latch coil. When the core gets demagnetised the relay opens and supply to unlatch coil is also disconnected through a normally open contact of the relay.

Latching relays are often used as memory relays on machines or processes where the work on machine must start from where it stopped when power had failed. When ordinary relays are used the machine cycle starts from the beginning when power is restored after a failure. Latching type relays can also be used where ac hum of the relay is objectionable. Here the relay coil is cut off once it is energised. A simple application of latching relay can be to start a motor automatically when power is restored after a failure. The control circuit is given in Fig. 2.17.

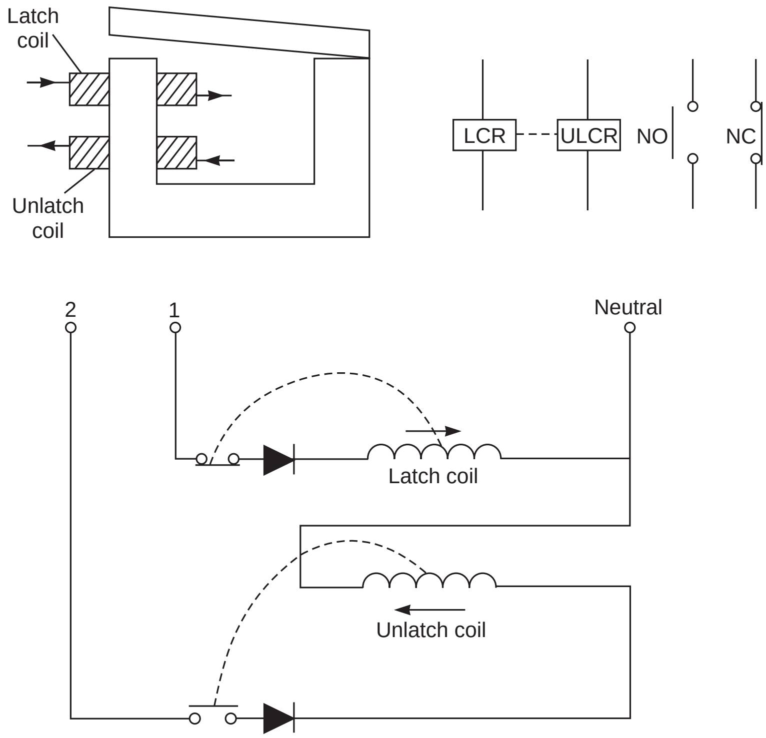


Fig. 2.16 Latching relay

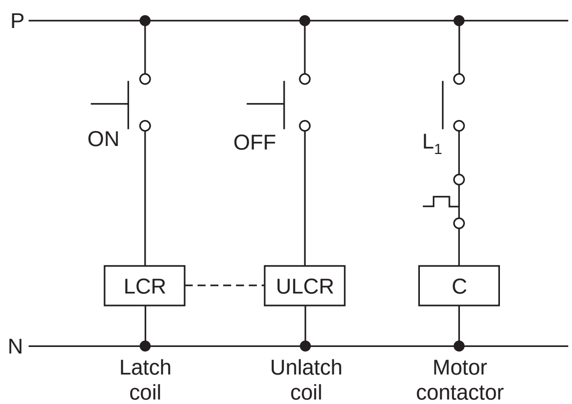


Fig. 2.17 Simple application of a latch relay

When ON-push button is pressed latching relay *LCR* is energised and contact L_1 closes. Closing of contact L_1 energises motor contactor *C*. When power fails relay does not drop and contact L_1 remains closed. Therefore when power is restored, contactor *C* gets energised automatically and there is no need to push the ON-push button. Whenever it is desired to stop the motor the OFF-push button is pressed which energises the unlatch coil and thus contact L_1 opens.

2.7 OVERLOAD RELAYS

The function of overload relay is to protect a motor against overloading. When a motor is mechnically overloaded it will draw more current than its rated value. The overload conditions can also be caused if the supply voltage is low or one of the supply phases is lost. When supply voltage falls the motor draws excessive current for the same load. In case one of the phases is lost the motor continues to run but draws excessive current through the remaining two phases. In both the cases if the excessive current is allowed to flow for a long time the motor windings will get heated up, resulting in failure of insulation and eventually burnout of the windings. To protect a motor against flow of excessive current an overload relay is connected in the power circuit. The relay is set at a certain value of current. When the motor current exceeds this value the contact of the control relay opens after a time delay depending upon the relay characteristic. The overload relays have inverse time current characteristic *i.e.,* time for relay operation decreases as the current increases. It means a small overload will take more time for the relay to operate whereas the heavy overload will operate the relay almost instan-taneously. However, the overload relay does not provide short circuit protection as the relay operating time is still large. In the control circuit the contact of the relay is connected in series with the contactor coil. Opening of the control contact causes deenergisation of the contactor thus disconnecting supply to the motor terminal. For large motors the overload relay may be connected indirectly through current transformers. These relays are built with auto reset or hand reset facility. In hand reset a knob has to be pressed to reset the relay contact. Different type of overload relays are discussed as follows.

2.7.1 Bimetallic Thermal Overload Relay

This is the most widely used relay because of its simple construction and minimal cost. The relay consists of three bimetallic strips with current coils wound on them as shown in Fig. 2.18. The whole of the assembly is mounted on a bakelite enclosure.

Bimetallic strips comprising two dissimilar metals having different thermal coefficients of expansion are used for the three phases. Current flowing through the coils heat the bimetallic strips. Upper ends of the strips are firmly held while lower ends are free to move. When temperature of the strips increases due to current flowing through the coils, the strips bend towards right due to different expansion of metals. When the strips bend towards the right, the tripping mechanism gets actuated and opens the relay contact (refer Fig. 2.18). More is the current flowing through the coils, faster will be the action of relay (as more current increases the temperature quickly resulting in faster bending and in turn faster operation of the relay). The relay thus has inverse time characteristic. A typical current curve of the relay is also shown in Fig. 2.18. From the curve we see that at 100% of rated current motor will not trip, while at 200% of rated current, motor trips in two seconds. For 300% of rated current, the tripping time of the relay is less than 1 sec. However due to inverse time current characteristic, tripping of the relay due to momentary high currents during motor starting is avoided.

As the thermal relays are heat dependent the relay cannot distinguish whether the heat is from the current flowing through the coil or from the surroundings. Therefore changes in ambient temperature changes the relay characteristic. To compensate for the ambient temperature changes, relays are designed with temperature compensating strip. The compensated overload relays are unaffected by variation in ambient temperature from – 22°C to 55°C.

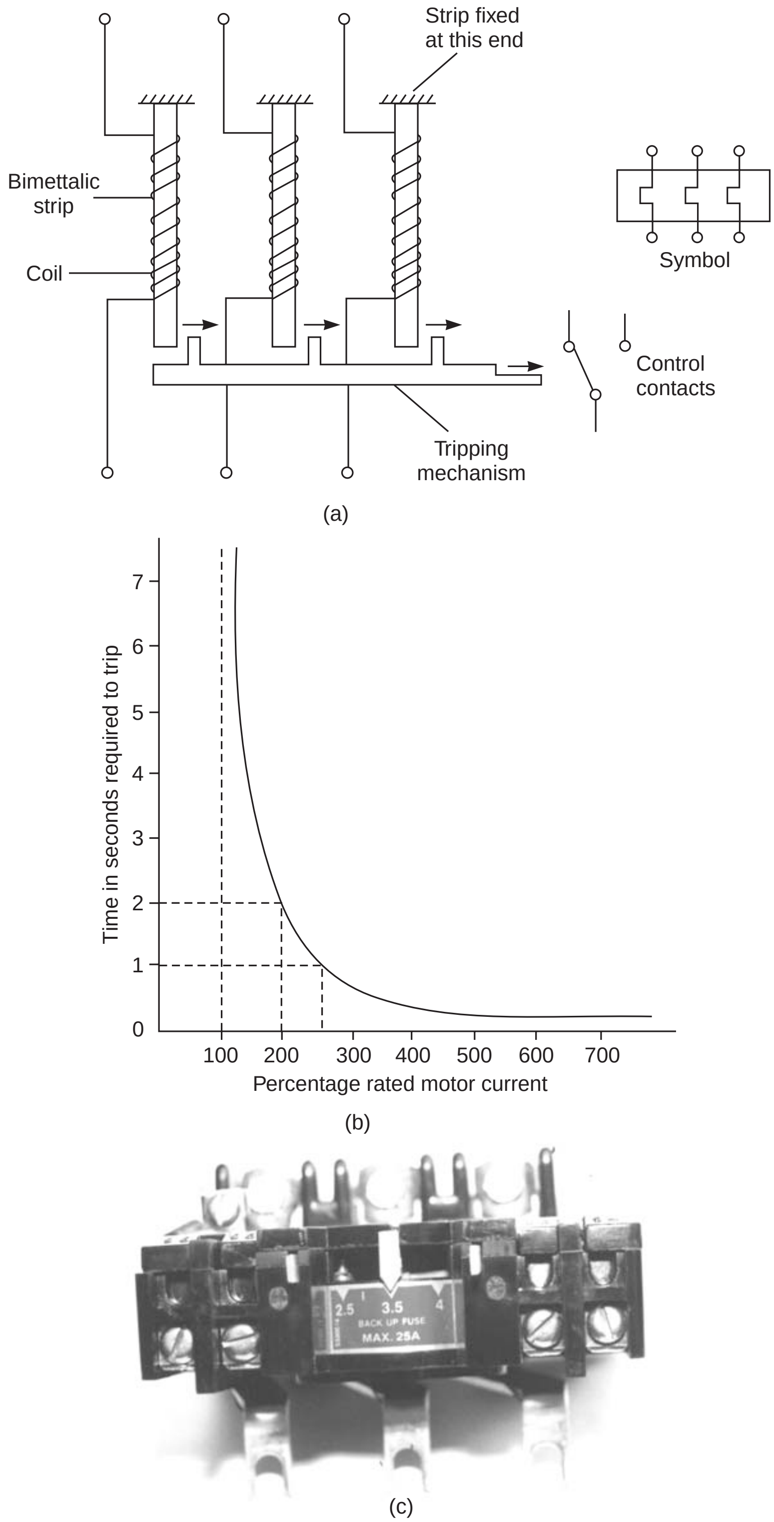


Fig. 2.18 Bimetallic overload relay (*a*) Construction (*b*) Tripping characteristic (*c*) Photographic view

2.7.2 Ratchet Type Eutectic Alloy Relay

It consists of a fixed metallic tube filled with an eutectic alloy in which a closely fitted rotating shaft is inserted. A heating coil through which the load current flows, surrounds the tube. Eutectic alloy has the property of instantly changing over from soild state to liquid state when a particular temperature is reached. A ratchet wheel is attached to one end of the shaft. When normal current flows through the heating coil, solidified eutectic alloy holds the rotating shaft and the ratchet firmly. A spring loaded contact actuating assembly is engaged with the ratchet wheel as shown in Fig. 2.19. Under normal condition the ratchet wheel does not rotate inspite of spring pressure. When overload takes place, excessive current produces heat to melt the eutectic alloy. Now the rotating shaft and the ratchet wheel are free and therefore cannot restrain the spring loaded actuating mechanism from moving from left to the right direction. The ratchet wheel therefore rotates and the actuating mechanism is released. The spring pressure causes the mechanism to move towards the right side and the actuating knob actuates the relay contact. The relay can be reset by hand when the eutectic alloy solidifies. This is done by engaging the mechanism with the ratchet wheel against the spring pressure.

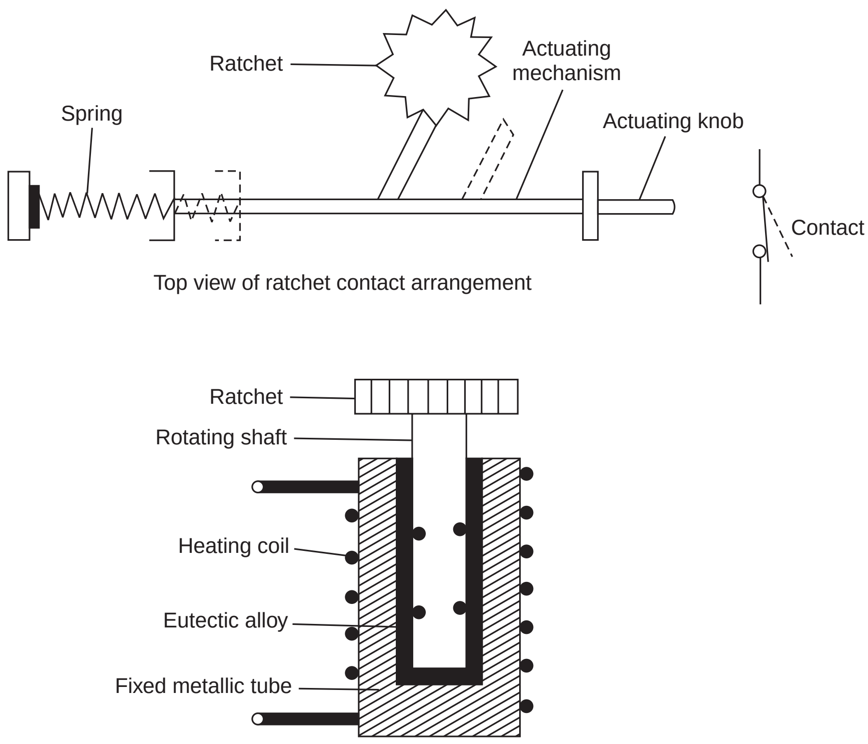


Fig. 2.19 Cross-sectional view of an eutectic relay

2.7.3 Magnetic Dash Pot Oil Filled Relay

This relay consists of a coil through which the motor current can safely flow. Inside the coil is a plunger which tends to rise up against gravity due to magnetic pull, when motor current flows through the coil. The relay, for each phase, consists of a coil, a plunger and a piston. One element for this type of relay is shown in Fig. 2.20.

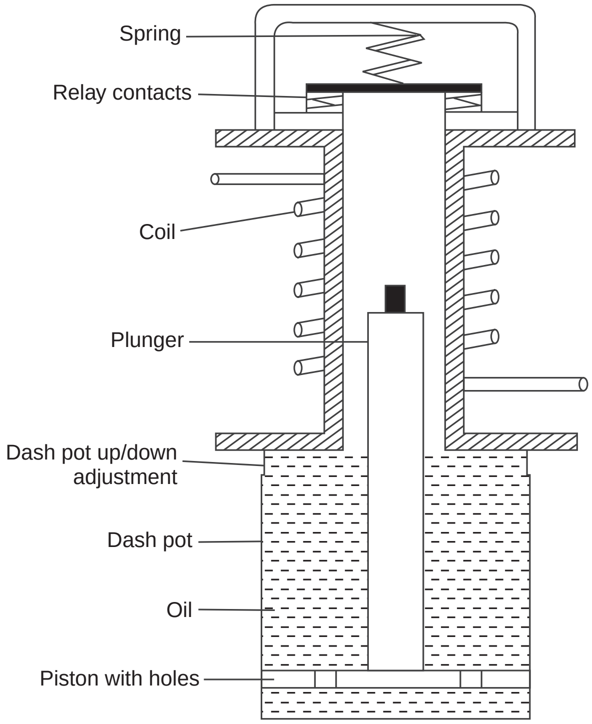


Fig. 2.20 Cross-sectional view of magnetic dash pot oil filled relay

The plunger, attached with a piston, is immersed in oil in the dash pot. The piston has bypass holes of different sizes. When current through the coil increases, the plunger and the piston move up. As the piston moves up, oil is forced through bypass holes which dampens the piston movement and provides delay. There is a provision for opening and closing of the bypass holes of different sizes by turning a valve disc over the piston. Thus by changing the area of bypass holes the delay characteristic of the relay can be changed. The relay provides inverse time current characteristics, larger is the overload, faster the plunger will move up and actuate the contact. Tripping adjustment can be obtained by adjusting the plunger core position with respect to the relay coil. This magnetic dash pot type of relays are used in controlling large motors.

Another form of magnetic type relay is the instantaneous trip magnetic current relay.

These relays are used to disconnect the motor when a predetermined load condition is exceeded. The relay does not have inverse time current characteristic, thus the relay cannot be used in place of an ordinary overload relay. It is a special purpose relay. To avoid tripping of this relay during starting of motors, the relay contact has to be by-passed during the starting period. See the control circuit shown in Fig. 2.21. The relay contact is used in parallel with the ON-push button and in series with the holding contact. As long as the ON-push button is held pressed the contact of the relay remains by-passed. When the motor accelerates fully the push button is released. The operating mechanism of the trip relay consists of a solenoid coil through which the motor current flows and a movable iron core within the coil. An over current causes the iron core to move up and operate a snap action contact mounted on top of the solenoid frame. The normal current of the motor does not exert sufficient magnetic pull to lift the core. The tripping values of the relay can be adjusted by changing the core position in the solenoid coil. If the iron core is moved down in the coil the relay will operate at a higher value of current. Moving the core position higher in the coil will operate the relay at a lower value of current. The important application of the relay is in conveyors where the driving motor is stopped before mechanical breakage results due to jam-up.

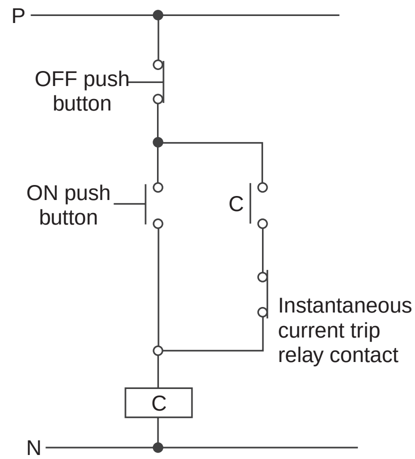


Fig. 2.21 Control circuit for instantaneous trip relay

2.8 TIME DELAY RELAYS (TIMERS)

In time delay relays the relay contacts change over their position after a pre set delay from the time of energisation or de-energisation of the relay coil. Time delay relays are also commonly known as Timers. Timer can be of ON-delay or an OFF-delay type. A timer is referred to as an ON-delay type if the contacts change over after a pre-set delay after energisation. On the other hand a timer is referred to as OFF-delay type if the contacts change over after a pre-set delay from the instant of de-energisation. Besides the delayed contacts a timer can also have another set of contacts which operate as in an ordinary voltage relay. These are known as instantaneous contacts as they changeover their positions instantaneously when the timer is energised or de-energised. The representation of ON-delay and OFF-delay contacts of a timer in a control circuit is as shown in Fig. 2.22.

We will represent the coil of the timer as the same for both ON- and OFF-delay but delayed contacts will be represented differently. Normally, most circuits require ON-delay timers. Applications requiring OFF-delay timers can also be covered by ON-delay timers with suitable modifications in the circuitry. However, OFF-delay timers can, in few cases, simplify circuitry and thereby reduce the cost. Though the OFF-delay timer find limited applications, the reader should however thoroughly understand the contact operation of OFF-delay timer, to avoid confusion between the two types of timers. The difference of operation becomes clear from the following explanation.

ON-delay timer is normally in de-energised condition. The normal position of delayed contacts is shown in Fig. 2.22. When the timer is energised, after a pre-set delay the contacts change over their positions. Contact 1 will become closed and contact 2 will open. However, when the timer is de-energised contacts change over almost instantaneously.

An OFF-delay timer is normally in energised condition. Thus, normally, contact 3 will be closed and contact 4 will be open. When the timer is de-energised the counting starts and after the pre-set delay, contacts 3 will open and contact 4 will close *i.e.,* their positions will be as shown in Fig. 2.22. In the control circuits the changed over positions of the contacts are shown. As the time delay is only on one side (*i.e.*, OFF-delay only), when timer is energised, contacts change over almost instantaneously.

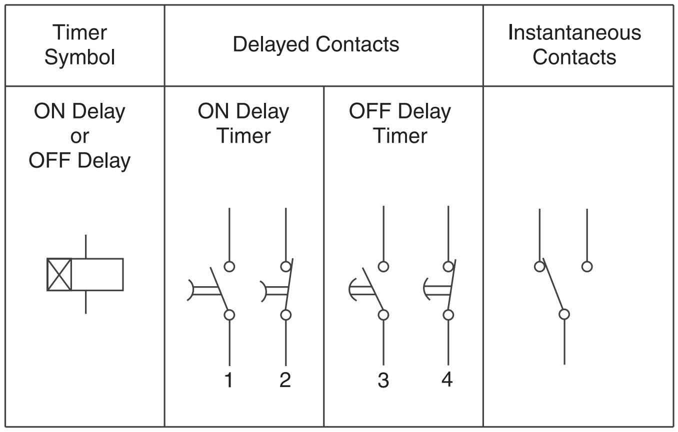


Fig. 2.22 Symbols for a timer and its contacts

Timers can also be classified as cyclic and non-cyclic timers. When a timer continues to repeat its sequence of operation till the supply is switched off, it is called a cycle timer. The change over contacts would continually switch ON and OFF at intervals as long as operating voltage is on. The non-cyclic timers operate only for one timing cycle when they are switched on. The change over contacts get switched over after the set time and stay in that state till they are reset either manually or by a knob or by switching ON or OFF an electrical signal.

Majority of applications require ON-delay, non-cyclic, non-manual reset type timers. There are four different types of timers utilising different operating principles. These timers are thermal timers, pneumatic timers, electronic timers and motor driven (synchronous) timers.

2.8.1 Thermal Timer

Principle of working of a thermal timer is the same as that of a bimetallic overload relay discussed earlier. These are available with a limited delay range of 0–20 sec. The timing error can be very large of the order of ± 10 to 30%. By timing error it is meant that the time variation (plus or minus) between successive timing operations on the same timer represented as a percentage of maximum range of the timer. Due to higher timing error thermal timers are used only in star-delta starters where such error does not matter much.

Pneumatic and Electronic timers are suitable for delay range of 0–3 minutes. For delays exceeding 3 minutes, synchronous timers are preferred. Pneumatic timers have a timing error of ± 10%, electronic timer, ± 5% and synchronous timers have timing error limited to ± 1%. The construction and working of these timers are discussed as follows.

2.8.2 Pneumatic Timer

It consists of solenoid coil, a plunger assembly, and an air bleed unit consisting of an air chamber divided into upper chamber and lower chamber by a diaphgram. The diaphragm is attached to an operating rod and disc D as shown in Fig. 2.23 (*a*). There is a provision of air bleed (air flow) from upper chamber to lower chamber through a needle valve. Air flow rate can be changed by adjustment of needle valve screw. Solenoid coil plunger assembly and air bleed unit are assembled together as shown in Fig. 2.23 (*a*) for ON-delay type operation. The contact block is mounted on the air bleed unit.

Before the coil is energised the diaphragm is in its down position as shown in the figure. A small orifice at the bottom of the lower air chamber is held closed by the diaphragm and does not allow air flow from upper air chamber to lower air chamber. Diaphragm is held in the down position as the plunger is pressing the disc and the operating rod down.

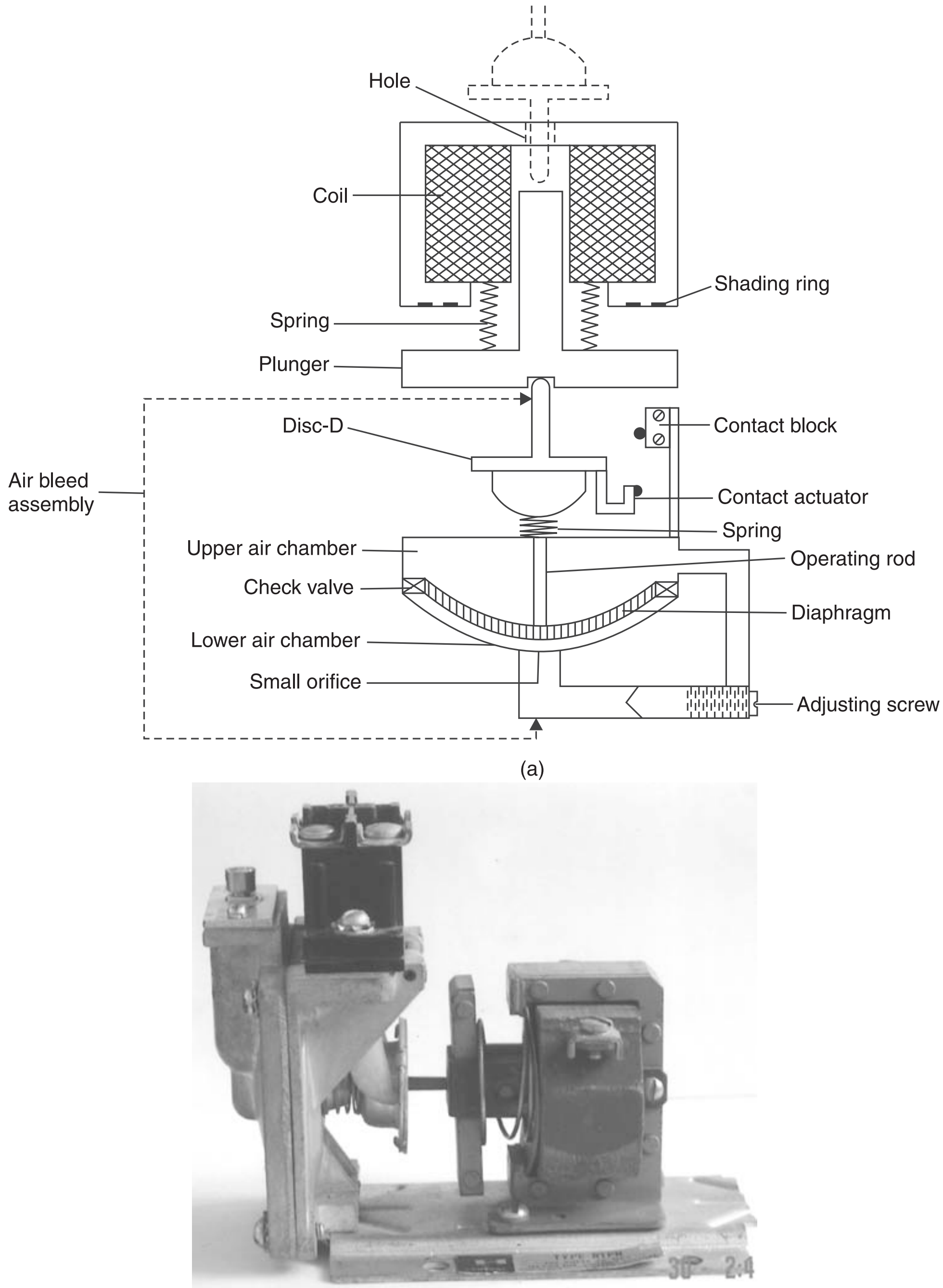


Fig. 2.23 (*a*) Cross-sectional view of pneumatic timer (*b*) Photographic view of a pneumatic timer

When the solenoid coil is energised the plunger is attracted and thus pressure on the disc (*D*) and the operating rod is released. Now the diaphragm is free. Air from upper chamber leaks to the lower chamber through the needle valve. The rate of air flow can be adjusted by the screw of the needle valve. As pressure of air in the lower chamber starts increasing the diaphragm moves up slowly at a speed which depends upon the rate of air flow through the needle valve. The diaphragm in turn moves the operating rod and the disc upward. The diaphragm will move up till air pressure in both the chambers is equal. An actuating lever attached to the disc, which moves upwards, actuates the timer contacts.

The delay or time for actuation can be varied by adjustment of the needle valve. Operating rod, disc and diaphragm remain in up position as long as the coil is energised and therefore relay contacts remains closed.

When the coil is de-energised, plunger falls down which in turn presses the diaphragm down through the disc and the operating rod. The air in the lower chamber is pressurised and it flows to the upper chamber through the check valves. It may be understood here that check valves allow air flow only in one direction. In this case this direction is from lower chamber to upper chamber and air flow is blocked in the reverse direction. On de-energisation the same position from where we started is reached and the relay is ready for another ON-delay operation.

In the OFF-delay type of timer the air bleed unit and solenoid assembly are so arranged that, normally, when the coil is de-energised and the plunger is down the diaphgram is in the centre position and the contacts are in actuated condition. This is achieved if the whole of air bleed assembly (refer figure) is inverted and assembled over the solenoid coil assembly so that the rod of disc (*D*) enters the hole at the top of the coil assembly (shown dotted).

When the coil is energised, the diaphragm is pushed by the plunger through the disc and the operating rod to close the orifice. Therefore the contacts also get de-actuated. When the coil is de-energised, diaphragm becomes free and starts moving towards the centre due to bleeding of air. Depending upon the speed of the operating rod and disc (*D*), the contacts are actuated after a delay.

2.8.3 Motor Driven Timers

This timer consists of a small motor, usually a synchronous motor, which is engaged with gear arrangement with the help of electrically operated clutch. Gear arrangement reduces the speed of motor to a desired low value. Motor thus rotates a contact actuating lever through gear arrangement. The actuating lever after travelling a pre-set distance operates the timer contacts. The time delay for actuation of contacts can be changed by a knob which varies the distance between the actuating lever and the contacts. If the distance between the actuating lever and the contacts is increased, the timer will take more time to actuate the contacts (as the motor speed is constant) and vice-versa. In ON-delay timers the motor starts counting time when the clutch coil is energised and in OFF-delay timers counting starts when the clutch coil is de-energised. Timer gets reset when the clutch is de-energised in an ON-delay timer and energised in case of an OFF-delay timer. In an ON-delay timer the motor can be energised along with the clutch but in an OFF-delay timer the motor has to be kept running continuoulsy.

Synchronous motor timers are also available in simple version without a clutch. In this case the timer starts counting time when motor is energised and actuates contacts after the actuating lever moves through a pre-set distance. The timer gets reset when supply to motor is disconnected. Another version of motor driven timer makes or breaks a number of contacts during its timing period with the help of cams mounted on the motor shaft. A cam is a circular plastic material which is fitted on the motor shaft as shown in Fig. 2.24. Cams are shaped to produce protruding portions which actuate the contact blocks.

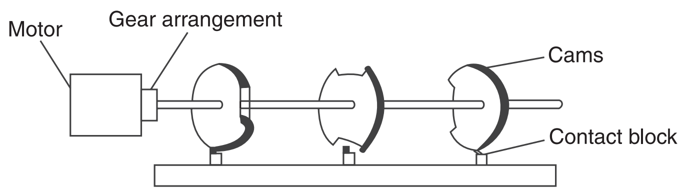


Fig. 2.24 Simplified representation of a motor driven cam timer

When the motor is energised the cams start rotating. Protruding portion of the cam presses the knob of contact block and thus contacts remains actuated as long as the protruding portion of the cam passes over the contact knob. For the remaining position of the cam the contact gets de-actuated.

The time period required for actuation and de-actuation of a particular contact can be obtained by adjusting the shape of the cam as per requirement.

These timers are very useful for initiating different processes in sequence. Another important application is starting of motors in a conveyor system.

A time switch is another form of a motor driven timer. It offers independent control of the ON and OFF-duration of the contacts. Any combination of ON-time and OFF-time can be selected as long as the total of ON-time and OFF-time does not exceed the maximum or full range-time of the device.

An important application of time switch is for street lighting control where the full range-time is 24 hours. Time switch, for this purpose, is provided with battery supply also which can run the timer in case the main supply fails. Thus interruptions due to supply failure does not effect the ON and OFF-time of the timer.

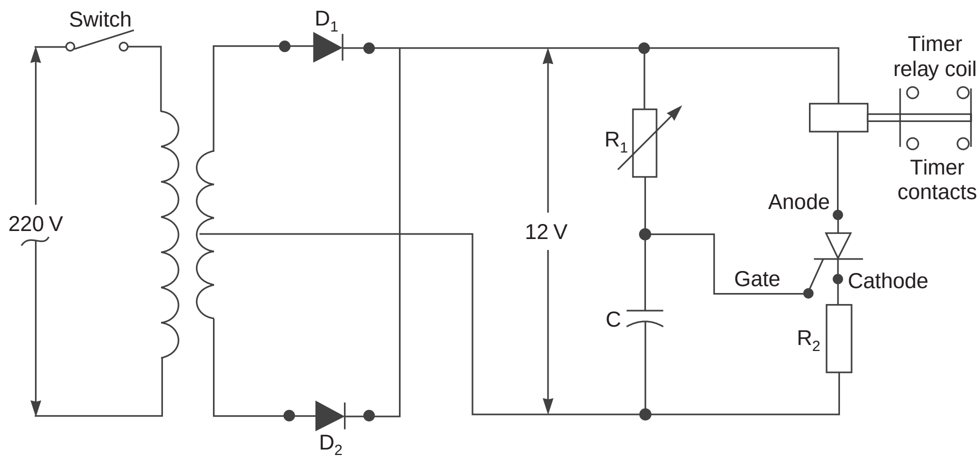
2.8.4 Electronic Timer

Electronic timers are widely used in industry for various applications due to their better accuracy and longer life than the pneumatic timers. They are less expensive than synchronous timers. Only critical processes which demand very high accuracy require synchronous timers.

Electronic timers achieve their timing action with an electronic circuit. Electronic timers are generally of the ON-delay type. When supply to the timer is given it starts counting and the contacts change over their positions after a pre-set delay. The length of time delay period is easily adjusted by a variable resistor placed in the electronic circuit. The timer gets reset when supply to the timer is cut off.

A very simple electronic timer circuit using a silicon controlled rectifier (SCR) is shown in Fig. 2.25. The SCR, also generally known as Thyristor, has three terminals Anode, Cathode and Gate. It conducts when a signal is applied between its Gate and Cathode and continues to conduct even if signal to the gate is removed after conduction starts. It conducts only when there is positive supply at the Anode and negative supply at the Cathode. The gate supply should be positive with respect to the Cathode to cause its conduction.

In the circuit of Fig. 2.25, control transformer (220/12 V centre tapped) and diodes D_1 and D_2 provide 12 V dc supply to the electronic circuit. When the timer switch is closed 12 V dc is available to the timer circuit. Resistance R_1 and capacitor C form the RC charging circuit. The coil of the timer relay is connected in series with the SCR as shown. The gate of SCR is connected to the capacitor terminal. When the timer switch is closed, the capacitor C starts charging. When the voltage of the capacitor is sufficient to send minimum gate current to trigger on the SCR, the SCR starts conducting. Resistance R_2 is there to limit the gate current. When the SCR starts conducting, relay coil picks up and closes its contacts. The required delay in closing the relay contacts may be obtained by changing the charging rate of capacitor (by varying the variable resistance R_1). A suitable time range of the timer can be designed by using required values of R_1 and C. The timer gets reset automatically when supply to the timer is cut off. The contacts of the timer then return to the normal position immediately.



(a)

(b)

Fig. 2.25 (*a*) Simple circuit of an electronic timer (*b*) Photographic view of an electronic timer

2.9 PHASE FAILURE RELAY (SINGLE PHASING PREVENTER)

In a 3-phase motor, when under running conditions, one of the three fuses blows and power to the motor is supplied by the remaining two phases, the motor is said to be running on single phasing condition. To maintain the same power input to the motor during single phasing the current in the remaining two phases will increase by 1.73 times. If the motor is lightly loaded, currents in healthy phases will not increase beyond the full rated current setting on the overload relay. Thus overload relay will not be able to detect single-phasing when the motor is lightly loaded. For example, consider a 10 hp motor with rated current of 14 A and over-load relay setting at 10 A. At a particular load, let the motor be drawing a current of 5 A. If one of the fuses blows out or a conductor breaks, current in the two phases will become 5 × 1.73 = 8.65 A, which is much below the relay setting of 10 A. Therefore, the motor will continue running under single phasing.

Single phasing of the motor results in superpositon of negative sequence of current flow over the positive sequence through the motor windings. These negative sequence currents are of double frequency as compared to positive sequence currents and produce a torque which is opposite to that produced by positive sequence currents. As the iron losses are proportional to frequency, the negative sequence currents cause higher iron losses and therefore greater heating of the rotor. Rotor heating is further increased due to skin effect (due to higher frequency). This undetected heating can damage the rotor and due to convection, stator windings also. This excessive heat can finally cause burn out of the motor. To avoid failure of the motor due to single phasing, phase failure relay or commercially known as single phase preventer is used in the motor circuit as shown in Fig. 2.26.

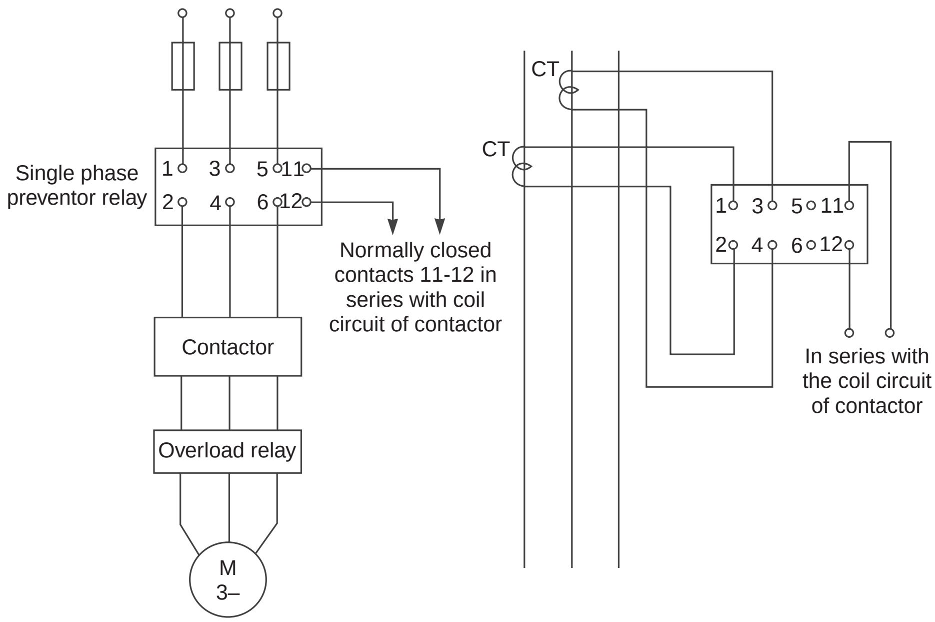


Fig. 2.26 Connection scheme for phase failure relay

As shown in the figure the relay is connected in the incoming supply phases. The control contact (11-12) is connected in series with the contactor coil circuit.

If the starting time of the motor is more, to avoid undesirable tripping, the control contact should be by-passed during starting.

Brief description of a relay which works on the basis of detection of negative sequence current is explained as follows.

The relay has two built-in current transformers which sense currents of the motor. The secondary of the CTs feeds a negative sequence filter. The output from this filter is proportional to the negative sequence component of currents. This output is fed to a sensor which detects the level of negative sequence components of current and thus trips the motor starter by opening its control contact. These relays are designed for different ratings of motors upto 20 hp. For motors above 20 hp, a relay rated for a 3 hp motor can be used by using current transformers on the lines as shown in Fig. 2.26. The CTs should have a secondary current of 5 A, the primary current should correspond to full rated current of the motor. The two secondaries are connected to two phases of the relay. The control contact is used as usual in series with the contactor coil.

2.10 PUSH BUTTON SWITCHES

It is a pilot device which provides control of an equipment by pressing an actuator which looks like a button. Push button switch can be divided into two parts. One part is the mechanical actuator or button assembly and the second part is the electrical portion or contact assembly called the contact block.

The mechanical actuator or button assembly can be of momentary-contact spring returned type or of maintained contact type. The momentary-contacts spring returned push button remains actuated as long as the button is physically held pressed by the human operator. Under pressed condition the contacts change their positions in the contact block. Once the button is released the contacts return to their normal position. Maintained contact push buttons are held actuated by some latching mechanism even when the operator releases the pressure on the push button. Such units consist of two push buttons, only one remains in actuated position at a time, when the other button is pressed the first one gets released.

A spring returned momentary contact push button is shown in Fig. 2.27. The contact block has two contacts, one normally open (NO) and the other normally closed (NC). When the push button is pressed, NC contacts opens and NO contact closes. When the push button is released a spring inside the actuator assembly brings back the push button and a spring inside the contact block brings the contacts back to their normal position. The symbol for the push button switch is also shown in Fig. 2.27.

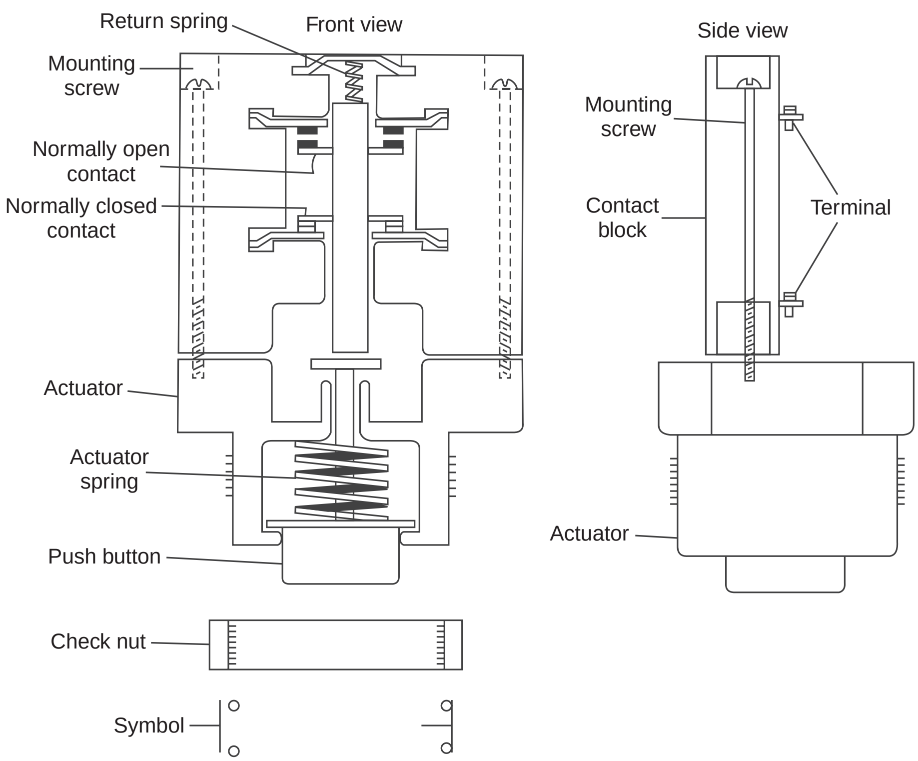


Fig. 2.27 (*a*) Cross sectional view and end view of a push button.

(b)

Fig. 2.27 (*b*) Photographic view of a push button

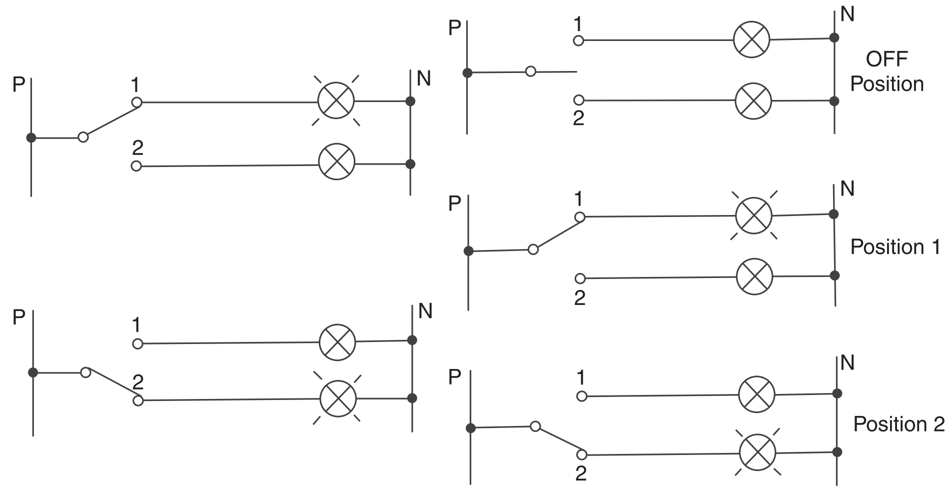
Push button switches can be of different types depending upon the type of actuator assembly. They are:

- Recessed button type
- Mushroom head type
- Illuminated type
- Key lock type.

Colour of the button is also an important factor in push button switches. Standards have been developed which specify certain colour for a particular function. For example, red push buttons are used for stop and emergency stop operations, while green push buttons are used for start operations. When two or three push button switches are mounted on a steel or plastic enclosure it is known as a push button station. For example, in a three push button station, one push button may be for running the motor in forward direction, the second for running the motor in reverse direction, and the third for stopping the motor.

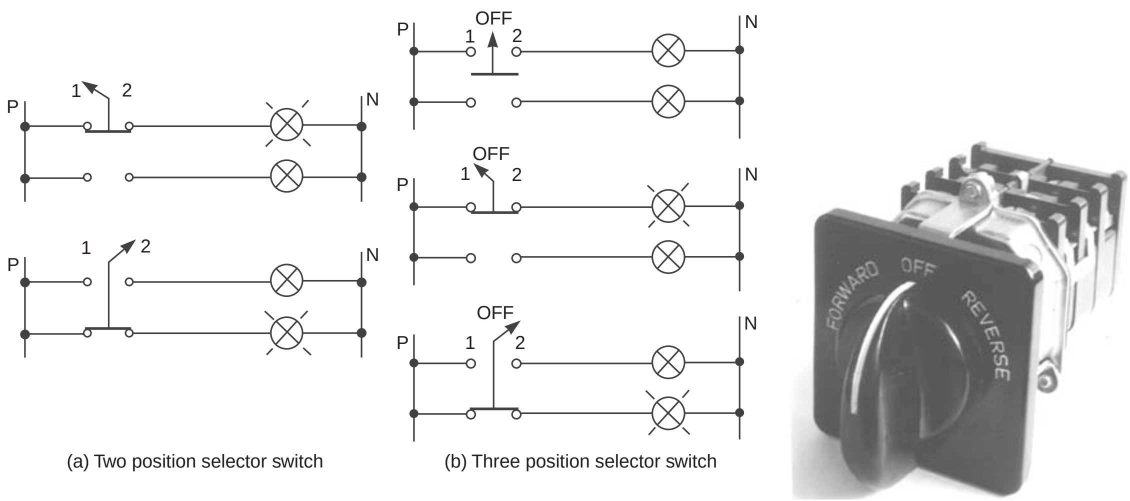
2.11 SELECTOR SWITCHES

Many machines and process operations are designed so as to function in any one of the several ways. For example, the three different modes of operation may be Manual, Semi-automatic and Automatic. A selector switch will enable the operator to predetermine the manner in which his machine is to operate. As with push-button switches, selector switches also have two main parts, the mechanical actuator and the contact block. Selector switches are usually of the maintained position type, although momentary spring return selectors are also available. Selector switches can have single break contacts or double break contacts. The symbols for both these type of contacts have been shown in Figs. 2.28 and 2.29.



(a) Two position selector switch (b) Three position selector switch

Fig. 2.28 Connection of two position and three position selector switches in a simple circuit



(a) Two position selector switch (b) Three position selector switch

(a) (b)

Fig. 2.29 (*a*) Connection of double break two position and three position selector switches in a simple circuit (*b*) Photographic view of a three positions selector switch

The selector switches are generally made for four positions. As the number of positions increase to four, manufacturer provide charts of tables which display positions of the selector switch actuator. Fig. 2.30 shows a four position selector switch. Note the use of × under the position number. This indicates that the contact in line with × is closed in that position.

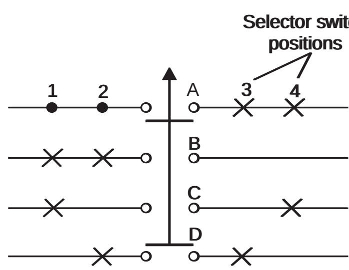


Fig. 2.30 Symbolic representation of four position selector switch

Below position 1 (Fig. 2.30) × is against contact *B* and *C i.e.,* in position 1 contact *B* and *C* are closed.

In position 2 contacts *B* and *D* will close, further in position 3 contact *A* and *D* will close and in position 4 contacts *A* and *C* will close.

2.12 DRUM SWITCHES

Drum switches, also referred to as Master Controllers are identical in function but of a different type of construction than selector switches. A selector switch uses components similar to a push-button while a drum switch consists of a shaft attached to the operating lever (actuator), which has a number of cams mounted on it. Cams actuate their respective contact when the operating lever is rotated. A single cam can operate two contacts, one mounted on right side and one on left side of the shaft cam arrangement. The contact ratings can be high depending upon the application. A Drum switch can be considered as the 'big brother' of a selector switch.

One of the important applications of Drum switches is in overhead cranes for controlling hoist, long travel, and cross-travel operations. Separate drum switches are used for each of these operations. Fig. 2.31 shows the symbolic representation of a master controller used for forward-reverse operation of a motor used in a crane.

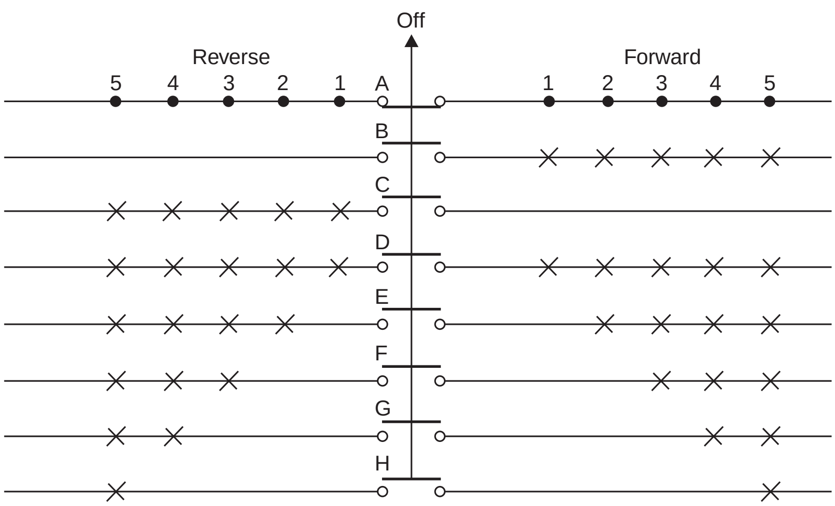
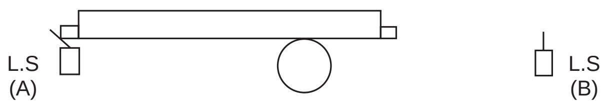


Fig. 2.31 Symbolic representation of master controller used for forward/reverse operation

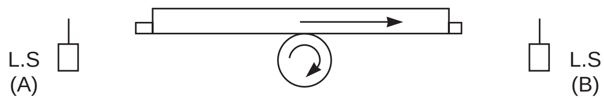
Master controller contacts are shown by *A*, *B*, *C*, *D*, *E*, *F*, *G*, *H*. When the lever is in OFF position, contact *A* remains closed, and opens for any other position of the switch. When the controller is moved towards right side (forward), contact *B* and *D* actuate at position 1 and these contacts remain actuated till the lever is moved to position 5. Let us co-relate the position, the × mark under the position, and the contact in line with the ×. Contact *C* will not actuate in any position on right side. On further moving the lever to position 2 contact *E* will close and at position 3 contact *F* will close and so on. Similar action takes place when the operating lever is moved towards left side. At this point one may wonder as to why so many contacts are needed for forward reverse operation of a motor ! In fact, master controller contacts are used to get different speeds of the slip-ring motor used in cranes by cutting the rotor resistance in steps. When we discuss the starter for slip ring induction motor at a later stage, we will again have to refer to the master controller explained above.

2.13 LIMIT SWITCHES

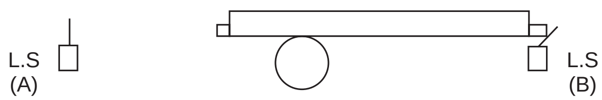
Limit switch is an important control element. Limit switch contacts change over their position when its actuating lever or knob is actuated by the mechanical part of a machine. The mechanical part attached to the machine which actuates the limit switch lever or knob is known as actuator or dog. Limit switches are used to stop a mechanical movement of a machine and may also be used to stop a particular movement, and initiate another movement. The simple application of a limit switch is in producing automatic to and fro movement of a planar machine bed shown in Fig. 2.32. It must be understood here that a limit switch is not used as a mechanical stop. A limit switch controls the electrical signal which is responsible for mechanical stop/movement.



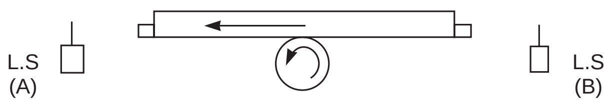
(a) Control off-motor standstill, bed at extreme left with limit switch 'A' actuated



(b) Control on-motor runs in clockwise direction and bed moves in right direction due to actuated condition of limit switch 'A'



(c) Limit switch 'B' actuates which stops motor and runs it in anti-clockwise direction



(d) Motor runs in anticlockwise direction till limit switch 'A' is actuated. On actuation of limit switch motor stops and again runs in clockwise direction

Fig. 2.32 Application of limit switch for automatic to and fro movement of planar bed

Actual control circuit for achieving this to and fro movement with help of limit switches shown in Fig. 2.32, will be discussed at a later stage.

2.13.1 A Simple Limit Switch

The simplest construction of a limit switch is shown in Fig. 2.33.

When the knob or pin is pushed the plunger attached to the knob move down against spring pressure. The moving contacts mounted on the plunger also moves down. Thus the terminals 1 and 2, which are normally closed, become open and terminals 3 and 4, which are normally open, get closed. When the pressure on the knob is released the contacts return to their normal position. Another commonly used limit switch is the lever type. This may be single side actuation type or double side actuation type, as shown in Figs. 2.33 (*b*) and (*c*).

In a single side actuation type limit switch the contacts operate when the limit switch arm moves in one direction, either the right or to the left. Movement on the other side does not actuate the contacts. The arm returns to the normal position when the actuating force is removed. The limit switch can also be of maintained contact type in which arm has to be brought

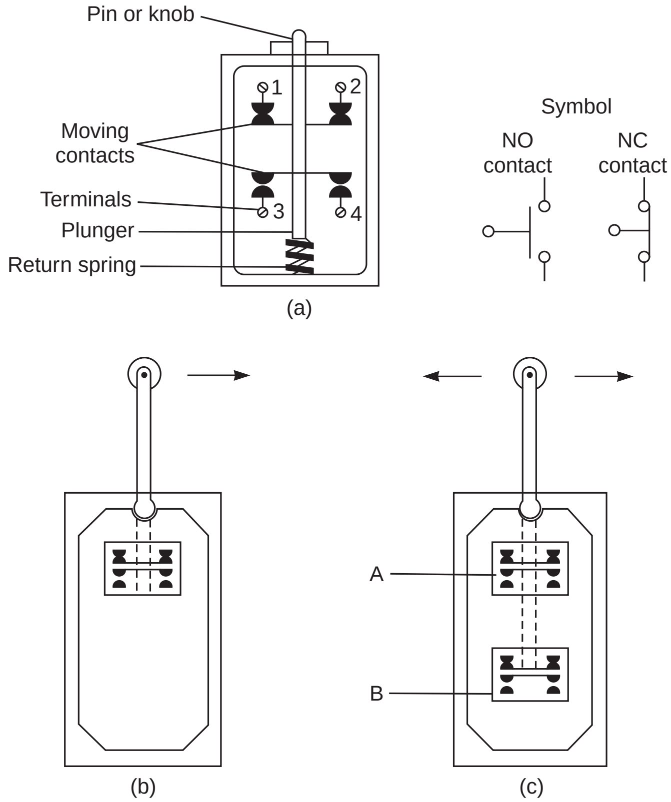


Fig. 2.33 Inside view of (*a*) Knob type limit switch (*b*) Single side actuation lever type limit switch (*c*) Double side actuation lever type limit switch

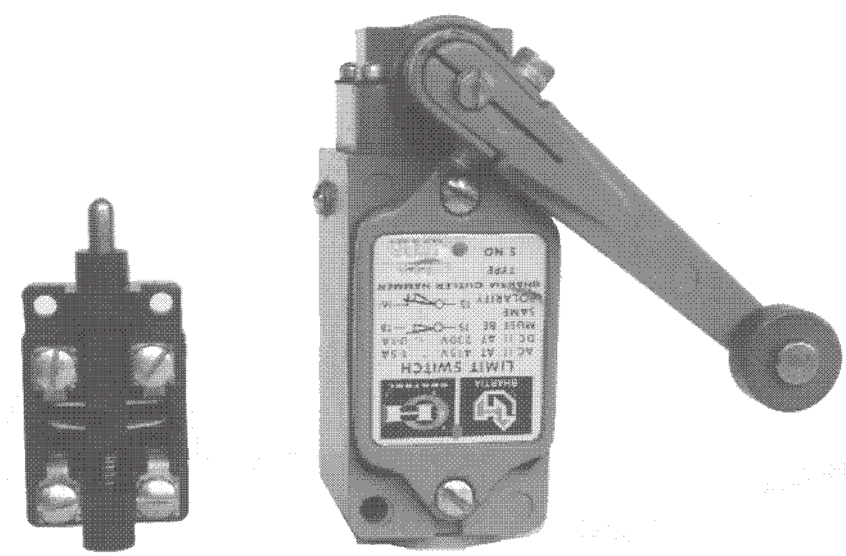


Fig. 2.34 Photographic view of (*a*) Knob type limit switch (*b*) Lever type limit switch

back manually to normal. However this type of limit switches are rarely used. In double side actuation type limit switch, when the arm is moved in one direction, say towards right, contact block A operates; and when the arm is moved towards left, contact block *B* operates. This type of a limit switch can serve the purpose of two single side actuation limit switches needed in controlling to and fro movement of a machine.

If the contacts of the limit switch change-over independent of the speed of operation, the limit switch is known as snap-action limit switch. At a particular position of the arm, the contacts change-over. If the contacts also move at the same speed as that of the arm of the limit switch, it is called a slow-action limit switch. Most limit switches used are the snap-action type. There are only few applications where slow acting limit switches are preferred.

2.13.2 Rotary Cam Type Limit Switches

In this type of limit switches, the contacts are mounted on the stationary frame. The cams, which have to actuate the contacts, are mounted on the rotating shaft. The position of the cams is adjustable. The rotating shaft is coupled to the driving motor of the machinery either through chain and sprockets or by gear arrangement. The rotation of the driving motor is thus transmitted to the shaft of the limit switch. The cams mounted on the shaft are shaped and their position adjusted to actuate the contacts at the desired instant. In the machinery, the rotary motion of the driving motor is converted into longitudinal motion through mechanical arrangement. Thus, the cam shaft of the limit switch rotates proportional to the longitudinal motion of the machine. The limits of travel of the machinery, therefore, can be adjusted by changing the cam position.

The advantage of a rotary cam limit switch over an ordinary limit switch is that the instant of actuation and hence limits of travel can be varied easily over a wide range by changing the cam positions. In an ordinary limit switch, however, once the limit switch is fixed, only very little adjustment is possible by adjusting the lever position. The reliability of rotary limit switch using sprocket and chain is however low and, therefore, wherever these are used a back-up-protection of ordinary limit switches is generally provided to avoid damage due to over travel, in case the rotary limit switch fails due to slipping or breaking of chain.

Rotary limit switches are preferred where frequent adjustment of limits of travel is required. One of its important application is in over-head cranes for hoisting and lowering motion. In over-head crane, for hoisting operation, the rotary motion of the motor is converted into longitudinal motion with the help of a rope wound on the drum attached to the motor shaft. The rope winds on the drum in one direction giving hoisting (raising) operation and unwinds in other direction giving lowering motion. The limits of hoisting and lowering can be easily adjusted by varying the cam positions which have to actuate the hoisting and lowering limit switch contacts.

2.13.3 Heavy Duty Limit Switches

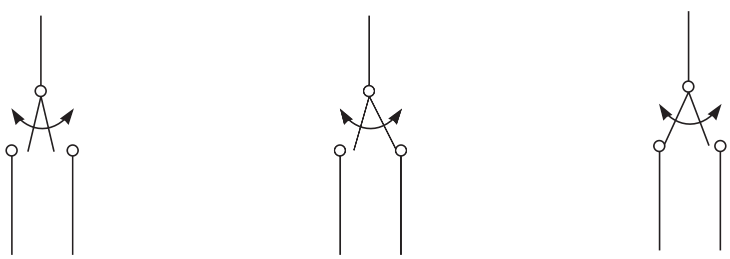
As the name signifies, these limit switches are used in heavy duty machines such as cranes, conveyors and heavy material handling equipment. The basic difference between an ordinary limit switch and a heavy duty limit switch is that the former is used in the control circuit while the latter is used in the power circuit. Actuation of a heavy duty limit switch cuts off power supply to the motor. Heavy duty limit switch requires a minimum of two normally closed contacts because to stop a motor two phases have to be cut off. A heavy duty limit switch may be either lever type or rotary cam type. They are rugged, and the current rating of their contacts matches with the motor rating. If the rating is quite high, arc chutes are also provided over the contacts. These heavy duty limit switches are used in addition to the control limit switches. They are generally used as back-up-protection for control limit switches. If the control limit switch fails or contactor gets stuck or welded, then the heavy duty limit switch operates to disconnect power supply to the motor.

The limit switch contacts are connected in series with the main contactor contacts. These limit switches therefore avoid damage and accidents due to over-travel of machinary like overhead crane and other heavy material handling equipment.

2.13.4 Speed Actuating Sensing Switches

These are also commonly known as plugging switches or zero speed switches. These switches have two sets of contacts, one each for either direction or rotation of the motor. The contacts for a particular direction of rotation open or close when a predetermined rotational speed in that direction is achieved. These switches are used in circuits where the motor is to be stopped quickly (*i.e.,* to be brought to standstill quickly by plugging method of braking). In plugging, the motor is stopped by reversing its two supply leads till motor comes to standstill. The torque developed during reversing causes the motor to come to standstill in a short time.

The most commonly used design of this device is the one which use the effect of induced magnetic forces. In this type, a shaft having a permanent magnet on it rotates inside a copper cup. The copper cup can rotate in either direction against spring pressures. The shaft of the switch is coupled with the motor shaft. As the motor shaft rotates, the permanent magnet on the switch shaft rotates inside the cup. Magnetic induction due to its rotation causes the cup to follow the rotation of the shaft. An actuator is connected on the copper cup which can actuate the contacts in either direction. The speed at which the contacts would operate can be adjusted by varying the spring tension which restrain the movement of the cup. The contacts get reset to their original position when the motor speed falls below the value set by the spring tension. If the contact of the speed switch is so adjusted that contacts operate immediately on rotation in either direction and reclose only when zero speed is reached the switch is known as zero speed switch. The plugging switch or zero speed switch is represented in a control circuit as shown in Fig. 2.35.



(a) Unactuated position

(b) Actuation at a forward speed

(c) Actuation at a reverse speed

Fig. 2.35 Representation of plugging switch or zero speed switch

2.14 SOLENOID VALVES

Solenoid valves are electromechanical devices like relays and contactors. A solenoid valve is used to obtain mechanical movement in machinery by utilizing fluid or air pressure. The fluid or air pressure is applied to the cylinder piston through a valve operated by a cylindrical electrical coil. The electrical coil along with its frame and plunger is known as the solenoid and the assembly of solenoid and mechanical valve is known as solenoid valve. The solenoid valve is thus another important electromechanical device used in control of machines. Solenoid valves are of two types:

(*i*) Single solenoid spring return operating valve,

(*ii*) Double solenoid operating valve.

In Fig. 2.36 (*a*) is shown a single solenoid spring return valve in its de-energised condition. The symbol for the solenoid and the valve are also shown. The solenoid valve is shown connected to the cylinder to help readers understand the solenoid valve action. In the de-energised condition, the plunger and the valve spool position are as shown in Fig. 2.36 (*a*). In this position of spool, port *P* is connected to port *A* and port *B* is connected to tank or exhaust (*i.e.,* atmosphere) if air is used. Spring pressure (*S*) keeps the spool in this condition as long as the coil is de-energised. Fluid pressure from port *P* through port *A* is applied to the left side of the cylinder piston. Thus the cylinder piston moves in the right direction. Now when the solenoid coil is energised, plunger is attracted and it pushes the spool against spring pressure. The new position of plunger and spool are shown in Fig. 2.36 (*b*) In this position of spool, port *A* gets connected to tank and port *P* gets connected to port *B*. Thus pressure is applied to the cylinder piston from the right and moves the piston rod to the left. At the same time fluid in the other side is drained out to the tank. When the solenoid coil is again de-energised, the spring (*S*) will move the spool to its original position as shown in Fig. 2.36 (*a*). Thus normally when the solenoid coil is de-energised the piston rod remains extended.

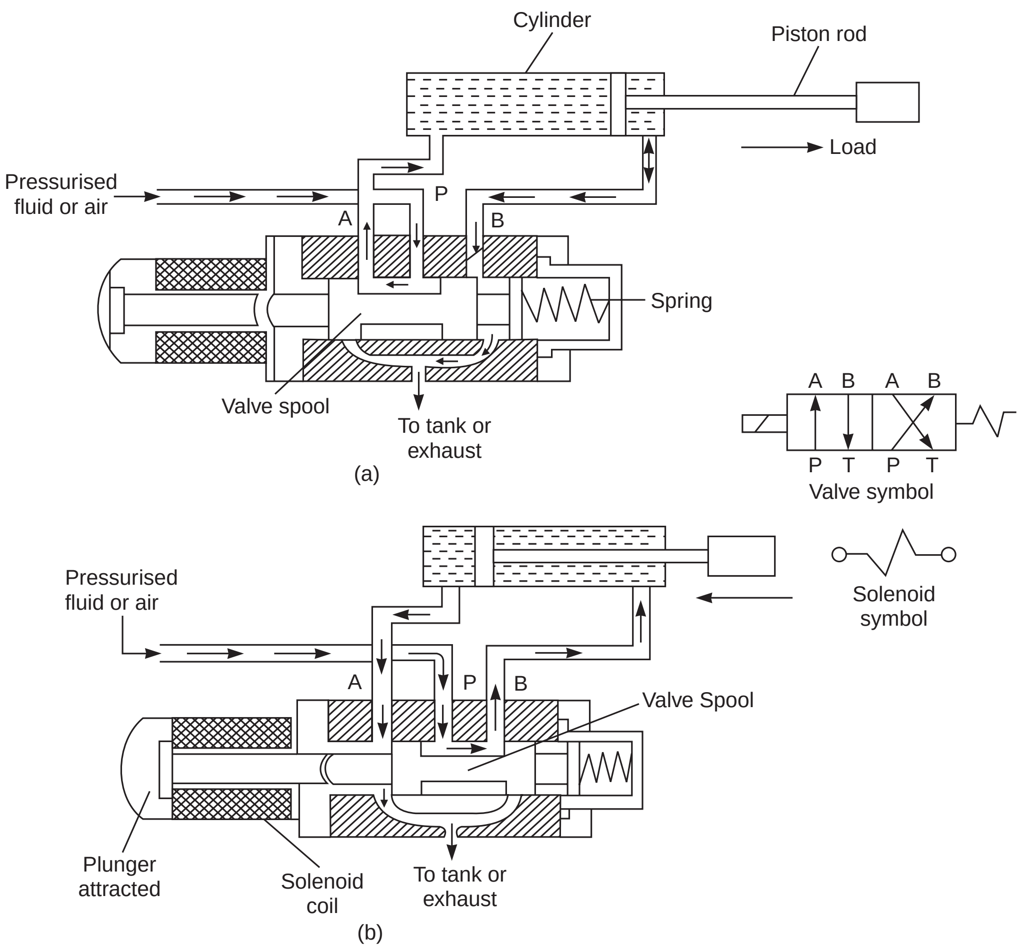


Fig. 2.36 Single solenoid spring return valve

Fig. 2.37 (*a*), (*b*) and (*c*) shows the double solenoid operating valve in three conditions. In Fig. 2.37 (*a*) both the solenoids are de-energised, and, therefore, the centering springs keep the spool in the position shown. In this position of spool, pressure port *P* is connected to tank while port *A* and *B* are closed by spool. No pressure is applied to either port *A* or port *B*. In Fig. 2.37 (*b*) is shown the spool position when solenoid *A* is energised. Energisation of solenoid *A* attracts its plunger and the spool moves in right direction compressing the right side centering spring. In this condition port *P* is connected to port *A* and port *B* is connected to tank (exhaust in case of air). Fig. 2.37 (*c*) shows the valve with solenoid *B* energised. The plunger is attracted and in turn spool moves towards the left, compressing the centering spring to the left. Now pressure port *P* is connected to port *B* and port *A* is connected to tank or exhaust. When the solenoid is de-energised the spool returns to the original position as shown in Fig. 2.37(*a*).

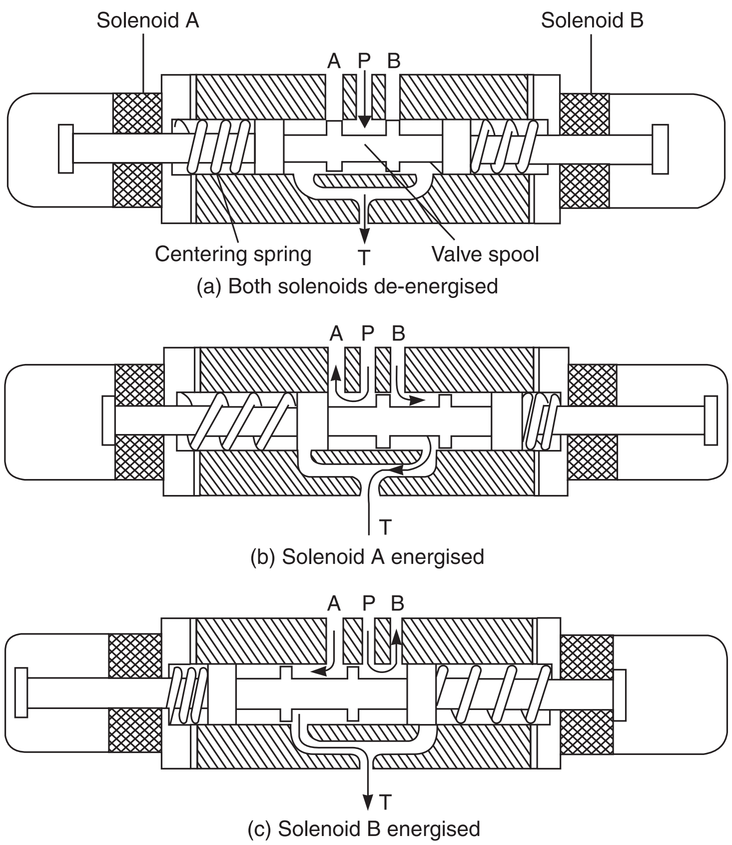


Fig. 2.37 Double solenoid valve in three operating conditions

2.15 PRESSURE SWITCHES

Pressure switches are used in the control systems to sense pressure of gas, air or liquid and feed a signal into the electrical control circuit. Pressure switch can have a normally open or a normally closed contact or it can have both types of contacts. The contact operation of a pressure switch is different from the switches we have discussed so far. The extra feature is the differential setting.

The cut out point of a pressure switch is that pressure at which its contact opens to de-energise the associated pump/compressor from raising the pressure further or to stop a machine cycle. Before we take up differential setting, we will see how the control system behaves if the pressure switch has only the cut-out point setting. For example, if a pump is used to raise water pressure in a tank to say upto 50 P.S.I. the pressure switch will energise the pump when pressure falls below 50 P.S.I. and will de-energise it when water pressure rises above 50 P.S.I. The variation from the above setting is generally only 1% of setting on either side which is called the accuracy of the pressure switch. When water pressure of the tank is being utilized the water pressure will fall and therefore opening and closing of the pressure switch contacts will be very rapid. Consequently the ON-OFF frequency of the pump motor will be high which will shorten its life. However, the pressure will be maintained very close to the value set on the pressure switch. To avoid this frequent switching ON-OFF of pump, a differential setting is provided in the pressure switch. Let us say a differential setting of 10 P.S.I. is provided. Now, what will happen is that when pressure drops below the cut out value of 50 P.S.I. the pressure switch contact will not open, it will open only when pressure falls to a lower value known as low pressure cut in, and this value is given by:

Low Pressure cut in = High pressure cut out—differential setting.

In this case the 'cut in value' is therefore equal to 40 P.S.I. Thus when water pressure falls below the cut in value of 40 P.S.I. the contact will again close and energise the pump to raise the water pressure again to 50 P.S.I. (the cut out value). The differential setting may be of a fixed value or it may be variable depending upon the provision made. Thus we see that if the cut out value is fixed and differential setting is varied, the cut in value changes according to the variation in differential setting.

In the above example the cut out point referred to as high pressure and cut in point referred to as low pressure. However, these terms may also refer to as carrying opposite meanings in other applications. Now, let us consider the case of a machine whose various operations are done by air pressure. Let us assume that for satisfactory operation of the machine the air pressure should be more than 80 P.S.I. *i.e.,* the machine should start only if the air pressure in the reservoir is more than 80 P.S.I. and it should stop if air pressure falls below 70 P.S.I. In this case, therefore, the cut in point is 80 P.S.I. above which the machine starts and cut out point is 70 P.S.I. below which the machine stops. As the value of cut in pressure is higher than the cut out pressure, it would be proper to mention these terms as high pressure cut in and low pressure cut out. Note that here the prefix high pressure and low pressure have changed their meanings from the previous example.

The pressure switches basically falls into three general categories depending upon the manner of operation. The principle of working of one type, called the bellow type, is illustrated in Fig. 2.38. The actual switches, however, vary considerably in their mechanical design. Further the differential setting arrangement is also not shown in this figure. The bellow expands or contracts depending upon the pressure. The movement of the bellow tilts the lever which rests on the micro switch knob. The thrust of lever on the micro switch knob can be varied by adjusting the screw. This would change the pressure at which the micro switch contact will change over.

The second general type of pressure switch uses a diaphragam in place of a bellow, the other operation being the same. The third type uses a hollow tube of semicircular shape. When pressure is given to this tube, it tries to straighten up and this action is transformed into a rotary motion and through a mechanical linkage a micro switch is actuated. Pressure switches are designed to operate within a certain range. For example a switch of 15-55 P.S.I. range cannot be used for higher ranges of pressure of say 100-150 P.S.I.

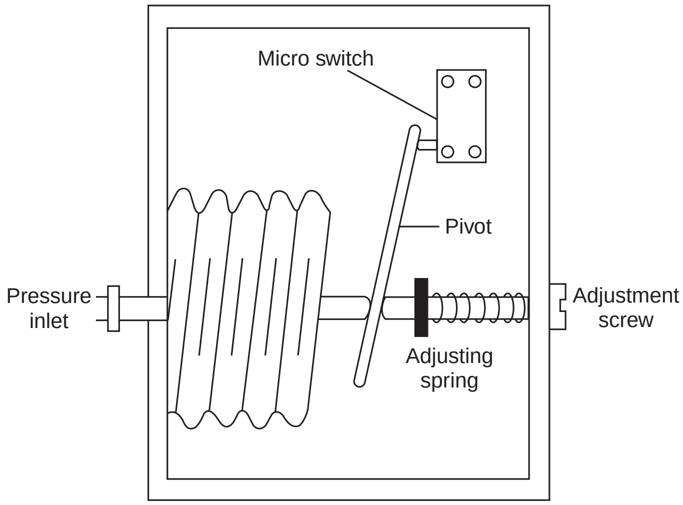


Fig. 2.38 Bellow type pressure switch

2.16 PRESSURE TRANSDUCER

A pressure transducer is an important pilot device of modern machines used in industry and controlled by programmable controllers. A pressure transducer utilizes piezo electric or semi-conductor strain gauges to measure presssure. Semi-conductor strain gauges are very small, typical dimension being 0.3 inch overall length, 0.01 inch width and 0.001 inch thick. A strain gauge changes its resistivity when it is stressed, the change in resistivity being proportional to the strain produced in the gauge due to external stress. In pressure transducers the strain gauges are epoxy bounded on the metallic diaphragm of pressure transducers. The four strain gauges Rsg_1, Rsg_2, Rsg_3 and Rsg_4 bonded on the diaphram are connected in the Wheat Stone bridge as shown in Fig. 2.39. Two strain gauges Rsg_2 and Rsg_4 are mounted such that increase of pressure increases their resistance and the other two strain gauges Rsg_2 and Rsg_3 are so mounted that increase of pressure decreases their resistance.

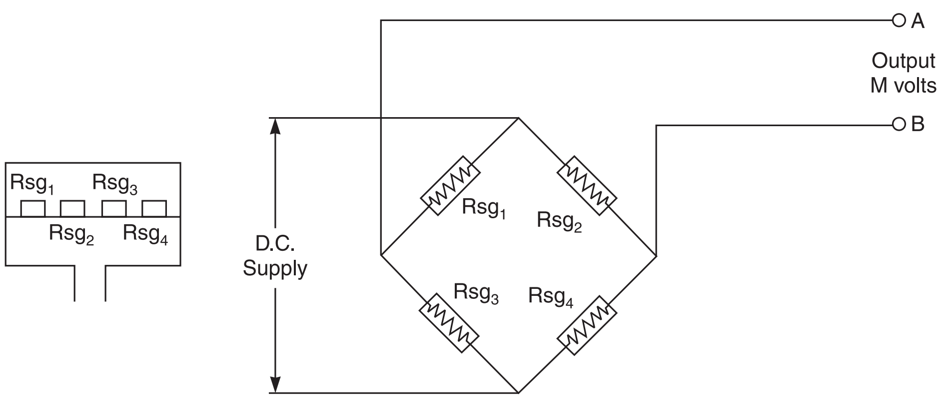


Fig. 2.39 Pressure transducer using strain gauges

At balance when there is no pressure, there is no output between terminals *A* and *B*. As soon as the pressure is applied, the strain gauges get stretched or compressed accordingly and the bridge circuit gets unbalanced due to changes in resistance of strain gauges. Thus, a voltage output becomes available between terminal *A* and *B* which is proportional to the pressure on the diaphragm.

2.17 TEMPERATURE SWITCHES (THERMOSTATS)

In many industrial processes temperatures have to be maintained within very close limits or otherwise, the finished product may not come up to the standards. Temperature switches or thermostats are used for maintaining a prescribed value of temperature.

There are two general types of temperature switches used in industry. The first one is bimetallic strip type which works in a similar way to that of an overload relay discussed earlier. The unequal expansion of two bimetallic strips causes them to bend and this bending movement is used to actuate a snap switch. The accuracy of this type of thermostats is not of a high order, it is mostly used where high precision work is not required such as for room heating, air conditioning and refrigeration. However, it has a compact and rugged construction.

Another type of thermostat which has wide industrial application uses either a liquid, a gas or a vapour as the sensing element in a short length of pipe or in a long thin tube called capillary tube with a bulb at one end. The expansion of the liquid, gas or vapour is utilised to actuate the switch contact. The temperature ranges for these units are as follows:

Liquid filled 100°F to 2200°F

Gas filled 100°F to 1000°F

Vapour filled 50°F to 700°F.

Figure 2.40 shows a view of a capillary tube type thermostat.

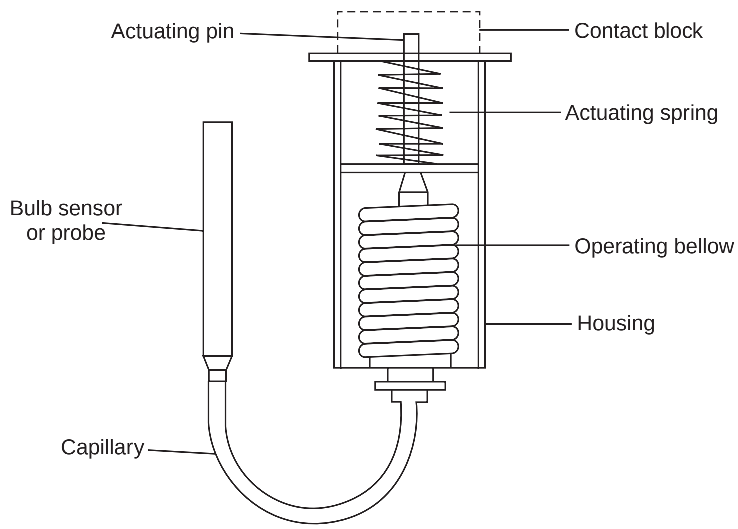


Fig. 2.40 Capillary type thermostat

The probe is inserted at the location where the temperature is to be measured, the liquid in the bulb expands and pressure is developed in the bellow which also expands and moves the actuating pin which operates the contact operating mechanism. This liquid filled type of thermostat has a very quick response. However if the length of the tube is long the response becomes a little slower. This thermostat is especially useful where the switch actuating mechanism has to be kept away from the temperature sensing side. The disadvantage of this type is that the capillary tube gets easily damaged if it is not carefully handled.

2.18 FLOAT SWITCH

Float switches are used to maintain liquid levels within a certain range in a tank by energising a pump when the liquid level falls to a certain lower pre-set height and by de-energising the pump when liquid level rises above a certain higher pre-set height. This level sensing switches using a float can be of two types, one using a rod and the other a chain with a counter weight. A float switch using a rod is shown in Fig. 2.41.

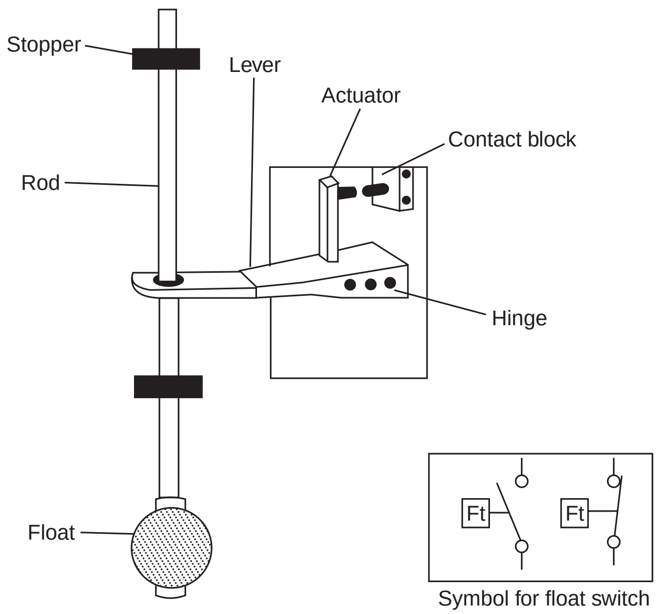


Fig. 2.41 Level sensing using a float and a rod

A float is attached to the lower end of the rod. The rod passes through a hole of a lever. Two stoppers fitted on two ends of the rod cannot pass through the hole (see Fig. 2.41). When the liquid level rises the float also rises and moves the rod up. At a certain level depending upon the position of lower stopper the lever gets tilted up and it inturn actuates the contact. When the water level starts falling the float and the rod also moves down. The lever, however, remains in the same position and keeps the contact actuated. At a certain lower level depending upon the position of the upper stopper the lever gets tilted down by the stopper and the contact gets deactuated. When the liquid level starts rising the contact remains unactuated till the higher level set by stopper position is reached. This actuation and deactuation of the contact are used to stop and start a pump motor for maintaining the desired liquid level in the tank.

The other form of float switch uses a chain passing over a pulley with float at one end and a counter weight at the other end (see Fig. 2.42).

The stoppers fitted on both sides of the chain tilts the lever. The contact is opened or closed by the position of mercury placed in a tube. The tube is mounted on the lever and thus tilting of lever causes the contact to open or close. When the liquid level raises the float, the stopper on the left hand side of the chain tilts the lever in clock-wise direction and thus the switch contacts open (see Fig. 2.42). When the liquid level drops and the counter weight rises and at certain limit the stopper fixed on the right hand side of the chain pushes the lever and tilts it in the anticlockwise direction, the switch contact closes. A float switch may not be suitable for certain applications, for example, in situation where there is some mounting difficulty or where ice may form on the surface of the liquid due to low ambient temperature. When the water level falls the ice layer remains fixed and therefore the decreasing liquid level below the ice remains undetected by the float. In such cases the liquid level is sensed by measuring the pressure of the liquid level. For this a special differential switch is used which compares two pressures from different sources. The switch has differential adjustment instead of range adjustment. The difference adjustment is used to set the maximum pressure difference between the two sources to actuate the switch contact. The differential adjustment is used to get the minimum pressure difference to deactuate the switch contact. In a tank where liquid level is maintained with the help of a differential pressure switch the top of the tank is filled with compressed air to maintain constant pressure in the outgoing lines. When water level falls, more compressed air enters the tank and thus the total pressure in the tank remains constant. In this case an ordinary pressure switch fitted at the bottom of the tank will therefore always read the constant pressure in the tank.

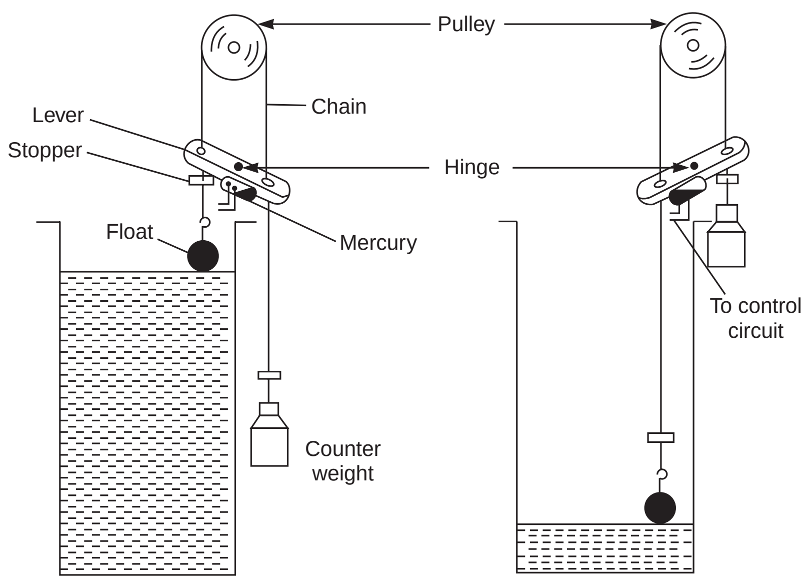


Fig. 2.42 Level sensing using a float, chain pulley and counter weight

The differential pressure switch solves the problem. It measures the difference between the total pressure in the tank *i.e.,* (air and water) and only the air pressure. This differential pressure is proportional to the height of water in the tank. One connection of the pressure switch is placed at the bottom of the tank to measure the total pressure of air and water column. The other connection is at the top of the tank which measures only the air pressure. The switch is easily set to control the water level in the tank by setting the maximum and minimum difference in pressure to actuate and deactuate the switch contact.

2.19 CONTROL TRANSFORMER

The function of a control transformer is to obtain the desired low voltage control supply from the power supply system. The stepped down control supply voltage may be 220 V or less. There are two advantages of using a low control voltage.

(*i*) Reduced risk to the operator, and

(*ii*) Reduced risk of insulation break down and grounding in the control wiring and pilot devices.

In India the most commonly used control voltage is 220 V, however in situation where the operator has to continuously hold the control console in hand such as in small hoist, a lower voltage of 110 V, 48 V or 24 V is used. Electro-magnetic devices such as contactors, relays, solenoids etc., are manufactured in these standard control voltage ratings. The disadvantages of using low control voltage is that the cross-section of control wire increases and hence the cost also increases.

The electromagnetic coils of contactors, relays and solenoids pick up above 85% of their rated coil voltage. This provides a higher safe value of operation as burn out of coils may occur above 110% of the rated voltage. These devices have inrush currents of nearly 6 to 9 times the continuous holding current. Both the inrush and holding currents have low power factor. The control transformer design should be such as to provide good regulation under poor power factor loads. It should maintain 95% of the rated secondary voltage at all load to avoid (*i*) chattering of relays and contactors; (*ii*) dropping of already energised devices; (*iii*) failure of solenoids being closed.

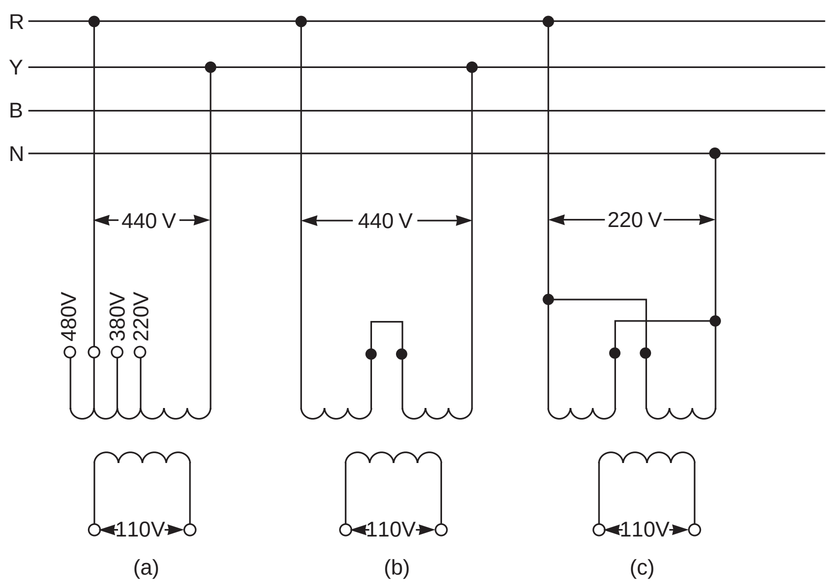


Fig. 2.43 Control transformer connections (*a*) Primary winding with tappings (*b*) Two primary windings connected in series (*c*) Two primary windings connected in parallel

Control transformers are generally of two types. First type is the simple one having one primary winding and one secondary winding with no tappings. To use the transformer at various supply voltage the primary winding is to have tappings. For example, a typical control transformer will have tappings at the primary winding at 440, 415, 380, 230, 200 V, while the secondary may have only one winding giving constant voltage. The number of turns upto 440 V tapping will be double the number than at 220 V tapping, thereby keeping the ratio of voltage per turn the same whether the tappings are connected to 440 V or 220 V. As the volt/turn remains same we get constant voltage on secondary side. The second type of control transformer known as Dual primary type is the most widely used control tansformer. It has got two identical primary windings and one secondary windings.

In India we have three phase supply system of 415 V line to line and 240 V line of neutral (declared voltage by the supply authorities at Consumers' end) with ± 6% variation. The primary of a dual transformer can be connected across line to line (415 V) if the two primary windings are connected in series (see Fig. 2.43 (*b*)). In series connection the number of turns on each winding are added together. The transformer primary can be connected across line and neutral (240 V), if the two primary windings are connected in parallel. The effect of connecting two windings of equal number of turns in parallel is the same as connecting only one winding as in Fig. 2.43 (*c*) because the effective number of turns for determining the turns ratio remains the same.

Determination of Rating of Control Transformer

The primary voltage of the transformer depends upon the supply voltage available while the secondary voltage depends upon the control circuit application. The voltage ampere rating of the transformer depends upon the continuous holding volt ampere (VA) rating and inrush current rating of various relays, contactors, solenoids and indication lamps to be connected to the transformer secondary. The volt ampere rating of the components are available from the manufacturers literature. The method of finding out the approximatte VA rating of the control transformer is to:

(*i*) Calculate the maximum continuous holding current by adding the holding current of all the coils that will get energised at the same time and then multiplying this amount by a factor of 5/4.

(*ii*) Calculate the total maximum inrush current by adding the inrush current of all the coils that will be energised together at any one time and then multiplying this figure by 1/4. Now taking the larger of the two figures calculated above, multiply this current by the control voltage. This product is the volt ampere (VA) required by the transformer.

When it is difficult to find out how many contactors are switched on simultaneously, take 80% of the holding capacity of all contactors and relays. Another simple method for finding out approximate VA rating of the transformer is to make calculations using the following formula:

$$P_{TR} = \Sigma P_h + P_{1C} + \Sigma P_L$$

where, P_{TR} = The nominal power (VA) of the control transformer.

ΣP_h = The holding apparent power (VA) of all the contactors energised simultaneously.

P_{1C} = Inrush apparent power (VA) of the contactor of largest size.

ΣP_L = Active power of all signal lamps.

2.20 SYMBOLS FOR VARIOUS COMPONENTS

Control diagram is the language of control and control circuits. Symbols for various components are the various alphabets of this language. The symbols for various components have been standardised by the Bureau of Indian Standards (BIS). In this book symbols recommended by BIS will be followed. However, in industry one comes across drawings having different symbols as Indian industry imports lot of machinery from outside the country. To make the students familiar with these alternate symbols some control circuits will be discussed using the Amercian and British standard symbols. Once an engineer is able to read and interpret the drawings, difference in symbol representation does not pose much problem as most of the drawings carry a key to various symbols at the bottom of the drawings in tabular form. We have already studied symbols for various components while studying about the components. Now all those symbols for various components have been compiled in a tabular form for ready reference as in Table 5.

2.21 CONTROL DIAGRAMS

As discussed earlier the control diagram is the language of controls and control circuits. In a control diagram is hidden the logic of the control, which can be decoded only if the reader is familiar with various control symbols and knows how to read the drawing. A good control diagram is that which any control engineer will be able to read even if he is not associated with the design of the circuit. To understand the working of control circuit, first one should get familiar with the various operations required from that control *i.e.,* the machine operations. The same knowledge is required when one has to design a control circuit for some machine. Before the various types of control diagram are discussed, the following points which are building blocks in the development of a control diagram may be gone through.

(*i*) All control components like contactors, relays, push buttons, etc., are designated by some alphabets. The alphabet is generally the first alphabet of the operation obtained by energisation of that particular contactor or relay. For example in forward and reversing of a motor the starter has two contactors one for forward motion and another for reverse motion. In control diagram the contactor responsible for forward motion is designated by letter F i.e., the starting letter of the word forward and reverse contactor is designated by the letter R. In most of the drawings this procedure of designating the components is followed.

(*ii*) All contacts of various contactors and relays shown in the diagram are for the coils in the de-energised state. The normally closed contact of contactor will open and normally open contact will close when that particular contactor is energised.

(*iii*) The various contacts of a particular contactor are designated by numerals. For example various contacts of a contactor F will be represented as F_1, F_2, F_3, F_4, in the control circuit.

(*iv*) The control wires are also designated with numbers in the diagram. These numbers are also actually marked on the wires by inserting numbering ferrules on the wires. Numbers of wires in the drawing makes the initial wiring easy and it also helps in tracing of wires during trouble shooting. The general trend is to mark the two supply leads from control transformer as L_1 and L_2, L_2 is generally grounded and L_1 acts as the phase supply for control circuit. L_1 is connected to a control fuse. After the control fuse the supply wire is marked as 1 and the neutral as 0. The other wires following from components and connected to supply wire no. 1 are marked 2, 3, 4 etc. We will now discuss the three types of control diagrams in general use. These three types of diagrams are:

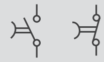
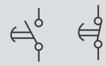
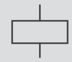
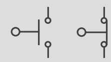
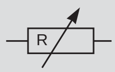
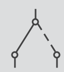
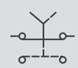
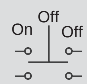
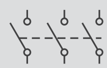
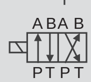
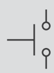
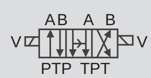
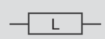
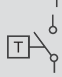
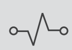
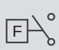
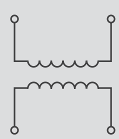
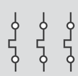
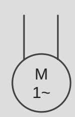
(*a*) Wiring diagram

(*b*) Elementary line diagram or Schematic diagram

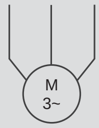
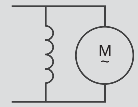
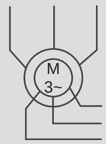
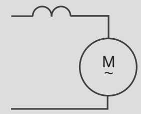
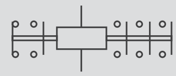
(*c*) Wireless connection diagram

In a wiring diagram various components are shown exactly according to their physical relationship and location in the panel. Components are represented by their standard symbols along with their terminals on it. A wire between two terminals is represented by a line.

Table 5 Symbols for Control Components

S.No.	*Name of Component*	*Symbol*	*S.No.*	*Name of Component*	*Symbol*
1	Crossing of Conductors		21	On-Delay Relay Contacts	
2	Joint or Junction of Conductors		22	Off-delay Relay Contacts	
3	Earth/Ground		23	Contactor or Relay Coil	
4	Chassis		24	Make Contact Normally Open (NO)	
5	Indication Lamp		25	Break Contact Normally Closed(NC)	
6	Resistor		26	Limit Switch	
7	Variable Resistor		27	Selector Switch 2-Position	
8	Capacitor		28	Selector Switch 3-Position	
9	Fuse		29	Selector Switch 2-Position Double Break	
10	Switch		30	Selector Switch 3-Position Double Break	
11	Switch Fuse Unit		31	Circuit Breaker	
12	Three Pole Switch		32	Solenoid Valve Single Acting	
13	On Push Button		33	Solenoid Valve Double Acting	
14	Off push Button		34	Winding	
15	Pressure Switch Contact		35	Inductor	
16	Thermostat Contact		36	Solenoid Coil	
17	Flow Switch		37	Control Transformer	
18	Thermal Overload Relay				
19.	Control Contact of Overload				
20	Time Delay Relay		38	Induction Motor Single Phase	

(Contd...)

S.No.	*Name of Component*	*Symbol*	*S.No.*	*Name of Component*	*Symbol*
39	Three phase Squirrel Cage Induction Motor		41	D.C. Shunt Motor	
40	Three phase wound Rotor Induction Motor		42	D.C. Series Motor	
			43	Contactor Representation with Contacts	

The wiring is represented as it is actually wired in the panel. In other words, a wiring diagram is a drawing of equipments and wires more or less as they should appear on the panel or on the machine. A wiring diagram is useful for initial wiring of the control circuit. It is also helpful in trouble shooting when actual wiring needs to be traced. The wiring diagram of 'Direct on line starter' with motor 'ON' indication, for a three phase motor is given in Fig. 2.44.

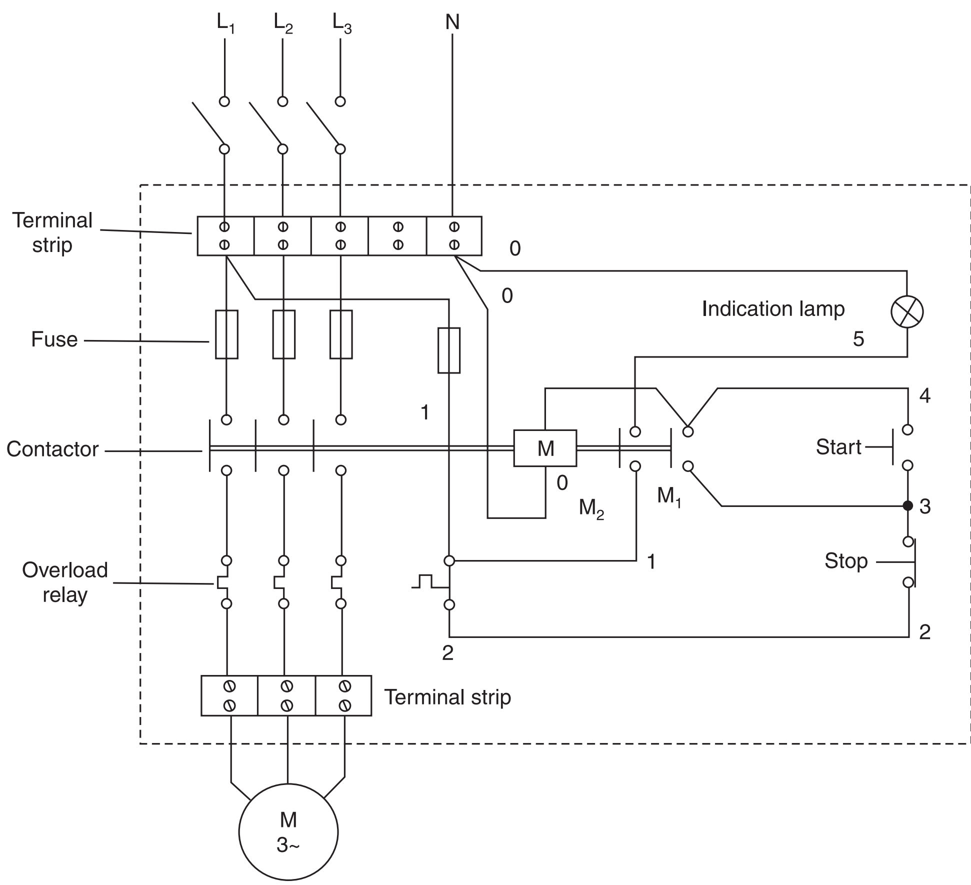
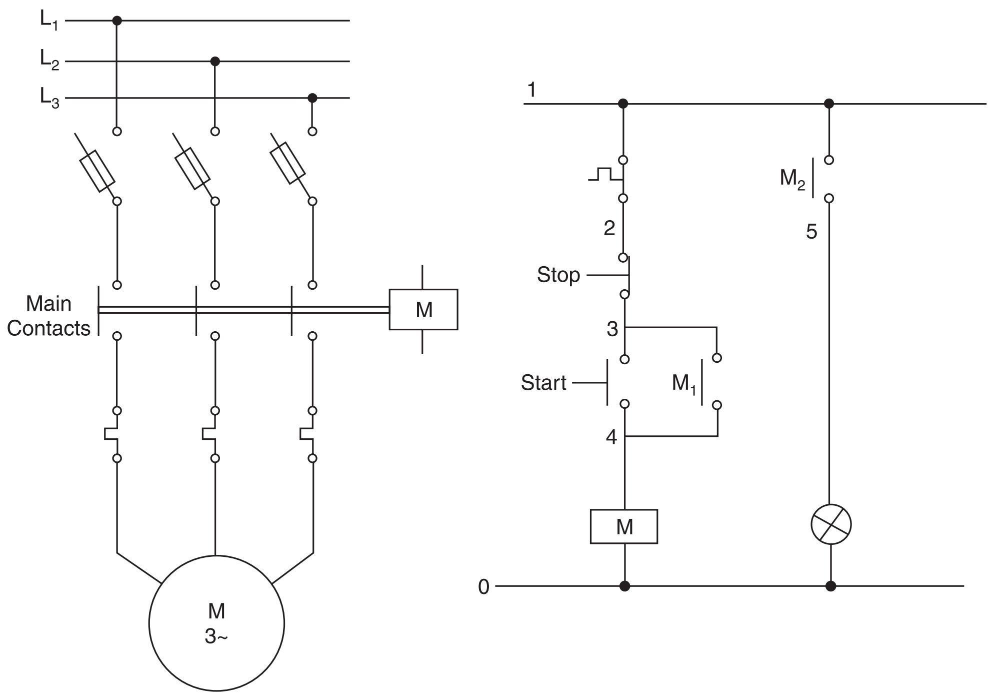


Fig. 2.44 Wiring diagram for a direct on line starter

Let us understand working of the control circuit by tracing the control wires from control fuse onward. The operation required here is only to run the motor by pressing the START-push button and when it is desired to be stopped, it should be by pressing the STOP-push button. This is the simplest control circuit, a little introduction to this direct on line starter was given at the beginning of the text book. If you can understand the circuit it is well and good, if not, let us study the circuit diagram shown in Fig. 2.45 which is the elementary line diagram or more commonly known as the Schematic diagram.



(a) Power diagram

(b) Control diagram

Fig. 2.45 Elementary or schematic diagram for a direct on line starter

This diagram is a representation of the circuit in its proper electrical sequence. Such a diagram provides easy understanding of working of the circuit. Whenever a control circuit is designed it is done in the schematic diagram form. A brief explanation of this circuit is as follows:

All contact positions in this control diagram are in their normal positions meaning that when the coil M is de-energised. In normal position the supply reaches upto wire number 3 through the normally closed contact of overload relay and STOP-push button. When the START-push button is pressed, supply reaches terminal 4 at contactor coil and energises the contactor coil. The main contacts of the contactor close and the motor starts running. At the same time auxiliary contacts M_1 and M_2 also close. Closing of M_1 provides a parallel path across the START-push button. Now, even if START-push button is released, contactor coil remains energised through the closed contact M_1. Closed contact M_2 energises the indication lamp showing that the motor is ON. Referring back to the wiring diagram it will be observed that the circuit is the same as the schematic diagram but is little difficult to read than the schematic diagram.

The schematic diagram is simpler as compared to the wiring diagram. As the circuit here is the simplest one, much difficulty may not be faced in reading the wiring diagram. However, for more complicated circuits, the wiring diagram becomes very difficult to read due to large number of wires crossing each other. Another point to observe is that in the schematic diagram the components and their contacts are placed in the sequence of their operation and not according to their physical position as is done in case of a wiring diagram. In a schematic diagram the contacts of a particular contactor or relay will be found scattered in the drawing. In the rest of this text book all control circuits will be discussed in their schematic diagram form due to simplicity in understanding and ease in the development of circuits.

The third type of control diagram is the wireless connection diagram. This kind of a diagram is not much used but is drawn in situations where the number of wire connections are large and there is possibility of creating confusion in reading the drawing. Such a wireless diagram for the same motor starter (DOL starter) is shown in Fig. 2.46.

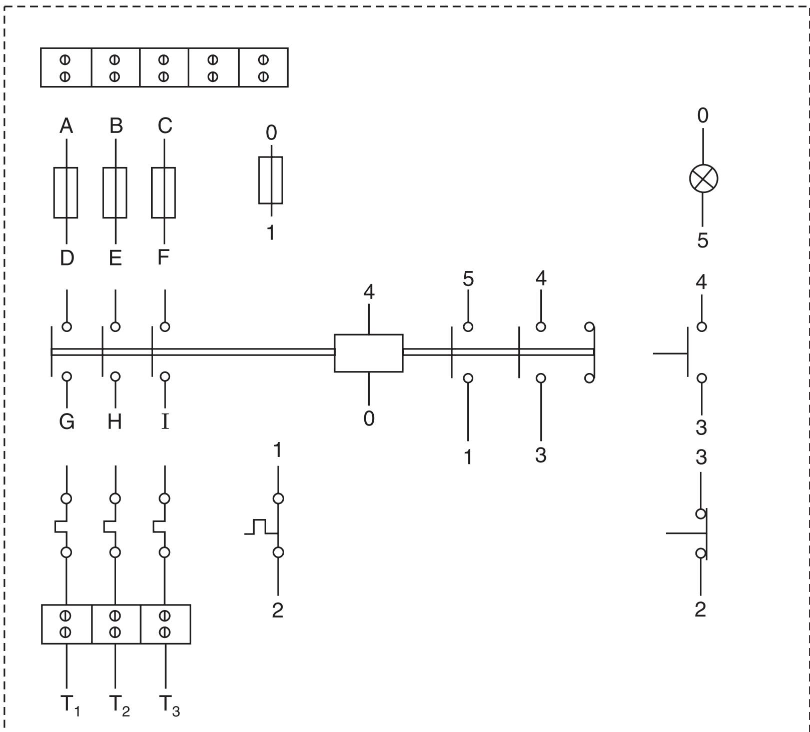


Fig. 2.46 Wireless connection diagram for a direct on line starter

In this diagram wiring is not shown but the wire numbers are shown on the terminals of the various components. The location of components in the diagram resembles their physical location in the panel (as in case of wiring diagrams). Comparing the wireless diagram with the wiring diagram, it may be observed that a wireless diagram is not at all useful in understanding the circuit. The drawing may however be used for wiring the control circuit when components are fixed in the panel as in the diagram.

REVIEW QUESTIONS

1. State the advantage of using a fuse switch unit over a switch and a fuse in series. Discuss the two types of fuse switch units in use.
2. What are the main features of moulded case circuit breakers? What are their advantages over conventional breakers and fuse switch units?
3. Explain with the help of a diagram the working of a solenoid type contactor.
4. Make a labelled diagram for clapper type contactor. Explain the function of its blow out coil.
5. Explain the working of two types of latching relays. Where are these relays used?
6. Discuss the working of a bimetallic type over-load relay.
7. Explain the working principle of eutetic type alloy and magnetic over-load type relays.
8. What is the difference between a ON-delay and OFF-delay timer? How does the contact changeover take place in these timers?
9. Explain with the help of a diagram the working of a pneumatic timer.
10. Explain various forms of synchronous motor timers.
11. Discuss the principle of operation of an electronic timer.
12. Explain the working of phase failure relay which operates on negative sequence components of currents.
13. Explain the function of push button, selector switch, drum switch and limit switch used in control circuits.
14. Mention the types of control diagrams in general use. Explain the use of each of them.
15. Explain why thermal timers are used only in star-delta starters.
16. What is a zero speed switch and where is it used?
17. State the function of differential setting in pressure and temperature switches ?
18. What are the respective temperature ranges for a liquid filled, a gas filled, and a vapour filled thermostats?
19. Explain how you will measure the liquid level in a tank where ice formation takes place in winters.
20. When speaking of current relays, what is meant by pull in current, drop out current and differential current.
21. Explain the purpose of using shading coil on magnetic pole faces of a relay for ac operation.
22. Mention the exact situation where a frequency relay is used.
23. Draw the symbols for permanent magnet type latch relay, ON-delay timer contacts, pressure switch, single acting solenoid valve and three position selector switch.
24. The purpose of quartz and fillers in the fuse is to:
    (*a*) increase voltage rating (*b*) increase current rating
    (*c*) increase heat transfer (*d*) increase weight.
25. Contactor coils are designed to drop the plunger when voltage falls to ______ per cent of rated voltage:
    (*a*) 50% (*b*) 65%
    (*c*) 75% (*d*) 85%
26. Which one of the following timers is the most accurate one ?
    (*a*) Thermal timer (*b*) Electronic timer
    (*c*) Synchronous motor timer (*d*) Pneumatic timer
27. Liquid filled thermostats can measure temperatures in the range of:
    (*a*) 50 to 700°F (*b*) 100 to 100°F
    (*c*) 150 to 2200°F

28. A pressure transducer consists of

(*a*) pressure switch and a special relay (*b*) a low resistance coil

(*c*) a semi-conductor strain gauge

29. Material used for contacts of high rating contactor is

(*a*) Copper (*b*) Silver

(*c*) Silver Nickel (*d*) Silver Cadmium Oxide

30. The error in synchronous timer is in the range of

(*a*) ± 10% (*b*) ± 5%

(*c*) ± 3% (*d*) ± 1%

3

Starters for 3-Phase Squirrel Cage Motor

3.1 INTRODUCTION

Three phase squirrel cage motors are the most widely used motors in industry. About 80% of the motors manufactured are squirrel cage motors. Simplicity, ruggedness and reliability of such a motor make it the standard choice for alternating current, all purpose, constant speed applications. These motors are less expensive, require less maintenance than dc motors of equal kilowatt rating and speed.

Before discussing the various types of starters for this motor, brief description of characteristics of this type of motor is included as follows:

A squirrel cage induction motor consists of a frame, a stator and a rotor. The stator or the stationary portion carries the three stator windings. The rotor consists of cylindrical member made of steel laminations mounted rigidly on the motor shaft. The rotor winding consists of copper or aluminium bars fitted into slots in the rotor member. The bars are shorted at each end by a closed continuous ring. This assembly of bars and end rings looks like a squirrel cage and this similarity has given the motor its name.

When a three phase supply is given to the three stator windings a resultant magnetic field is set up which revolves around the rotor. The resultant magnetic field revolves around at a speed given by equation,

$$N_s = \frac{120\,f}{p}$$

where N_s = Speed in revolutions of the magnetic field

f = Supply frequency

p = Number of stator poles for which the stator winding is made.

The minimum number of poles for a winding can be two. Thus, at 50 Hz supply the maximum speed of revolution of the field is 3000 r.p.m. For a 4 pole machine it would be 1500 r.p.m. This revolving field cuts the rotor bars and induce current in them. The induced current in the rotor produces its own magnetic field. The stator magnetic field and rotor magnetic field interact and the rotor magnetic field follows the stator magnetic field thereby establishing a torque on the motor shaft.

The current in the rotor is maximum at standstill (when the rotor is stationary, emf induced in the standstill rotor is maximum). As the motor picks up speed, the rotor current decreases as the relative speed between the rotating field produced by the stator and rotor speed decreases. The torque speed characteristic of a typical squirrel cage motor is shown in Fig. 3.1.

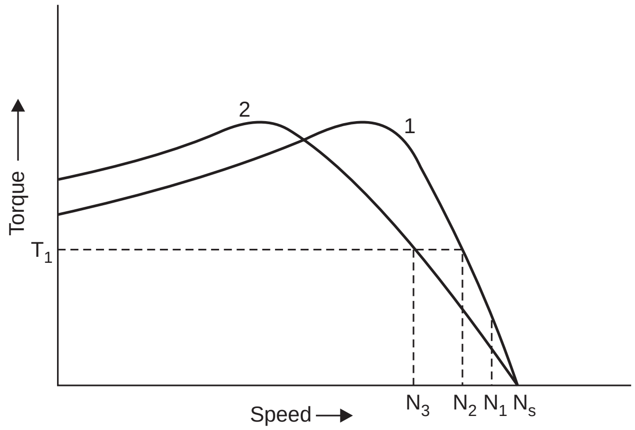


Fig. 3.1 Torque speed characteristic of a three-phase induction motor

This characteristic remains fixed for a particular rotor design. The characteristic can be changed by making changes in the rotor resistance and reactance.

3.1.1 Motor Current at Start and During Acceleration

At standstill when voltage is applied to the stator winding, the rotor winding acts like a short circuited secondary of a transformer. The secondary current and thus in turn the primary current drawn by stator winding from supply is large. The starting current may be as high as 4.5 to 6 times the full load current of the motor depending upon the motor characteristics. As the motor accelerates, the current goes on decreasing but at a slow rate. The current decays sharply when motor reaches near its rated speed. Fig. 3.2 shows the current versus speed characteristic of an induction motor.

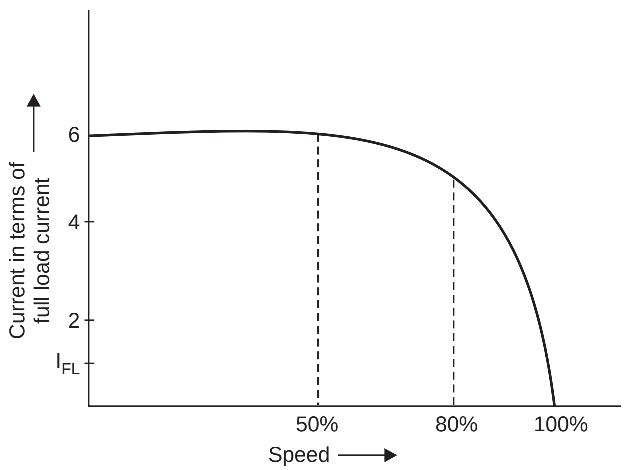


Fig. 3.2 Current drawn by a three phase induction motor during starting

As shown in Fig. 3.2 upto 50% of the rated speed the current drawn remains approximately 6 times the full load current. When motor reaches about 80% of the rated speed the decline in the current is very fast. The motor heating rate is proportional to I^2R (copper-loss). Thus the rate of heating of the motor is high during acceleration.

3.1.2 No-load Speed and Final Speed of Motor

On no-load motor accelerates until the necessary speed is reached to overcome windage and friction losses. This speed is very near to the synchronous speed which is the speed of the revolving magnetic field. The motor, however, never reaches synchronous speed, since then a current will not be induced in the rotor and the motor will not produce any torque. Refer Fig. 3.1 for a motor with a particular characteristic designated as 1, the no-load speed is shown as N_1. When the motor is loaded, speed adjusts itself to the point where the force exerted by the magnetic field on rotor is sufficient to overcome the torque required by the load. In Fig. 3.1 say for torque requirement of T, the motor will run at speed N_2. The difference between the speed of magnetic field (synchronous speed) and rotor is known as slip. The slip in the first case is $N_s - N_1$ and in the second case it is $N_s - N_2$. The slip is also generally expressed as percentage of the synchronous speed. the percentage slip for the above two cases then becomes,

$$\% \text{ slip (No-load)} = \frac{N_s - N_1}{N_s} \times 100$$

$$\% \text{ slip (On-load)} = \frac{N_s - N_2}{N_s} \times 100$$

With the same load requirement if the characteristic of motor is changed to the characteristic designated as 2 (see Fig. 3.1), it is seen that the motor will run at a speed of N_3. From the above it follows that the slip necessary to carry the full load depends upon the characteristic of the motor. As mentioned earlier the characteristic of motor depends on reactance and resistance of the rotor.

The slip of the motor varies also with variation in line voltage. An increase in line voltage causes a decrease in the slip (*i.e.,* motor runs at higher speed) and a decrease in line voltage causes an increase in the slip. In either case sufficient current is induced in the rotor to carry the load. For a particular load on motor, when line voltage decreases the rotor current and hence the line current increases to produce the same torque. This causes increase in the heating

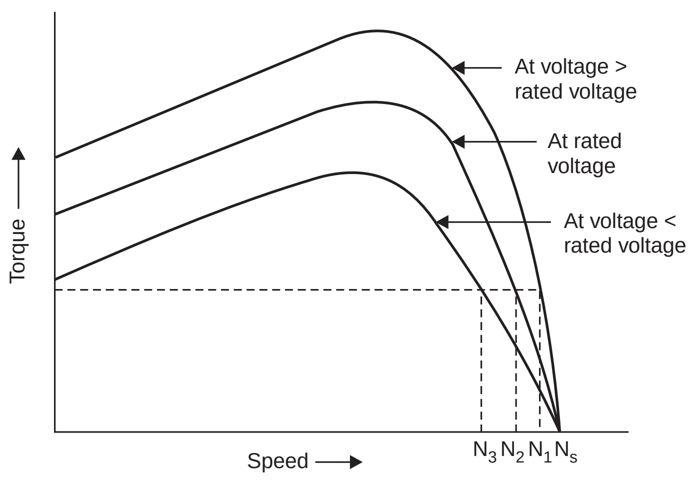


Fig. 3.3 Variation of slip with variation of line voltage for an induction motor

of the motor. On the other hand increase in line voltage decreases the rotor current and also the line current and there is decrease in heating. In other words the motors can carry a larger load. The slip at rated load may vary from 3 per cent to 20 per cent for different types of motors. The variation of slip at a particular load for different voltages is shown graphically in Fig. 3.3. Observe that variation in slip is very small.

3.1.3 Starting of Motor

A motor may be required to start on no-load or on full load depending upon the machinery to which it is connected. Many industrial applications require a machine to be started at no-load, while some machines may require starting at its full-rated load. In the first case during no-load starting motor needs only a small torque to overcome the starting inertia. In the second case the motor starting torque should be enough to start with the normal load against the starting inertia.

The most common method of starting of poly-phase squirrel cage motor is to connect the motor directly to the main supply through a manual or magnetic starter. At starting, the inrush current is high but due to this high current a high starting torque is developed, which accelerate the motor quickly to its final speed. As the accelerating rate is fast the I^2R heating time in the motor is small.

This starting method is however used only for small motors upto 5 hp.

Higher capacity motors are generally started at a reduced voltage for the following two reasons:

(*i*) The high starting current drawn from the main supply is objectionable to the supply authorities as it causes heavy line voltage drops which adversely effects the performance of other loads connected to the system. The supply authorities, therefore, impose restriction on the industries not to start large motors directly from supply. Consider a 415 V, 50 hp motor whose full load current is about 70 amps. The motor if started direct-from main supply will draw a current of about 6 × 70 = 420 A. Thus it is apparent that such a high current will disturb the supply network system. The motors are therefore recommended to be started at a lower voltage so that the inrush current drawn from supply is lower.

The voltage, however, can be reduced upto a certain level as, lowering of voltage also lowers the starting torque. (as $T \propto V^2$). To start a motor from standstill, certain minimum starting torque is required depending upon the load on the motor.

For motors which have to start on full-load the supply authorities allows the direct on line starting, provided the peak current is drawn in steps so that the rate of rise of current/sec is reduced. The purpose is to enable the automatic voltage regulators provided in the supply system to have sufficient time to adjust system voltage due to peak currents drawn.

(*ii*) The second reason for starting motors on reduced voltage may be to obtain low starting torque. This may be desired in certain machinery where full voltage starting torque applied suddenly may cause machinery to get damaged due to sudden jerk. The sudden application of high torque may cause wear or damage of gears, chains or couplings. The belts may slip and the material being processed on conveyors may get damaged.

It thus follows that squirrel cage motors are usually to be started at a reduced voltage. The desired result may be either reduced current drawn from supply to avoid disturbance in the supply system or reduced torque to avoid jerk. The reduced voltage at the motor terminals can be applied by using different types of starters. Different types of reduced voltage starter used are:

(*i*) Resistance reduced voltage starter;

(*ii*) Increment resistance starter;

(*iii*) Reactance reduced voltage starter;

(*iv*) Auto transformer reduced voltage starter;

(*v*) Part winding reduced voltage starter;

(*vi*) Star delta starter.

Detailed description on all these starters are included in the next section. It is very important to understand the behaviour of an induction motor during the start up and acceleration periods. Such an understanding would enable one to select the proper starting method to confirm to local supply authorities regulation. Though several starting methods may appear suitable for a particular motor application, a careful examination of the specific application will lead to the selection of the best method of starting.

3.2 PRIMARY RESISTOR TYPE STARTERS

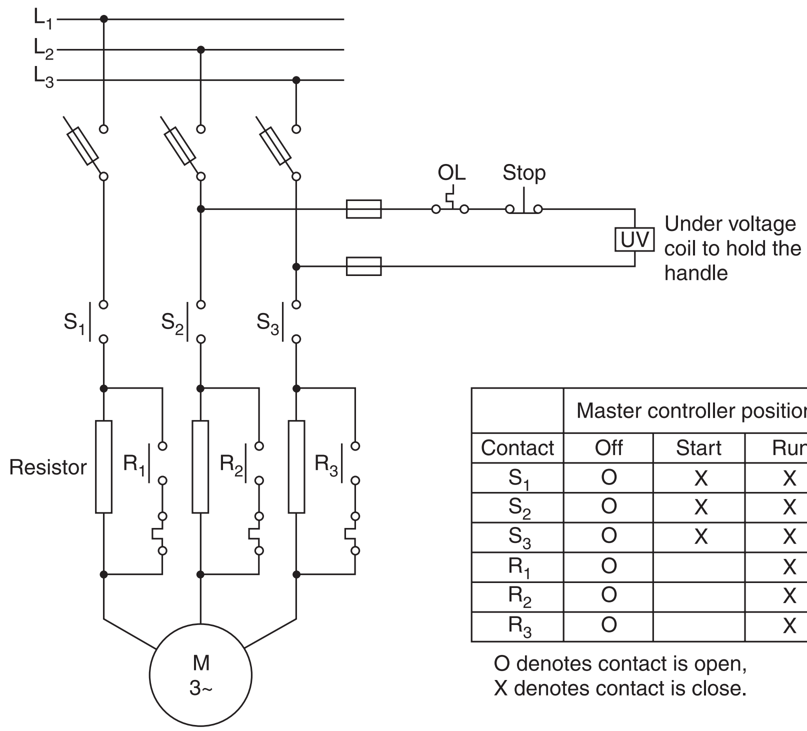
This is a simple and common method of starting a motor at reduced voltage. When motor is first started, a line resistance is inserted in the motor circuit. Voltage drop takes place across the resistor and reduced voltage is applied at the motor terminals. As the motor accelerates, the current drawn by motor reduces and therefore less voltage drop takes place across the resistor and more voltage is available at the motor terminals. Thus a smooth acceleration is obtained with gradually increasing voltage and torque. The resistance is disconnected when the motor reaches near its rated speed and full line voltage appears across the motor terminals. The purpose of inserting resistance during starting is two fold. On one hand it reduces the inrush current of the motor which may be objectionable to the supply authorities as it would cause a high line voltage drop. Secondly, reduced voltage applied to the motor at start provides a reduced starting torque which prevents damage to the driven machinery, avoiding a sudden jerk. The value of resistance connected should, however, be so selected that besides limiting the current inrush the motor should be able to develop sufficient torque to start from standstill.

The resistance type starters are used for small horse power rating motors where main consideration is limiting the starting torque to avoid damage to the connected machinery rather than controlling the line voltage drop. These starters also have a low starting economy because the starting resistors dissipate electrical energy. Depending upon the equipment and arrangement, these starters may be manually operated or may be semi-automatic or automatic. The various types of resistance starters are discussed as follows:

3.2.1 Manual Primary Resistor Type Starter

Manual starters use Master switches or Drum controllers for connecting the motor terminals to supply. Master switch used for this starter has three positions of the operating handle *i.e.,* OFF-START-RUN. In OFF-position all contacts are open. In START-position only start contacts are closed and in RUN-position both Start and Run contacts are closed. Fig. 3.4 shows the manual starter scheme for single step resistance.

In the OFF-position of Master switch all the contacts S_1, S_2, S_3 and R_1, R_2 and R_3 are open. When the drum controller handle is brought to START-position contacts S_1, S_2 and S_3 close as denoted by × in Fig. 3.4 (*b*).



(a)

	Master controller positions		
Contact	Off	Start	Run
S_1	O	X	X
S_2	O	X	X
S_3	O	X	X
R_1	O		X
R_2	O		X
R_3	O		X

O denotes contact is open,
X denotes contact is close.

(b)

Fig. 3.4 Manual primary resistor type starter

The motor starts with resistance in the circuit. When the motor picks up speed the master switch handle is brought to RUN-position by the operator, contacts R_1, R_2, R_3 also close and they short circuit the line resistances and the motor gets directly connected to the supply. Master switch handle is held in the RUN-position by an electro-magnet shown in the diagram as under-voltage (latch) relay UV. This relay coil is connected through STOP-push button and over-load relay contact across two supply lines. Whenever the over-load relay trips or power fails, the coil is de-energised and the Master switch handle is released, which falls back to OFF-position. The switch is also released when voltage falls below a certain value thus giving under voltage protection to the motor. The operation of this starter depends upon the skill of the operator. The time gap between START and RUN-position may be varied by the operator to suit the particular load requirement of the motor. The motor current versus time characteristic during starting is shown in Fig. 3.5.

The motor current versus time characteristic is shown by a dotted line when the motor is started direct ON-line. The starting current has been taken as six times the full load current of the motor. The motor current versus time characteristic with resistance in circuit has been shown through a continuous line as shown in Fig. 3.5. The current has been shown reduced to four times the full-load current. The motor current follows the path parallel to dotted line but at a reduced level. At time t_1, when motor has reached near its normal speed, the resistance is cut off from the circuit and full supply voltage gets applied to the motor terminals. At this time there is sudden inrush of current as shown in the figure. Afterwards, the motor follows the upper curve and runs at its rated speed.

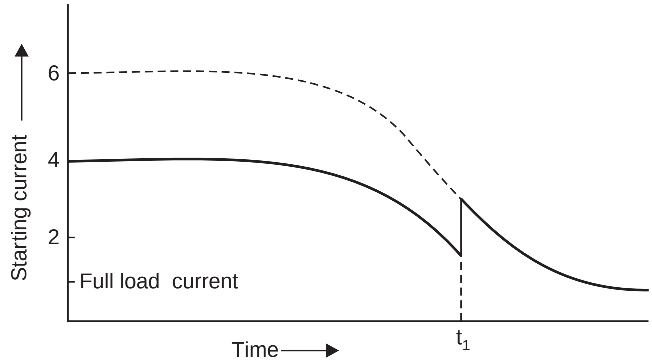


Fig. 3.5 Motor starting current versus time in primary resistor type starter

3.2.2 Semi-automatic Stepless Resistance Starter

This is another type of line resistance reduced voltage starter which gives stepless decrease of line resistance. In this, resistors are made up of stacks of specially treated graphite discs placed in steel tubes. The inside surface of steel tubes are lined with insulating refractory material. When a mechanical force is applied to the columns of graphite discs through a manually operated handle the discs are compressed. The compressing of the discs reduces air gap between the discs and thereby resistance is decreased. As the pressure on the top of discs is increased the resistance decreases gradually (steplessly). These types of units provide a wide range of variation of resistance and in addition have good heat dissipating capacity. This type of starter can therefore be employed for squirrel cage motors upto 200 hp. The starter consists of a steel cabinet which houses the resistor units, contactors, over-load devices and control contacts

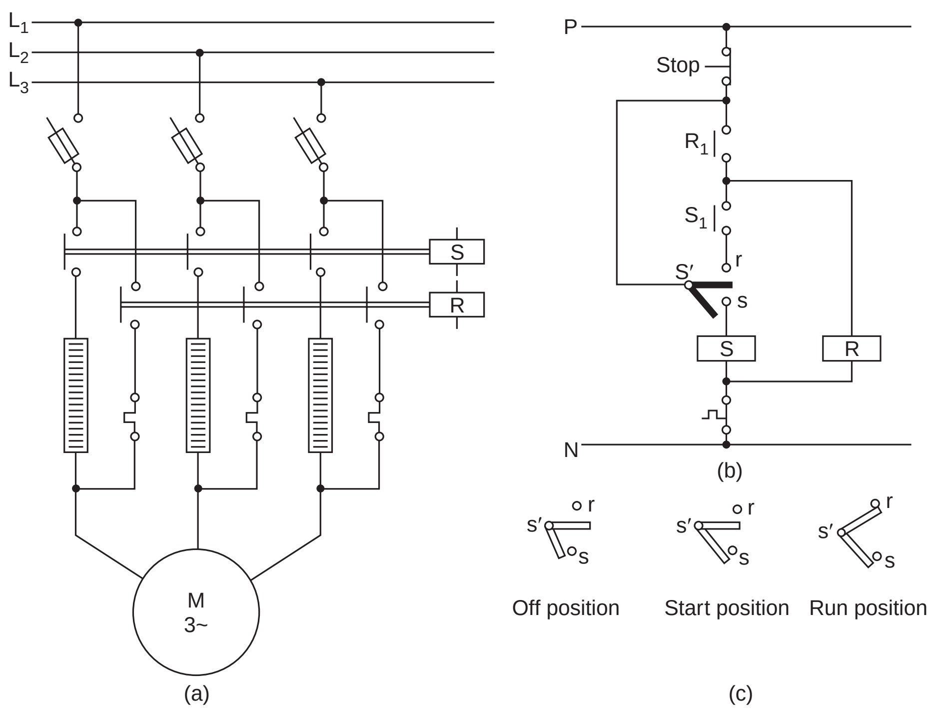


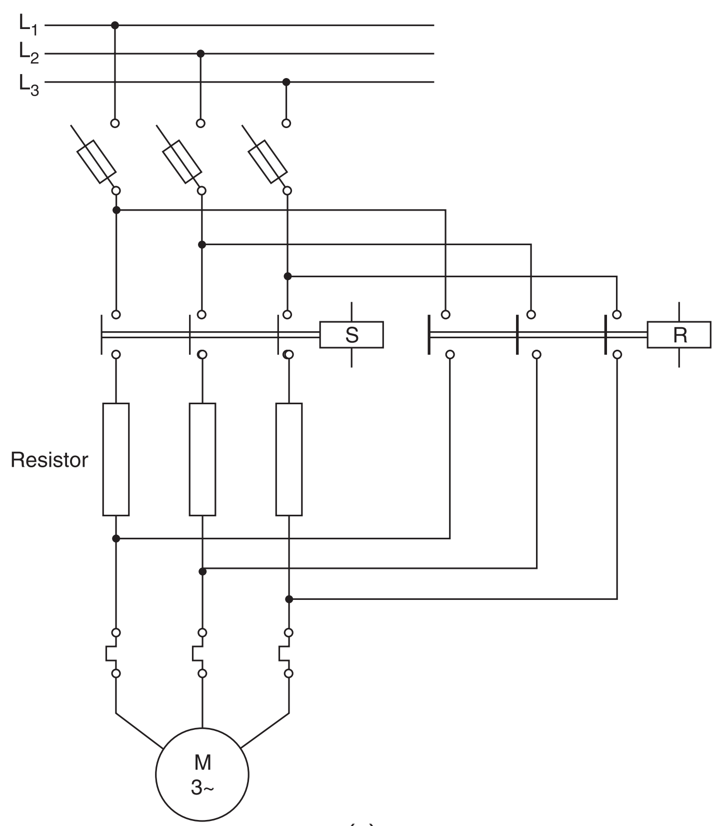
Fig. 3.6 Semi-automatic stepless resistance starter (a) Power diagram (b) Control diagram (c) Control contacts of operating lever

associated with the operating lever. The operating lever is provided outside the enclosure which apply varying equalised pressure to the stacks of graphite disc when moved from OFF-position to RUN-position. Diagram showing wire connections for the starter is shown in Fig. 3.6.

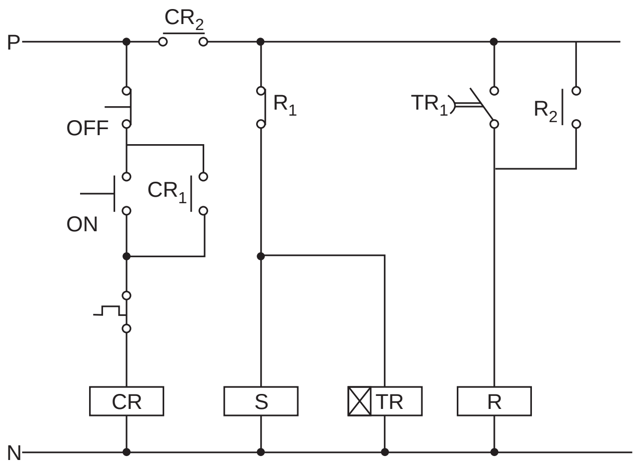
When the operating lever is in the OFF-position both contactors *S* and *R* are de-energised. To start the motor lever is raised quickly to START-position where pilot control contacts *s′* and *s* close and contactor *S* is energised. Its main contacts close and energise motor terminals through the graphite resistance disc tubes and thus a reduced voltage is applied to the motor terminals. As the motor accelerates, operating lever (handle) is moved up from the START-position toward RUN-position. This movement of handle applies equally increasing pressure on the graphite disc in the tubes and thus resistance gets reduced uniformly and steplessly. When the lever reaches the end of its travel *i.e.*, to RUN-position, contact is made between *s′* and *r*. This leads to energisation of contactor *R*. Contactor *R* then gets hold on through its own contact R_1. The main contacts of contactor *R* close and thereby by-pass the resistors. Once the contactor *R* is energised, the handle can be dropped down to the OFF-position which de-energises contactor *S*. The motor can be stopped by pressing the STOP-push button. In case of over-loading the over-load relay control contact opens and de-energises contactor *R*.

3.2.3 Automatic Primary Resistor Type Starter

This starter also has two contactors marked START and RUN as in the case of semi-automatic starter. Here, the time gap between closing of start contactor and run contactor is controlled automatically with the help of an electrical timer. The time can be adjusted as per requirement. The power and control diagram for the starter is shown in Fig. 3.7.



(a)



(b)

Fig. 3.7 Automatic primary resistor type starter (a) Power diagram (b) Control diagram

When ON-push button is pressed the control relay *CR* gets energised and is held energised through its contact CR_1, the over-load relay contact being in closed condition. Normally open contact CR_2 also closes and energises the rest of control circuit. Closing of CR_2 energises contactor *S* and the time delay relay *TR* through normally closed contact R_1 of contactor *R*. Energisation of contactor *S* causes the main contacts to close and the motor starts running with resistance connected in series with the supply lines [see Fig. 3.7 (*a*)]. When the time delay relay *TR* operates after a pre-set time, its delayed contact TR_1 closes and thereby energises the run contactor *R*. Contactor *R* remains energised by getting supply through its own contact R_2. Closing of contactor *R* short circuits the resistances and the motor gets supply through the closed contacts of contactor *R*. The energisation of contactor *R* causes switching off of start contactor *S* and time delay relay *TR*. De-energisation of contactor *S* disconnects resistors from main supply. Also opening of delayed contact TR_1 of time delay relay *TR* does not effect the working of the run contactor as it is now held through its own contact. The time set on the time delay relay determines the acceleration time of the motor with resistors in circuit. This time can be increased or decreased depending upon the load on the machines.

3.3 INCREMENT RESISTANCE STARTER

In increment resistance starter the resistance connected in the motor circuit is cut off in steps. The motor starts only when all the resistances have been cut off and motor gets connected to full supply voltage and draws the normal direct on line current, which is about six times the full load current. At this point one may wonder, that what is then the need for inserting resistance in the circuit and cut it off in increments till the motor again gets connected to supply ! This starter is used for large motors which require high starting torque to start from standstill. A reduced inrush current cannot start these motors from standstill. The current required for starting such motors is the direct on line current. However, if this large current is drawn by connecting the motor directly to supply, the supply network gets unstable. The voltage regulators connected in the network cannot correct the voltage drop due to this sudden heavy current drawn from supply. In order to allow time for the voltage regulators to correct the system network voltage, the direct on line inrush current from the supply is drawn in two or three steps with certain fixed time delays. This time delay after each current inrush allows the voltage regulators to adjust the network voltage. This would become more clear when we look at the motor current versus time characteristic of this increment resistance starter as shown in Fig. 3.8.

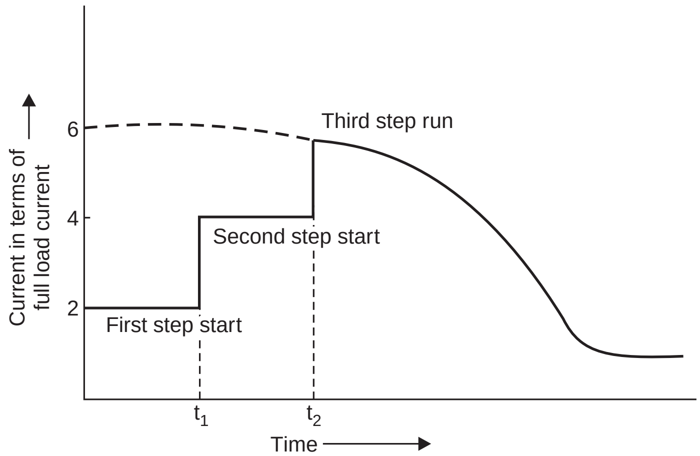


Fig. 3.8 Current versus time characteristic of an increment resistance starter

When motor is first switched ON, the current drawn from supply is 2 times the full load current and the motor does not start up as the starting torque developed is not sufficient to pull the motor from standstill. After time t_1, some resistance is cut out from the motor circuit and as a consequence another inrush of current takes place. The current drawn becomes 4 times the full load current but even then the motor is not able to pull from standstill. After another gap of $t_2 - t_1$ seconds the rest of the resistance is cut off and the motor gets directly connected to supply. Now the current inrush reaches 6 times the full load and motor develops sufficient starting torque to start from standstill. Beyond this time the current time curve follows the direct on line starting current as shown in Fig. 3.8. Thus it is seen that although the current drawn from supply is high, rate of rise of current is reduced very much to allow system voltage regulators to adjust for the increase of current from the network. The power circuit and the control circuit for this type of a starter are shown in Fig. 3.9.

Referring to the power circuit it is seen that when contactor 1*S* closes, the motor gets connected to supply with full line resistances. When contactor 2*S* is energised half of the resistance is by-passed and when the contactor *R* closes, the whole of the resistances is by-passed and the motor terminals get connected to full supply voltage. Let us see how this operation is accomplished through the control circuit. When the ON-push button is pressed, control relay *CR* gets energised and is held through its own contact CR_1. It's another contact CR_2 energises the rest of the control circuit. Contactor 1*S* and timer 1*T* gets energised through the normally closed contact R_1 of the contactor *R*. Energisation of contactor 1*S* connects motor terminal to supply through the resistance. When timer 1*T* times out (say in 5 secs), its delayed contact $1T_1$ closes and energises contactor 2*S* and the coil of timer 2*T*. Energisation of contactor 2*S*, closes its main contacts and half of the resistance is cut off from the motor circuit. After 5 secs the timer 2*T* also operates and its delayed contact $2T_1$ closes and energises the coil of the run contactor *R*. Run contactor immediately gets held through its own contact R_2. The normally closed contact R_1 of contactor *R* is now open which de-energises contactor 1*S*, 2*S* and timers 1*T* and 2*T*. The RUN contactor *R*, however, remains energised through its own contact and the motor runs by getting supply directly from the mains, the resistances being by-passed.

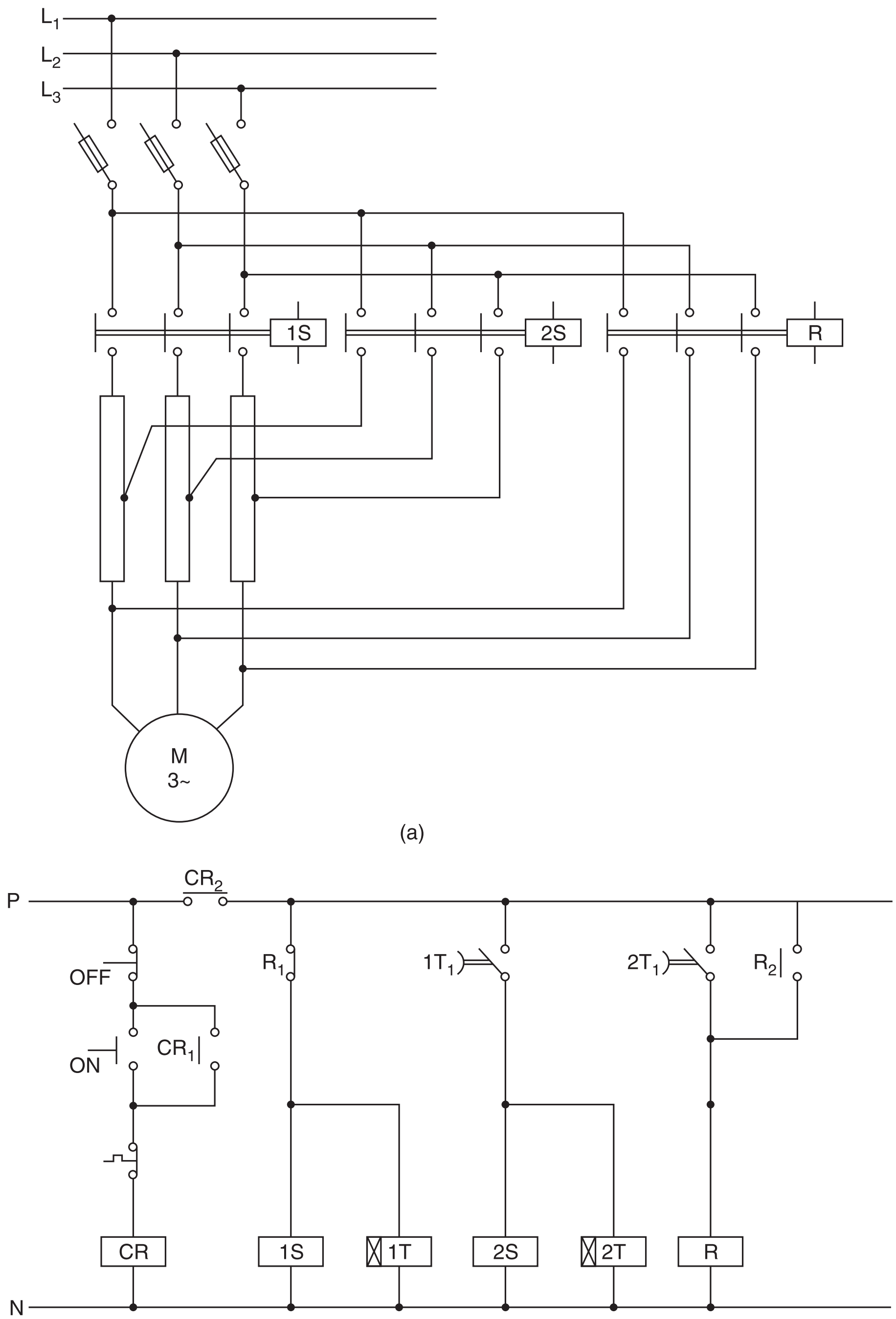


Fig. 3.9 Increment resistance starter (a) Power diagram (b) Control diagram

3.4 LINE-REACTOR REDUCED VOLTAGE STARTER

A line-reactor reduced voltage starter works on the same principle as the line resistance starter, however, it is used for comparatively high voltage or high current installations where resistors become bulky and heat dissipation is a problem. Like a line resistor starter, a reactor starter is also preferred where emphasis is on getting a lower starting torque than on reduction in starting current. Where reduction in starting current is the main consideration, autotransformer starters are preferred.

The disadvantage of reactor type starter is that the starting power factor is low which tends to increase the line regulation. Line reactors used consists of coils wound on three legged core. Standard tappings give 50%, 65% and 80% of the supply voltage at the motor terminals. Special care has to be taken while designing the core so that core does not saturate during the period of acceleration. If the core saturates during acceleration period the reactance becomes low (reactance, which depends upon $\frac{d\phi}{di}$, is small when the core is saturated), and the starting current drawn by the motor becomes high.

The power circuit for the starter is shown in Fig. 3.10. The control circuit is the same as that drawn for a line resistor starter as shown in Fig. 3.7 (*b*).

In Fig. 3.10, 50% tapping has been used. When contactor *S* is energised the whole of the reactor winding gets connected in circuit and thus 50% of the supply voltage gets applied across the motor terminals. For getting 65% or 80% of the supply voltage the motor terminals are to be connected at 65% or 80% tapping terminals on the reactor. The working of the control circuit is the same as that of the resistance starter already explained. As this type of starter is

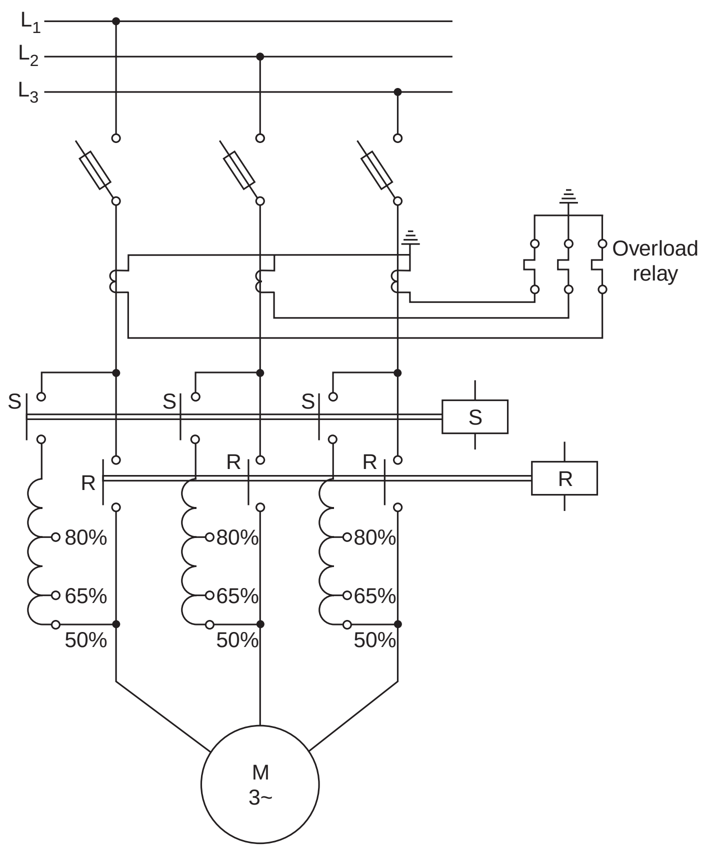


Fig. 3.10 Power circuit for a line-reactor reduced voltage starter

used for large motors, the over-load relay is to be connected through current transformer as has been shown in Fig. 3.10.

A manual reactor starter will be controlled by a master-switch or a drum controller as explained in case of a manual primary resistor type starter in section 3.2.1.

3.5. AUTO-TRANSFORMER REDUCED VOLTAGE STARTERS

This type of starters use an auto-transformer between the motor and the supply lines to reduce starting current of the motor. Taps are provided on the auto-transformer to select 50%, 65%, 80% of the line voltage for starting. The advantage of this starter is that for the same starting torque to be developed, the line current drawn from supply is less than that in case of resistance and reactance starters. For example for starting voltages of 50%, 65% and 80% line currents will respectively be 25, 42 and 64 per cent of the full-voltage values. Because of high cost of auto-transformer starters, they are used for large motors only. An auto-transformer being an inductive load, the power-factor of the total load circuit during starting is low.

Auto-transformer starters are of two types: (*i*) open circuit transition type; and (*ii*) closed circuit transition type. As observed in the resistance and reactance starters, after the motor has picked up speed, run contactor is energised and then immediately afterwards start contactor is de-energised. In this sequence, when motor shifts from start to run mode, the motor terminals do not get disconnected from supply. This way of energising the contactors is known as closed circuit transition. The other way of switching the contactors is to ensure that the start contactor is de-energised first and immediately afterwards the run contactor is energised. In this case, for a small gap of time between the opening of start contactor and closing of run contactor, the motor terminals get disconnected from supply, the rotor continues rotating and, therefore, emf is induced in the motor stator windings due to rotor flux. Now when the stator is energised by closing the run contactor with full line voltage, in certain conditions, the polarity of generated voltage and the supply voltage may be additive to give a high inrush current which may be harmful to the motor. This type of starting is known as *open circuit transition*.

Now the question arises if open circuit transition is not desirable then why use it at all ! The reason is that open circuit transition starting for auto-transformer starter and star-delta starters are widely used due to economical reason. Closed circuit transition in case of auto-transformer and star-delta starter is not easily obtained as in the case of resistance and reactance starters. This will become clear when we discuss these two types of starters. Closed circuit transition starters are used for motors of very large ratings only.

Auto-transformer power connections for open circuit transition: The usual practice is to construct a 3-phase auto-transformer with two tapped windings around the outer legs of a three legged core and connect the coils in open delta as shown in Fig. 3.11 (*a*). In this connection however due to internal impedance drops, the voltages at motor terminals are unbalanced and thus starting torque developed is relatively low. Where relatively high starting torques are required, auto-transformers with three coil construction are used. The power circuits in Fig. 3.11 (*b*) shows the three winding auto-transformer connections.

From Fig. 3.11 (*a*) it is clear that reduced voltage is applied between terminal $T_2 - T_1$ and $T_2 - T_3$. In three winding connections, reduced voltage from tapping is applied to all the three motor terminals.

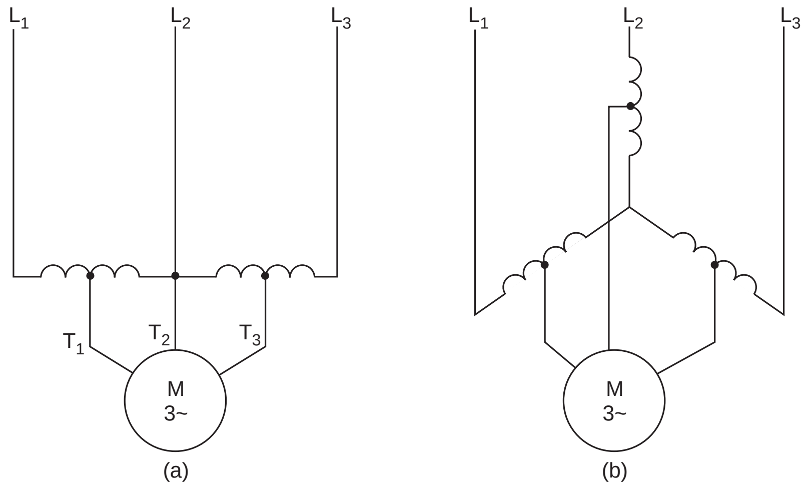


Fig. 3.11 Two winding and three winding auto-transformer connections

3.5.1 Manual Auto-transformer Starter

A commonly used manual auto-transformer starter consists of a three legged laminated core around the outer two legs of which are placed the coils. Each coil is tapped at approximately 50, 65 and 80 per cent from one end.

As starting torque of a motor is proportional to the square of the applied voltage, connection at 50, 65 and 80 per cent tapping will therefore yield starting torques of 25, 42 and 64 per cent of the full-voltage starting torque. Thus for a motor which develops starting torque of 1.5 times the full load torque (1.5 T_{FL}), the starting torques of 0.38 T_{FL}, 0.63 T_{FL} and 0.96 T_{FL} respectively can be obtained by using the above mentioned tappings. These values of torques are usually sufficient to start with loads in most of the cases.

The starter connections are shown in Fig. 3.12. Connections of the motor to the supply lines are made through two sets of contacts, namely, START (*S*) and RUN (*R*). These contacts belong to the Master Switch which is operated by a handle.

When the handle of the Master switch is in OFF-position, all the *S* and *R* contacts are open. When the handle is brought up towards START-position, all the five *S* contacts close. Contacts S_1 to S_5 connect the auto-transformer to line in open delta. As contacts R_1 to R_3 are open, the voltage across the motor terminals is 50% of the supply voltage as shown in Fig. 3.12. When the motor picks up sufficient speed the handle is moved over to RUN-position. As the handle leaves the START-position, first the *S* contacts will open and after a split of a second the *R* contact will close. Closing of contacts R_1 to R_3 will connect the motor terminals directly to full supply voltage. The master switch handle is held in the RUN-position by an electromagnet, the coil of which is shown in the figure as under voltage relay UV. As in the case of primary resistor type of starter here also the coil is connected in series with a STOP-push button and an over-load relay contact. When there is over-load or voltage dip or when the STOP-push button is pressed, the under voltage relay coil is de-energised leading to the release of the handle. When the handle of the switch is released the switch falls back to the OFF-position.

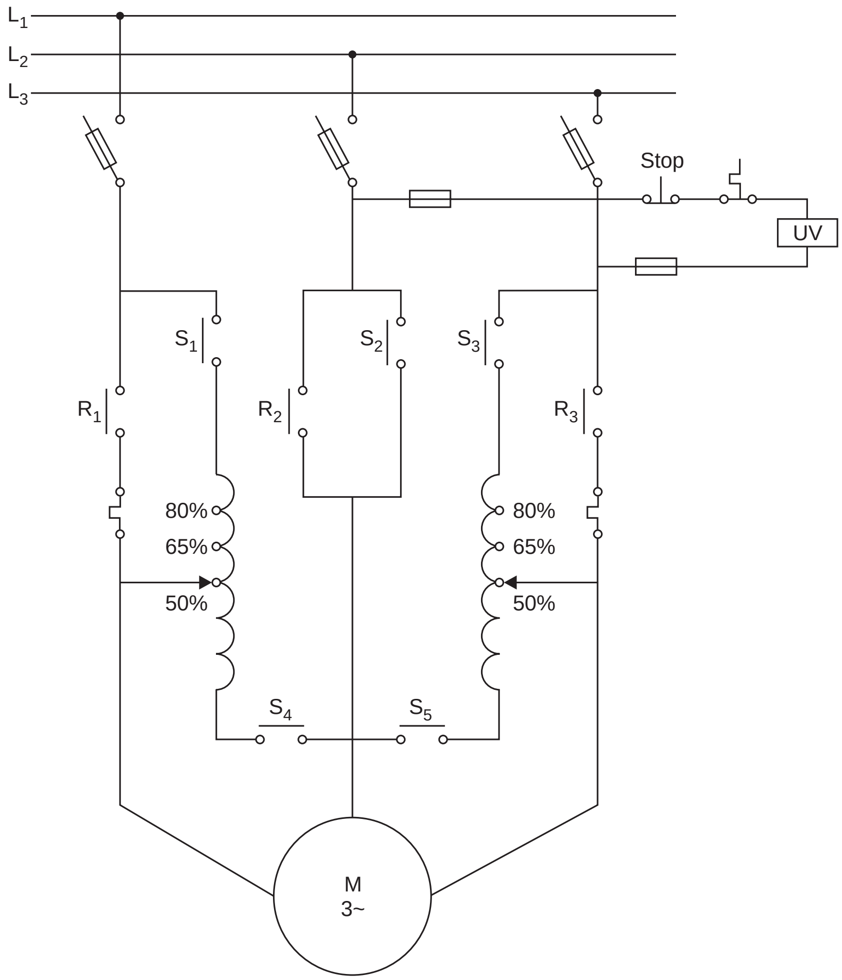


Fig. 3.12 Manual auto-transformer starter connections

3.5.2 Automatic Auto-transformer Starter (Open Circuit Transition)

In automatic starter, the transition from start to run condition takes place automatically with the help of a timer. The motor is connected to the lines through contactors as shown in power diagram shown in Fig. 3.13 (*a*). The control circuit diagram has been shown in Fig. 3.13 (*b*).

Four main contacts of start contactor (S) have been used to connect the auto-transformer windings in open delta. As the starter shown is for a large motor, motor has been connected to supply through, circuit breaker and magnetic overload relay.

When the start contactor is energised, contacts S_4 and S_5 connect the transformer windings to neutral points. At the same time closing of contacts S_1, S_2 and S_3 causes supply of reduced voltage from the transformer taps to the motor terminals. The motor accelerates at this reduced voltage. After the motor reaches near its final speed, if contactor R is energised keeping contactor S ON, a circulating current will flow in the auto-transformer windings between the transformer taps and neutral points, causing severe over heating of the transformer windings. Heavy mechanical stresses produced will also be harmful to the windings. Thus the design is such that contactor R cannot be energised unless contactor S is open. This however

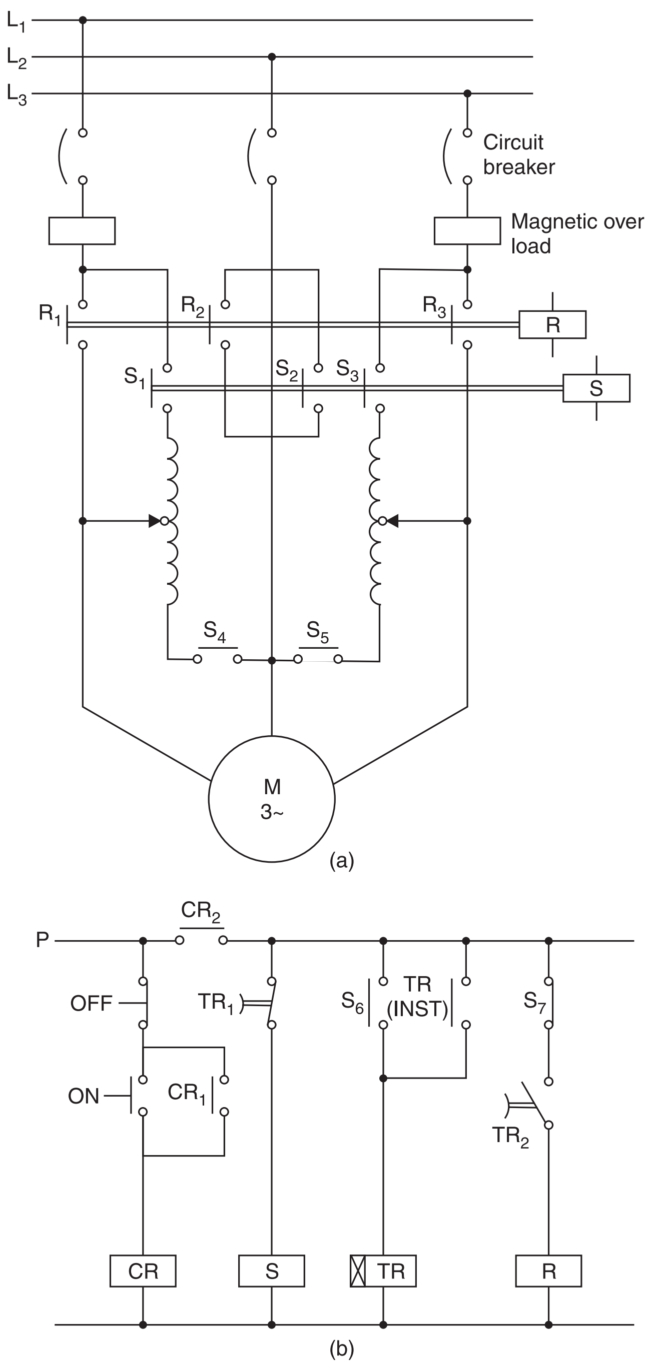


Fig. 3.13 Automatic auto-transformer starter: (a) Power circuit (b) Control circuit

will be an open circuit transition and a transient inrush current may flow into the motor. Opening of contactor *S* first and then energisation of contactor *R* is accomplished with the help of a control circuit shown in Fig. 3.13 (*b*). On pressing the ON-push button, the control relay *CR* is energised and the contactor *S* gets energised through normally closed delayed contact

TR_1 of timer TR. Timer TR coil is energised through closed contact S_6 of the contactor S and gets hold through its own instantaneous contact. The operating time of timer TR determines the accelerating time for the motor. When after a pre-set time the timer TR operates, its normally closed contact TR_1 opens and normally open contact TR_2 closes. Opening of contact TR_1 de-energises contactor S. Due to de-energisation of the contactor its auxiliary contact S_6 opens and S_7 closes. Opening of S_6 has no effect on timer TR while closing of S_7 causes energisation of the run contactor R through the closed contact TR_2 of the timer. The motor runs on full voltage when the run contactor gets energised after a pre-set time from the instant of starting of the motor. The motor starting current versus time characteristic during the starting is shown in Fig. 3.14.

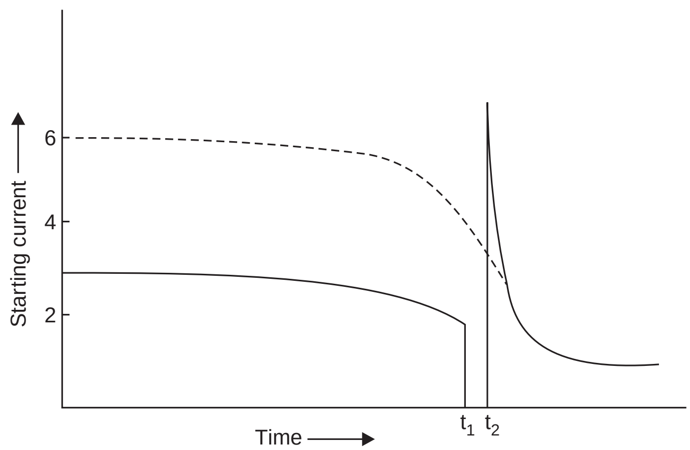


Fig. 3.14 Motor starting current in open-circuit transition

The dotted line in Fig. 3.14 shows the direct on line characteristic while the full line shows the current with auto-transformer in the circuit. At time t_1 the start contactor is opened and at time t_2 the run contactor is closed. For a time gap $t_2 - t_1$ the motor winding is disconnected from the supply. During this period a voltage is generated in the motor winding due to rotor flux. At t_2 when run contactor is energised the induced voltage and supply voltage may get superimposed to give a high transient current of short duration which may be higher than even the direct on line starting current.

In case the motor requires a large starting torque, three winding auto-transformer connection may be used. In this case a start contactor having six main contacts will be required. The power connection will be as shown in Fig. 3.15 on next page. The control circuit will however remain same as discussed earlier.

3.5.3 Auto-Transformer Voltage Starter (Closed Circuit Transition)

Closed circuit transition operation requires two starting contactors, both having three poles. The contacts used are as shown in Fig. 3.16.

Contacts of contactor 1S are used for the neutral of the auto-transformer windings. Contactor 2S connects the transformer windings to the supply. When contactors 1S and 2S are closed, the transformer is energised from the supply. Reduced voltage from the tapping A, B and C is available at the motor terminals. After the motor picks up sufficient speed contactor 1S is first de-energised. Auto-transformer neutral connection gets disconnected. The motor

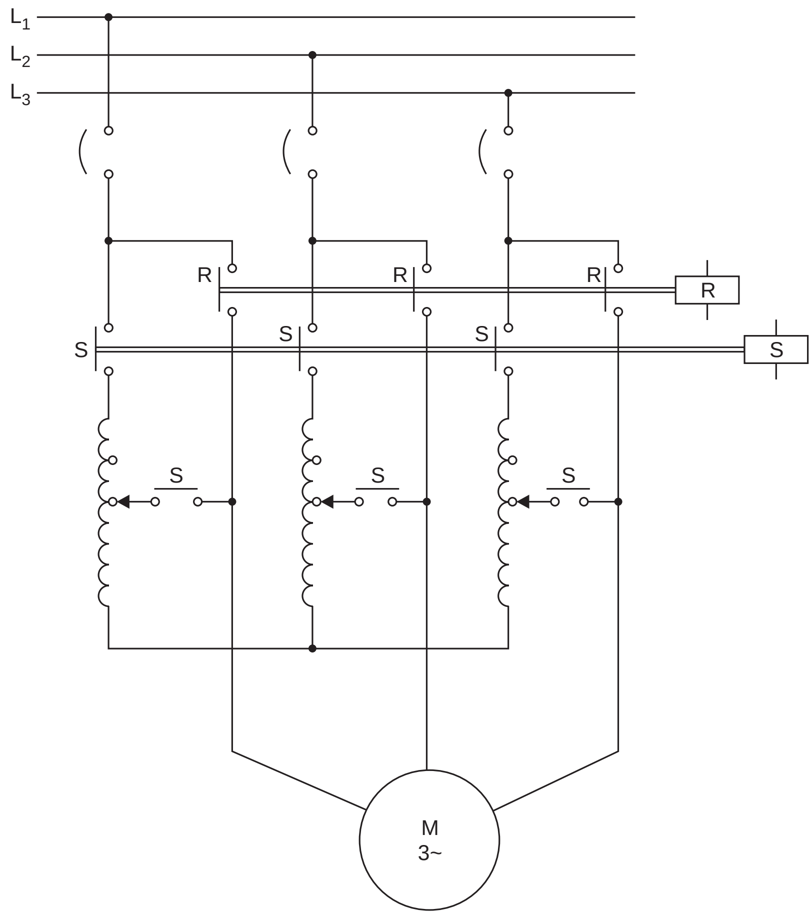


Fig. 3.15 Power connection with three winding auto-transformers

remains connected to mains through contacts of contactor 2S and the transformer acts as a reactance in the motor circuit. Next, the run contactor R is energised which by-passes the reactance and connects the motor directly to the supply. Thus, it is seen that the motor gets connected to full supply without getting disconnected from the supply. This avoids the sudden inrush of current as experienced by motor windings in open circuit transition. The control circuit for an auto-transformer reduced voltage starter in closed circuit transition is shown in Fig. 3.17.

When by pressing ON-push button the control circuit is energised, the contactor 1S gets energised through normally closed delayed contacts of timer 1TR and simultaneously the coil of timer 1TR is also energised. Closing of contactor 1S also causes closing of contactor 2S through its auxiliary contact 1S_1 and normally closed delayed contact of timer 2TR. Contactor 2S is held through its auxiliary contact 2S_1. When timer 1TR times out, the NC contact 1TR_1 opens and NO contact 1TR_2 closes. Opening of 1TR_1 causes de-energisation of contactor 1S.

When contactor 1S is open, its auxiliary contact 1S_2 closes and thus contactor R gets energised. Alongwith contactor R, timer 2TR is also energised. When timer 2TR operates, its delayed contact which is in series with coil of contactor 2S, opens and de-energises the contactor 2S. De-energisation of 2S disconnects the windings of the transformer which were acting as reactance. The motor now runs directly from the supply. The starting current versus time characteristic for closed circuit transition is shown in Fig. 3.18.

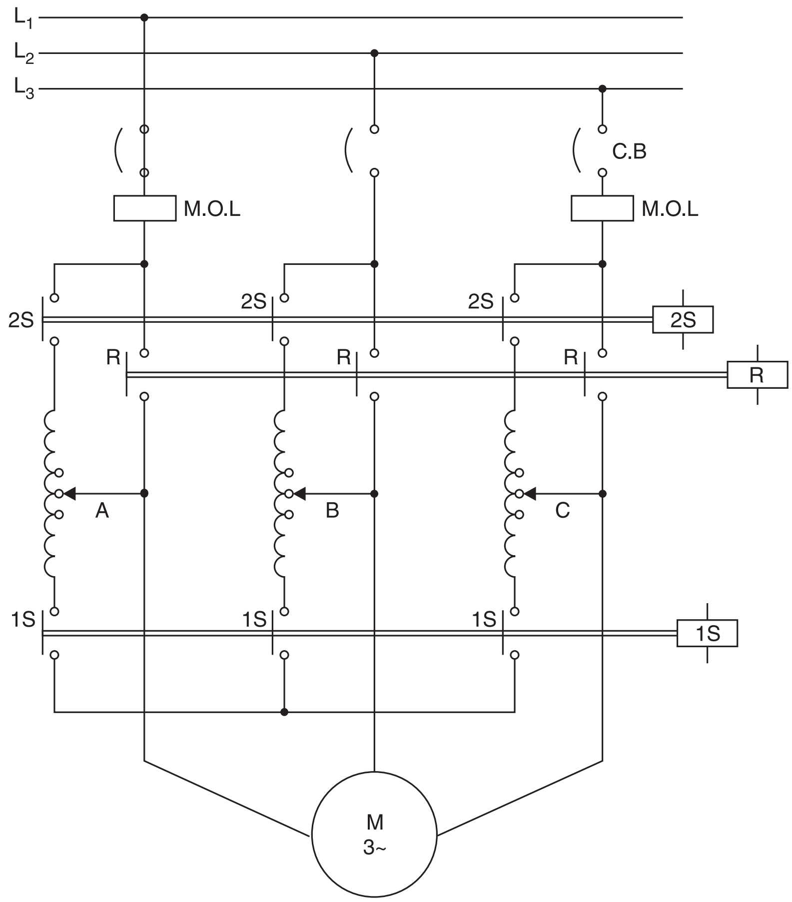


Fig. 3.16 Auto-transformer reduced voltage starter for closed circuit transition

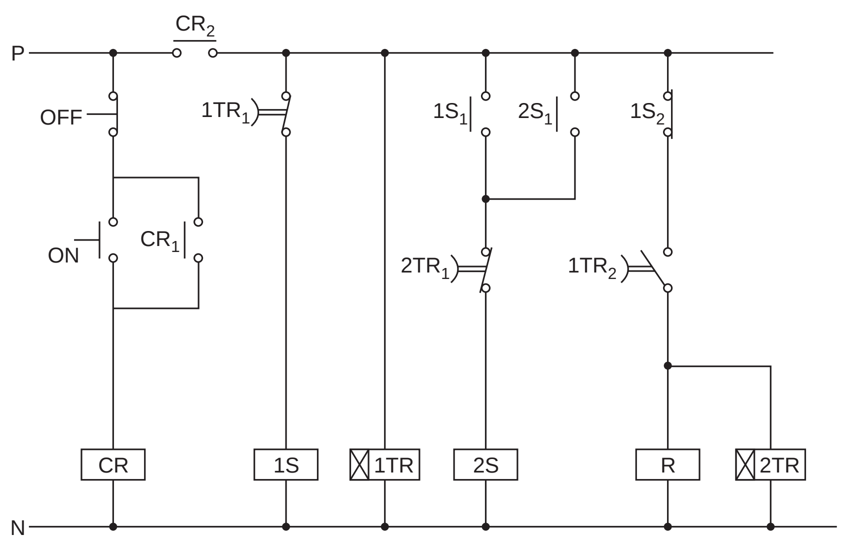


Fig. 3.17 Control circuit for closed circuit transition

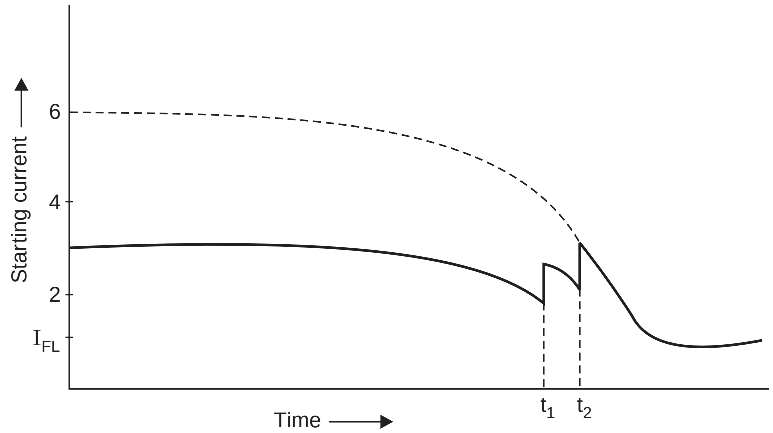


Fig. 3.18 Motor starting current in closed circuit transition

As seen from Fig. 3.18, two small inrush of currents take place at time t_1 and time t_2. First inrush at t_1 takes place when motor gets disconnected from transformer tappings and runs with reactor in the circuit. Second inrush at t_2 takes place when reactor is by-passed due to energisation of the Run contactor.

After that, motor characteristic follows the original direct on line current path. When this characteristic is compared with open circuit transition characteristic of Fig. 3.14, it is quite evident that high inrush current experienced in the former is eliminated in this circuit.

3.6 PART WINDING MOTOR STARTER

Part winding starters are used with squirrel cage motors having two separate and parallel stator windings. Large motors can be built with three parallel windings also. The windings may be star connected or delta connected depending upon the design of the motor. Part winding motors are used to drive centrifugal loads such as fans, blowers or centrifugal pumps. These motors can also be used for other loads requiring low starting torque. In cases where the motor is started with only one winding, the starting current drawn from line is reduced. When started on one winding the motor draws approximately two thirds of the normal starting current and develops approximately one half of the normal direct on line starting torque. It may however be clearly understood here that if the motor is connected to a heavy inertia load, the starter would work as incremental starting device. The motor will not begin to accelerate until the second winding is connected.

The advantages of the part winding starters are:

(*i*) It is less expensive than other reduced voltage starters using resistors, reactors and transformers;

(*ii*) It requires only two contactors having half the rating of the full-load rating of the motor;

(*iii*) The starter provides closed circuit transition.

The disadvantage of part winding starting are:

(*i*) The starting torque is fixed and is low;

(*ii*) Neither of the two windings has thermal capacity to operate along for more than a few seconds. Thus, this type of starting is unsuitable for high inertia loads where starting time is long.

Part-winding starter may be of the following two types, namely:

(*i*) Two-step starting, and

(*ii*) Three-step starting.

3.6.1 Two Step Starting

In two step starting, two contactors control the two windings of the motor. Refer power and control circuit diagrams shown in Fig. 3.19.

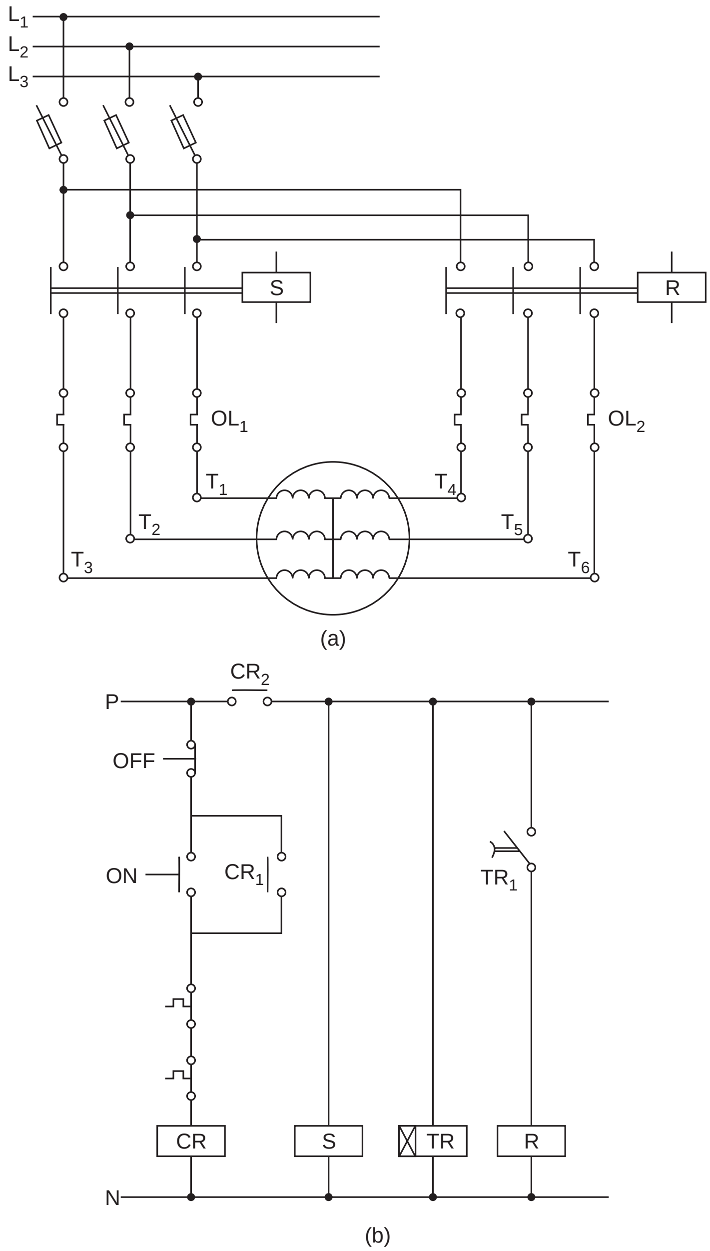
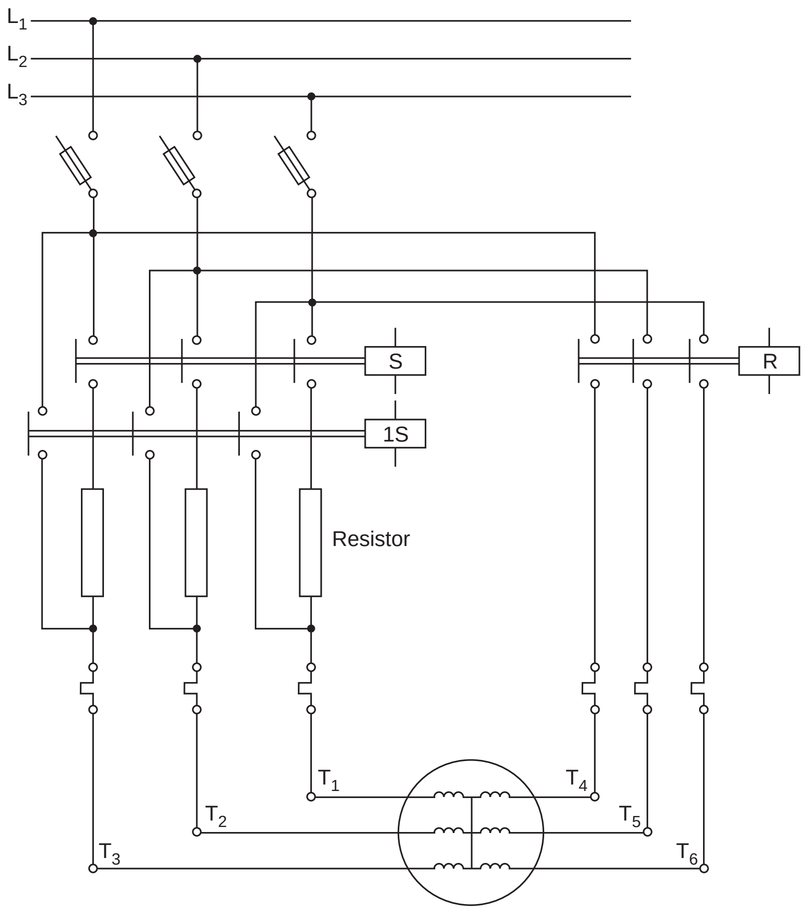


Fig. 3.19 Two step starting circuits for induction motors (a) Power circuit diagram; (b) Control circuit diagram

When the ON-push button is pressed, the control relay, *CR* is energised which inturn energises contactor *S* and timer *TR* simultaneously. Closing of contactor *S* connects one winding of the motor to the lines. After some time, when timer *TR* operates, Run contactor *R* gets closed and therefore the second winding also gets connected to the lines in parallel with the first winding. Now the motor runs with two windings in parallel. Current drawn by the motor gets equally divided between the two windings. The over-load relays are connected in both the windings. Setting of these relays is done according to the current taken by the individual windings. If current increases in any one of the windings and the corresponding overload relay trips, both the contactors get de-energised. This happens because both the contacts are connected in series with the coil of the control relay (*CR*).

3.6.2 Three Step Starting

In three step starting when first contactor is closed, one of the two windings gets connected to the lines through resistors in each of the phases. After a time delay of approximately two seconds, the resistances are cut off and this winding gets connected to the full line voltage through the closing of the second contactor. After another time delay of two seconds, the Run contactor is energised to connect the second winding to the lines. The value of resistance can be so selected that 50% of the line voltage is available at the motor terminals during first step. Thus the motor starts with three approximately equal increments of the starting current. The power and control circuit diagrams for three step starting is shown in Fig. 3.20.



(a)

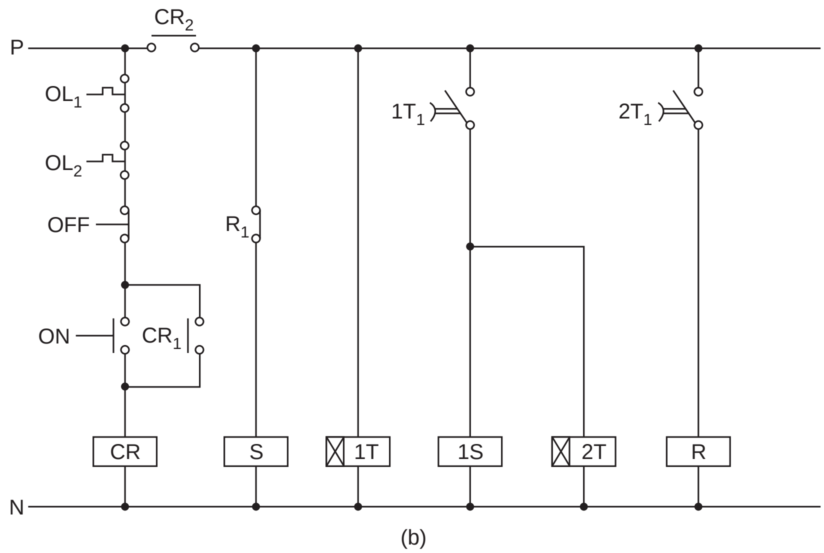


Fig. 3.20 Three step starting of an induction motor
(a) Power circuit diagram; (b) Control circuit diagram

Pressing of the ON-push button will energise contactor S and timer $1T$. Contactor S closes to start the motor with resistors in circuit and the supply reaches motor terminals T_1, T_2 and T_3. When Timer $1T$ operates after 2 seconds, its delayed contact closes to energise contactor $1S$. Closing of contactor $1S$ shorts the resistances from the circuit. A timer $2T$ is also energised alongwith $1S$. When timer $2T$ operates after 2 second the Run contactor R is energised, which closes to connect the second winding of the motor also to the lines. Now both the windings are connected in parallel to the lines through contactors R and $1S$. Contactor S opens when the Run contactor is energised (due to opening of NC contact R_1).

3.7 STAR-DELTA STARTER

Star delta starting is the most commonly used reduced voltage starting method. The stator windings of the motor are first connected in star and full voltage is connected across its terminals. As the motor reaches near the rated speed, the windings are disconnected and then re-connected in delta across the supply terminals. The current drawn by the motor from the lines during starting is reduced to one third of the value of current the motor would have drawn if connected in delta. This would become clear when we examine the details given in Fig. 3.21.

In Fig. 3.21 (a) the windings are connected in delta. The voltage across each winding is V. Phase current through the winding is say I amps., then the line current, $I_L = \sqrt{3}\, I$ amp. (as in delta connection line current is $\sqrt{3}$ times the phase current).

Now refer to star connection as shown in Fig. 3.21 (b) the voltage across the windings is $V/\sqrt{3}$ so the current through winding is also reduced proportionately. Thus phase current $I_p = I/\sqrt{3}$. As in star connection the line current and phase current are the same, thus line current $I_L = I/\sqrt{3}$. A comparison between line current in the two cases shows that:

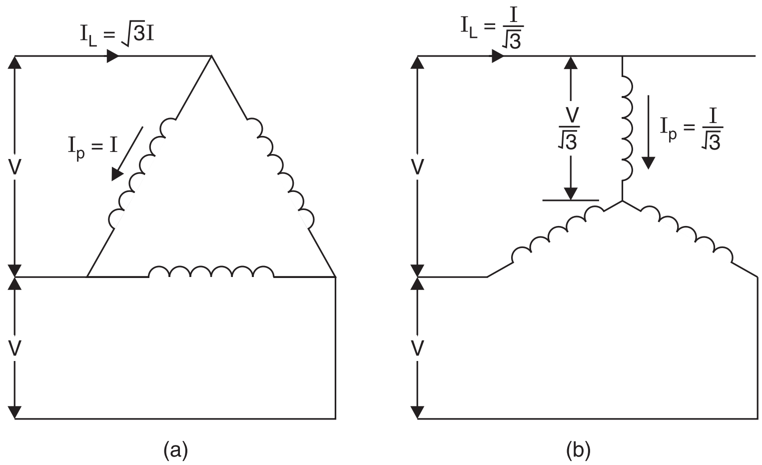


Fig. 3.21 Comparison of current drawn from the lines when windings are delta connected and star connected

$$I_L\,(\text{Delta}) = \sqrt{3}\ I$$

$$I_L\,(\text{Star}) = \frac{I}{\sqrt{3}}$$

Thus it is clear that line current drawn from supply in Star connection is reduced to 1/3 times the line current in delta connection.

From the theory of machines it is known that, starting torque is proportional to square of voltage applied to the motor windings *i.e.,*

$$T \propto V^2$$

It has been seen that in star connection, the voltage across the motor winding is $\frac{V}{\sqrt{3}}$ times the voltage across the winding in delta connection. Thus the starting torque in star connection will be one third of the starting torque in delta connection. It thus follows that along with reduction of current in star connection, the starting torque also gets reduced proportionately.

Before different types of star-delta starters are discussed, it is necessary to have some explanations about motor winding connections. The three stator windings of a squirrel cage motor are designated as $A_1 - A_2$, $B_1 - B_2$, $C_1 - C_2$ where A_1, B_1, C_1 are the starting ends and A_2, B_2, C_2 are the finishing ends of the respective windings. To connect the windings in star either the finishing ends or the starting ends of the three windings are connected together to form the neutral connection. As shown in Fig. 3.22 (*a*), the finishing ends of three windings *i.e.,* A_2, B_2 and C_2 are connected together to form the neutral connection, the supply being connected to terminals A_1, B_1 and C_1.

When the three windings are to be connected in delta, finishing end of one winding is connected to starting end of the other winding as shown in Fig. 3.22 (*b*) where finishing end A_2 of first winding ($A_1 - A_2$) is connected to starting end B_1 of second winding ($B_1 - B_2$) and finishing end B_2 of second winding is connected to starting end C_1 of third winding ($C_1 - C_2$), and then finishing end of third winding C_2 is connected to starting end A_1 of first winding. After these connections are completed supply is given at the junction $A_1\,C_2$, $A_2\,B_1$ and $B_2\,C_1$.

The connection of windings in star during starting and then in delta during running is done by a manual switch in a manual starter while contactors and timers are used in an automatic starter.

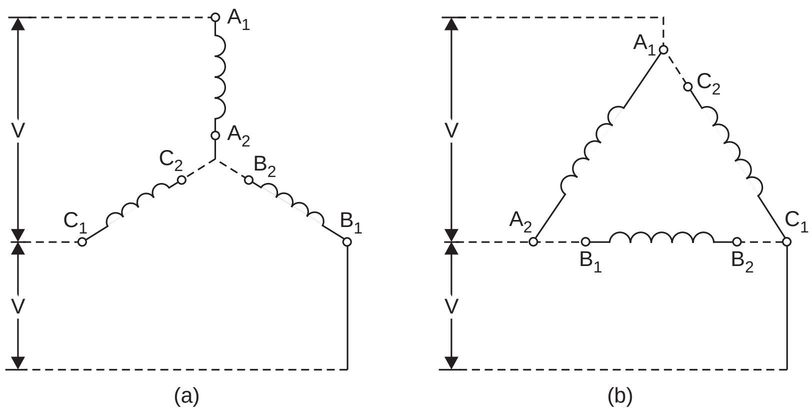


Fig. 3.22 Connection of three phase motor windings (a) in Star (b) in Delta

3.7.1 Manual Star-delta Starter

A simple manual star delta starter is shown in Fig. 3.23.

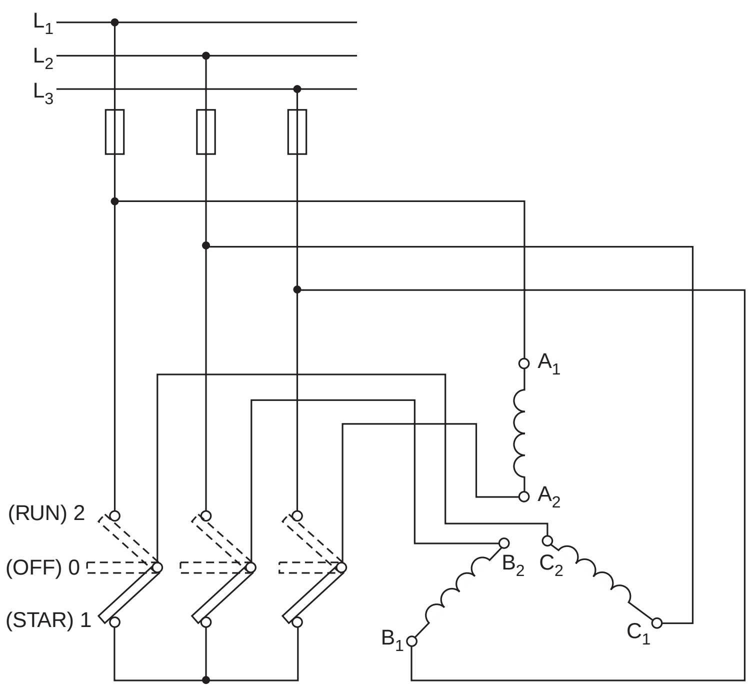


Fig. 3.23 Manual star-delta starter

When the starter switch is in 0-position the windings are open. When the switch is moved to position 1 (STAR-position) the terminals A_2, B_2 and C_2 get shorted, the windings get connected in star and the motor starts rotating. As the motor reaches near its rated speed the switch is moved to position 2 and connections are established at $A_2 B_1$, $B_2 C_1$, $C_2 A_1$ as shown in Fig. 3.23 and the motor continues to run with its stator windings connected in delta. The other type of star-delta starters discussed in the sections to follow are:

(*i*) Push button operated manual star-delta starter

(*ii*) Semi-automatic star-delta starter

(*iii*) Automatic open circuit transition star-delta starter

(*iv*) Automatic closed circuit transition star-delta starter.

3.7.2 Push-button Operated Manual Star-Delta Starter

This starter is constructed using one contactor, two push buttons, an over-load relay and a four pole-three position switch connected as shown in the wiring diagram as shown in Fig. 3.24. The three poles of the switch have been used in the power circuit to connect the motor to the supply lines while the fourth one is used in the control circuit. The three positions of the switch are 0 (OFF)-position, 1 (STAR)-position and 2 (DELTA)-position. The moving contacts (blades) of the switch have been shown by dotted lines. With the switch in off position, if the ON-push button is pressed, the contactor cannot be energised and therefore the motor cannot be started (see Fig. 3.24). Now let us put the switch in RUN or DELTA position and press the ON-push button. It can be seen that the control circuit does not get supply and therefore the contactor *M* cannot be energised. This implies that the motor cannot be started in delta. When the switch is placed in STAR-position contactor coil can be energised by pressing the ON-push button. The main contacts now close and the motor runs in star. It thus follows that by pressing the ON-push button the motor can be started only when the windings are connected in star *i.e.,* when the switch is in star position. The push button is to be kept pressed till the motor picks up speed and the switch is changed over to delta. The ON-push button can then be released as the contactor *M* will get hold through its own contact M_1 and the control contact (fourth contact) of the switch which is in delta position. It thus follows that the ON-push button has to be kept pressed as long as we want to run the motor in star-connection. The push button can only be released when winding connections have been changed to delta by operating the switch. The schematic diagram for the control is given in Fig. 3.24 (*b*). The reader is advised to study the control circuit according to the control requirement described above. The diagram does not explain the transition from star to delta clearly. However the explanation is as follows:

In the schematic diagram, Fig. 3.24 (*b*), it may be observed that initially the switch contact is in position 1 (STAR). The contactor gets energised when the ON-push button is pressed. The contactor does not hold as contact C-2 is open. Now when the switch is changed from position 1 to 2 the contact between C-1 is broken, the contactor *M* will get de-energised and contact M_1 will open. When contact is established between C-2, the contactor *M* will remain de-energised as supply to its coil is disconnected due to opening of contact C-1. Thus the question that arises is how the operation which we have described earlier holds true *i.e., the contactor M should remain energised till switch is brought to position 2 through pressing of the ON-push button.* The contactor *M* remains energised during the transition from position 1 to 2 of the switch due to a special design feature of the switch. The switch is so made that when its handle is shifted from position 1 to 2 the main contacts open and then change over to their new position while the control contact *i.e.,* the contact between C-1 is maintained till the contact C-2 is eatablished. After the closure of contact between C-2 the contact between C-1 is broken. This way the contactor coil remains energised while the switch is transferred from STAR-to-DELTA position.

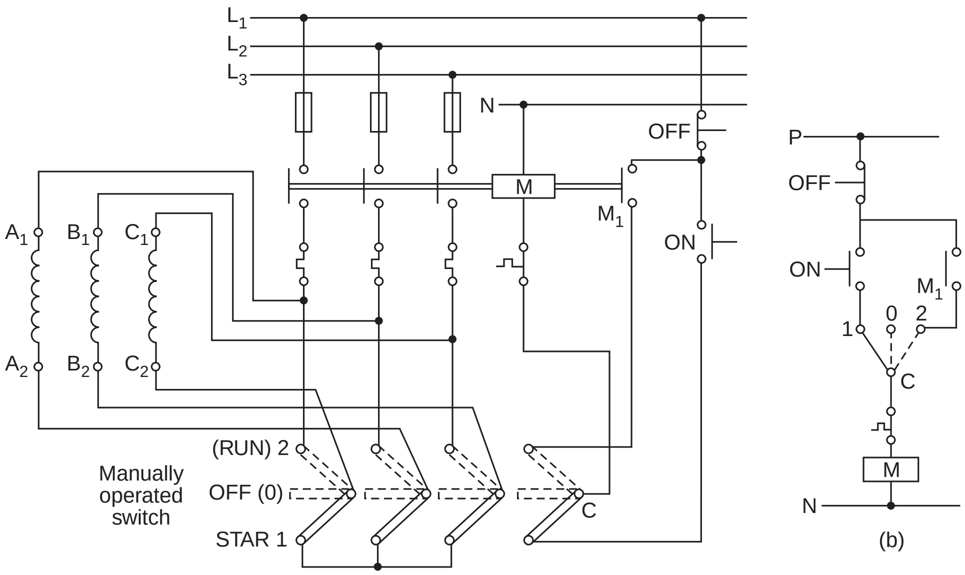


Fig. 3.24 Push-button operated manual star-delta starter
(a) Wiring diagram (b) Schematic control diagram

3.7.3 Semi-automatic Star-Delta Starter

Semi-automatic and fully automatic starters require three contactors to connect the motor windings first in star and then in delta. The power circuit diagram showing the scheme is given in Fig. 3.25.

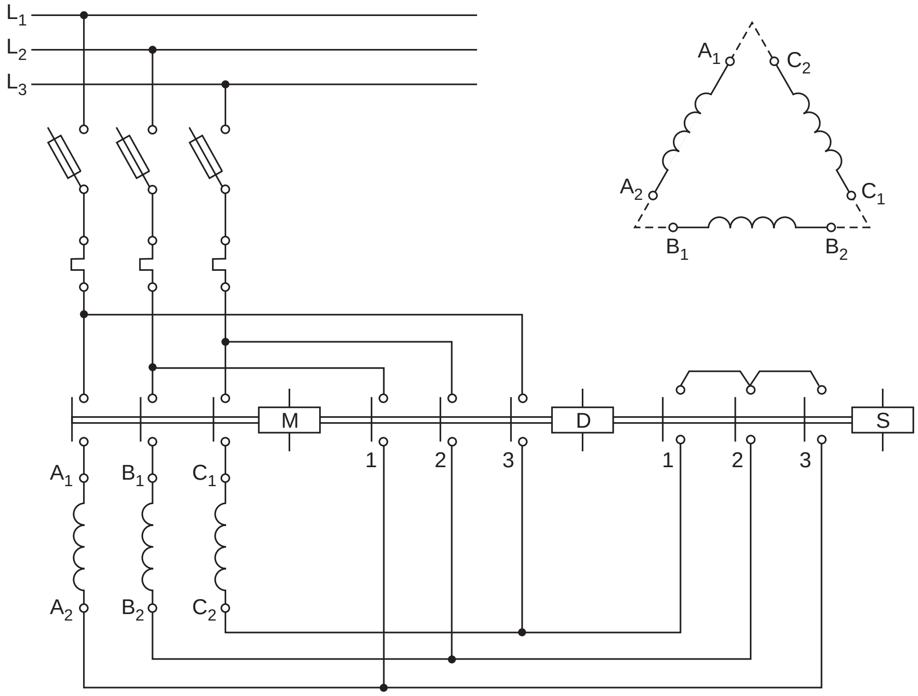


Fig. 3.25 Power circuit diagram for a star-delta starter

Whenever one has to make connections for a star-delta starter it is advantageous to draw the winding diagram as shown in the right hand side of Fig. 3.25. It helps to remember that for delta connection, finishing end of one winding is to be connected to starting end of the other winding as shown in the figure. The three phase supply is then given at the three junctions. Now let us refer to the power circuit diagam of the starter as given in Fig. 3.25. The sequence of operation of the contactors is as follows. First the contactor S will close for star connections, then the main contactor M will close and lastly contactor S will open and contactor D will close for delta connection. When star contactor is first closed, winding terminals A_2, B_2, C_2 get connected together through the contacts of contactor S and thus the windings get connected in star. Now when the main contactor is closed supply reaches terminals A_1, B_1, C_1 and therefore the motor windings are energised in star-connection.

For delta connection, first the star contactor should open before the delta contactor is closed. If delta contactor gets closed while star contactor is still ON, dead short circuit takes place at the outgoing leads of over-load relay through contactor D and S. This is taken care of by providing interlocking of auxiliary contacts between contactors S and D. When star contactor opens and delta contactor closes motor winding terminals A_2, B_2, C_2 get connected to B_1, C_1, A_1 through the closed contacts of contactor M and the motor runs in delta connection.

In a semi-automatic starter, the motor runs in star connection as long as ON-push button is kept pressed. When ON-push button is released the motor gets connected in delta and continues to run till the OFF-push button is actuated or over-load relay trips. The control diagram for a semi-automatic starter is shown in Fig. 3.26. Explanation of control operation is as follows:

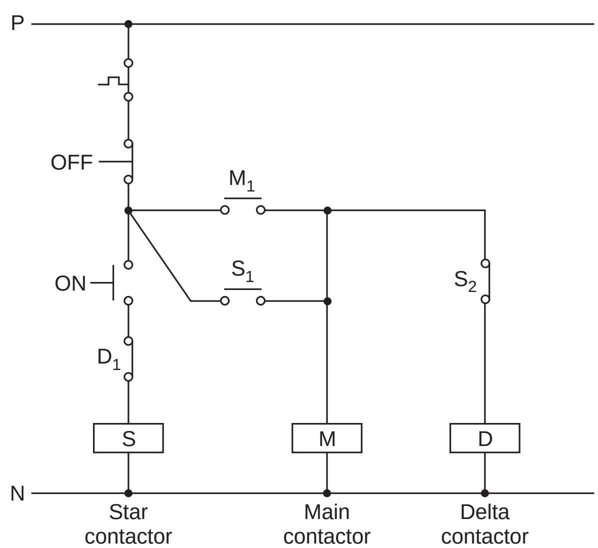


Fig. 3.26 Control circuit for a semi-automatic star-delta starter

When ON-push button is pressed contactor S gets energised and it connects the motor windings in star connection. (Refer power diagram in Fig. 3.25). Simultaneously the auxiliary contact S_1 closes and S_2 opens. Closing of S_1 causes energisation of contactor M which is then kept energised through its own auxiliary contact M_1. Opening of contact S_2 provides interlocking *i.e.,* the delta contactor cannot get energised as long as contactor S is energised. Contactor S

remains energised as long as the ON-push button is kept pressed because there is no holding circuit for contactor S. When the ON-push button is released, contactor S gets de-energised, its auxiliary contacts come back to their original positions as shown in Fig. 3.26. Opening of S_1 does not make any difference in operation as the main contactor is now held through its own contact. However, closing of contact S_2 causes energisation of the delta contactor. Thus, now the main contactor and the delta contactor are energised simultaneously and the motor runs with its windings connected in delta. Whenever the motor is to be stopped the OFF-push button is pressed, both the contactors M and D are de-energised (as holding through auxiliary contact of M is broken). Similar action takes place when the control contact of the overload relay opens.

3.7.4 Automatic Star-Delta Starter (Open Circuit Transition)

In an automatic star-delta starter, the time required to change from star to delta connection is obtained with a time delay relay. A knob on the time delay relay can be adjusted at the desired time setting required for running the motor in star. The time setting is around 10 sec. For lightly loaded motor time setting is a little less, while for fully loaded motors the time setting may be a little more than 10 secs. The power circuit diagram for an automatic star-delta starter is the same as that shown in Fig. 3.25. The control circuit is as shown in Fig. 3.27.

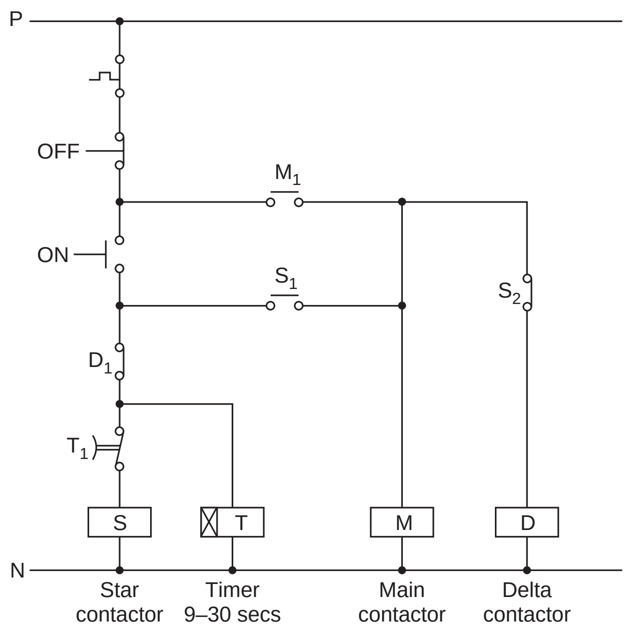


Fig. 3.27 Control circuit for an automatic star-delta starter

When the ON-push button is pressed the star contactor S is energised. Its contact S_1 closes and therefore main contactor M gets energised. Contactor M and contactor S get hold through their own contacts M_1 and S_1 respectively. A time delay relay T is also energised along with contactor S. Energisation of contactor S and then M cause the motor to run in star connection. This continues till timer T operates after a pre-set time of say 10 secs, its delayed contact T_1 opens and causes de-energisation of contactor S. When contactor S is de-energised its contact S_1 opens and S_2 closes *i.e.,* they come back to their normal positions. As contact M_1 is already closed the delta contactor gets energised and the motor runs with its windings in delta connection. As soon as the delta contactor is energised its contact D_1 opens which provides interlocking avoiding simultaneous energisation of star-contactor. At the same time it also de-energises timer T. In running condition therefore contactor M and contactor D remain energised while contactor S and timer T remain de-energised. The circuit just discussed is for open circuit transition from star to delta *i.e.,* the delta contactor closes only after the opening of star-contactor. Thus for a small duration of time the motor windings get disconnected from the supply. During this period voltage is induced in the windings due to rotor flux. When the star contactor closes, the induced voltage in the windings and the supply voltage get superimposed and high transient current may be drawn from the supply depending upon the phase relationship of supply voltage and the induced voltage. The current versus time characteristic of the open circuit transition starter is shown in Fig. 3.28.

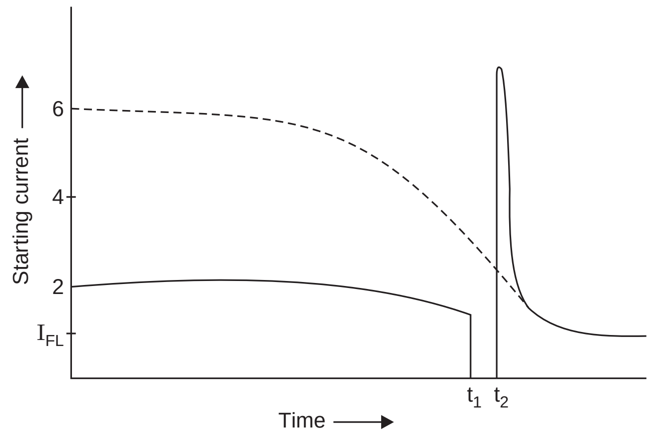


Fig. 3.28 Starting current versus time characteristic for an open circuit transition starter

The starting current, due to motor starting in star connection, reduces current to one third of the rated full load current. At time t_1 when the motor reaches near its rated speed, star contactor opens. After a small time gap of $t_2 - t_1$ the delta contactor closes. At instant t_2 a transient current may flow, the peak value of which may be even higher than the direct on line starting current.

Inspite of these disadvantages, this starter is the most commonly used starter in industry.

3.7.5 Automatic Star-Delta Starter (Closed Circuit Transition)

For most installations the open circuit transition starter discussed in the previous section works satisfactorily. However, some installations may require closed circuit transition starting to prevent power line disturbances. Closed circuit transition starting is achieved by adding one more three pole contactor and resistors in the circuit of an open circuit transition starter.

In closed circuit transition, the motor windings are kept energised with resistors in the circuit when the connections of the winding are changed from star to delta. As the windings remain connected to supply during transition, the incremental current swing during the transition period is reduced to a low value. The power circuit for a closed circuit transition starter is shown in Fig. 3.29. The connection scheme is the same as that for open transition except that a contactor T is connected in parallel with the delta contactor with resistances in the circuit. Thus when contactor T and M are energised, the windings get connected in delta with a resistance in series with each winding. The operating sequence of the contactor is that first the star contactor S and the main contactor M are energised and as the motor picks up speed contactor T is energised.

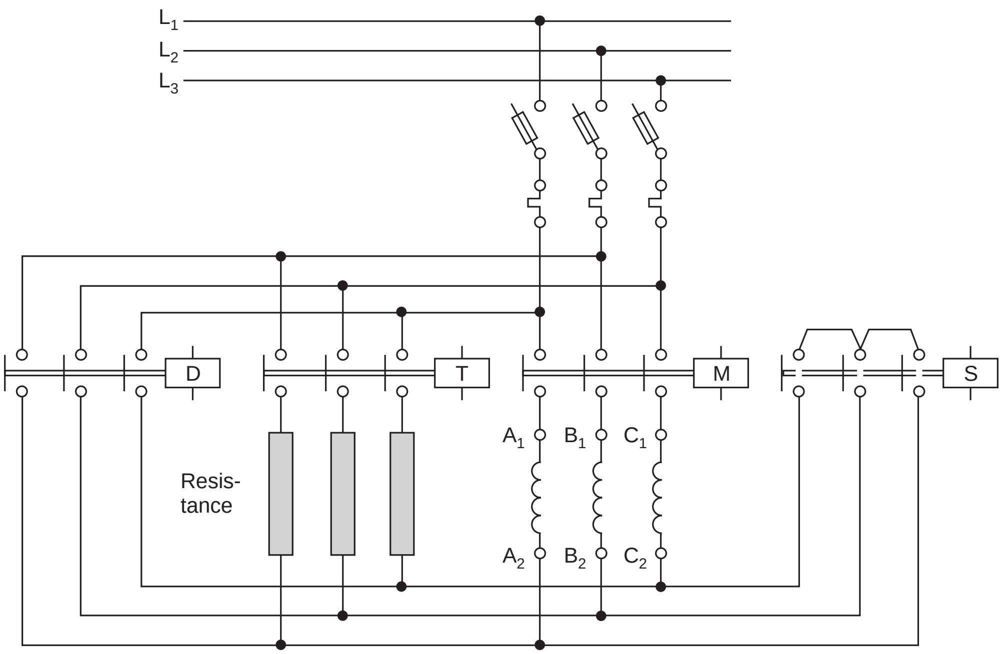


Fig. 3.29 Power circuit diagram for closed circuit transition type star-delta starter

Contactor *T* connects a resistance in parallel with each of the windings. The motor continues to run in star connection as contactor *S* is still closed. Connections due to contactor *T* is not effective as value of resistances are very high. After a little more delay, contactor *S* is de-energised. With de-energisation of contactor *S*, contactor *D* closes. During the small time gap between opening of contactor *S* and closing of contactor *D* the windings remain connected to supply (through contactor *T*) in delta connection with resistances in series. After the closure of contactor *D* the contactor *T* becomes open with some time delay. It may be noted that just at the instant of closing of contactor *D*, the windings get connected in delta as the contactor *D* gets connected in parallel with contactor *T* and thus by-pass its action. The operating sequence for star-delta closed circuit transition is shown in Fig. 3.30.

The control circuit which accomplishes this control sequence is shown in Fig. 3.31.

The control operations performed by the circuit of Fig. 3.31 are as follows:

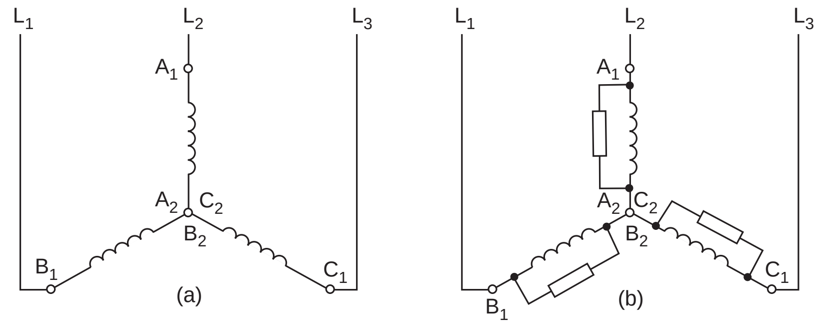
(*i*) Pressing of the ON-push button energises control relay *CR*. Its contacts CR_1 and CR_2 close. Closing of contact CR_2 energises star contactor *S*.

(*ii*) Energisation of star contactor *S* leads to closing of its contact S_1 and opening of S_2. Contactor *M* gets energised through contact S_1 and gets hold through its own contact M_1. Thus the motor runs in star connection [see Fig. 3.30 (*a*)].

(*iii*) Timer *A* gets energised along with the main contactor *M*. Timer operates after a pre-determined time and its delayed contact A_1 closes to energise contactor *T*.

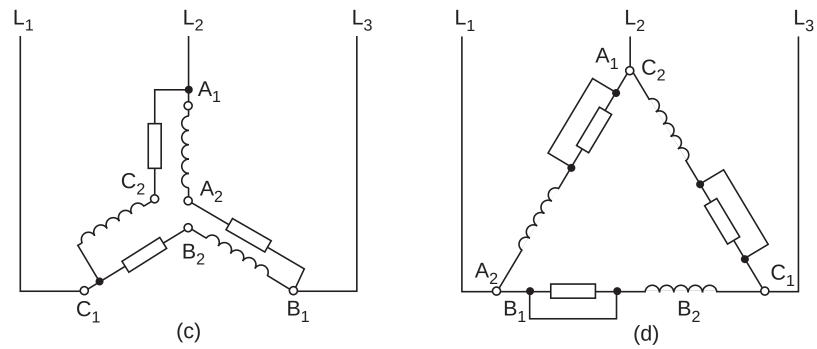
(*iv*) Energisation of contactor *T* connects a high value resistance in parallel with each of the windings, the windings being connected in star and the motor continues to run in star connection [see Fig. 3.30 (*b*)].

(*v*) Timer *B* also gets energised along with contactor *T*. After some delay the timer operates and its contacts B_1 opens and thereby de-energises the star contactor *S*.



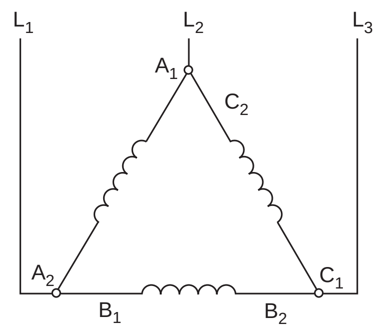
(1) Contactor S and M close

(2) Contactor T closes (S and M also closed)



(3) Contactor S opens (While M and T are closed)

(4) Contactor D closes (While M and T are ON)



(5) Contactor T opens (While M and D are closed)

Operation	Contactor			
	S	M	T	D
Start	X	X		
Transition 1	X	X	X	
Transition 2		X	X	
Run (Delta)		X		X

Note: X indicates closed condition

(6) Contactor operating sequence

Fig. 3.30 Operating sequence of a closed circuit transition star-delta starter

(*vi*) De-energisation of contactor S leads to closing of the contact S_2 and thus the delta contactor D is energised. During the gap between opening of star contactor and closing of delta contactor, contactor T connects the winding in delta with resistances in series [see Fig. 3.30 (*c*) and (*d*)].

(*vii*) Energisation of contactor D leads to opening of its contacts D_1 and D_2. Contact D_1 opens to provide interlocking with contactor S while opening of contact D_2 de-energises contactor T and resets timer A and timer B by de-energising their coils.

(*viii*) In the run condition motor runs in delta connection with contactor *M* and *D* energised [see Fig. 3.30 (*d*)].

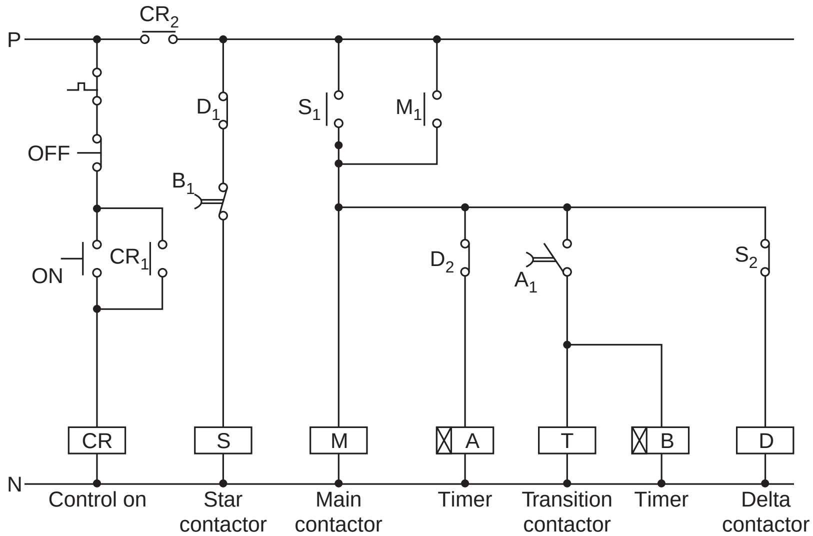


Fig. 3.31 Control circuit for closed circuit transition automatic star-delta starter

3.8 STARTERS FOR MULTI-SPEED MOTORS

A squirrel cage motor is basically a constant speed motor, its speed being determined by the line frequency and the number of poles of the stator winding. Such motors, however, can be designed to have different speed by:

(*i*) having two separate stator windings wound for different number of poles;

(*ii*) having a consequent pole winding which can be reconnected to have two speeds. In this type the choice of number of poles is restricted to a two-to-one ratio. For example, a consequent pole winding can be wound for four and eight poles, eight and sixteen poles, and so on. Fig. 3.32 shows how poles are doubled by reconnection of windings.

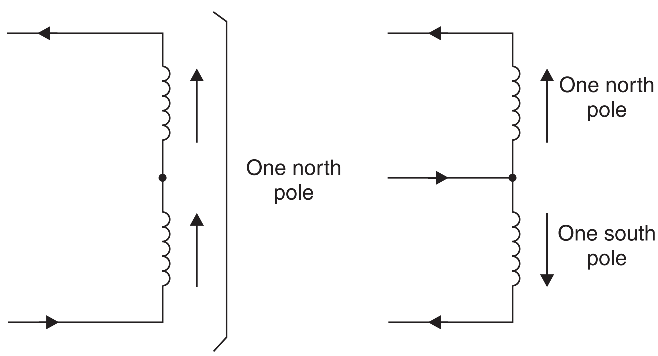


Fig. 3.32 The number of poles are doubled by reversing current through half a phase (connection shown for one phase only)

Multi speed motors are divided into three categories according to the torque developed at various speeds. Before these three types are discussed, let us recall the relationship between horse-power, torque and speed, which is expressed as:

Horse-power developed = torque × speed.

(*i*) **Constant horse-power motors.** These motors develop the same horse-power at all speeds. Thus the torque varies inversely as the speed according to the above equation.

(*ii*) **Constant torque motors.** These motors develop same torque on all speeds. Horse-power rating of the motor varies in proportion to the speed.

(*iii*) **Variable torque motors.** These motors are designed to develop a torque which is proportional to the speed. Horse-power rating of these motors is therefore proportional to the square of the speed.

Torque speed curves are shown dotted for a typical two-speed motor with a two to one ratio for constant horse-power, constant torque and variable torque design.

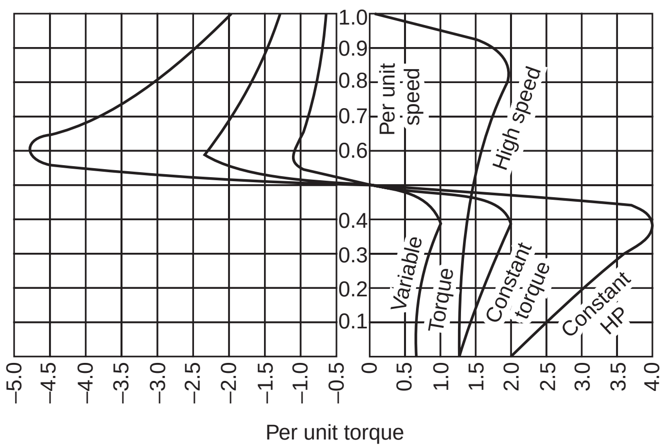


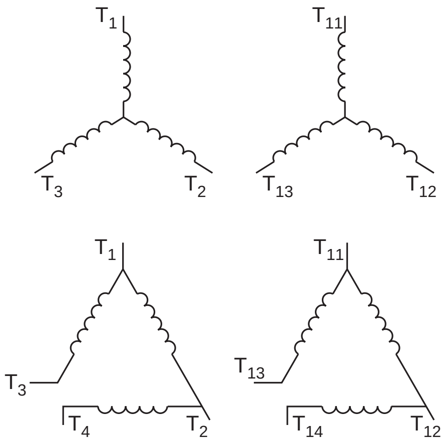
Fig. 3.33 Typical speed-torque curves of two-to-one multispeed squirrel-cage induction motors

We can infer from the curves that when the motor is switched from its high speed winding to the low speed winding the low speed winding develops a considerable amount of retarding torque which in constant horse-power motor may exceed the maximum torque developed by the high speed winding. This high retarding torque is accompanied by high stator currents which can be harmful to the motors. These high currents can be avoided by connecting buffer resistance in the low winding while switching from high to low speeds.

Another problem faced while switching from one speed to another is that when the motor is disconnected from the lines and reconnected with a different number of poles, the stator windings remain open during transition. The entrapped flux will generate emf in the winding which may add to the line voltage and a high transient current may flow which may be harmful to the windings. It is thus desired that sufficient time should be allowed for the transition from one speed to another in order to permit decaying of flux entrapped in the magnetic circuit.

3.8.1 Starter for Two-Speed, Two Winding (Separate Winding) Motor

The two separate stator windings meant for different speeds may be connected either in star or in delta. The windings are shown in Fig. 3.34 (*a*) alongwith their connections for low speed and high speed in a tabular form.



Speed	L_1	L_2	L_3	Open
Low	T_1	T_2	T_3	All others
High	T_{11}	T_{12}	T_{13}	All others

Speed	L_1	L_2	L_3	Open
Low	T_1	T_2	T_3 T_4	All others
High	T_{11}	T_{12}	T_{13} T_{14}	All others

Fig. 3.34 (a) Winding connections for two-speed, two winding motor

Refer table for star connection. For low speed, motor terminals T_1, T_2, T_3 have to be connected to L_1, L_2 and L_3 while terminal T_{11}, T_{12} and T_{13} have to be left open. For high speed T_{11}, T_{12} and T_{13} should be connected to L_1, L_2, L_3 while T_1, T_2 and T_3 should be left open. Similarly for delta connected windings, the connection scheme for two speeds is shown in table of Fig. 3.34 (*a*). In the delta winding connections, it is seen that windings get connected in delta when terminals T_3 and T_4 are shorted in low speed winding and terminals T_{13} and T_{14} are shorted in high speed winding. This is done because the winding which is idle should remain open otherwise current will circulate in it when motor is running on the other winding. The power diagram for star connected winding for two speed operation of motor is given in Fig. 3.34 (*b*).

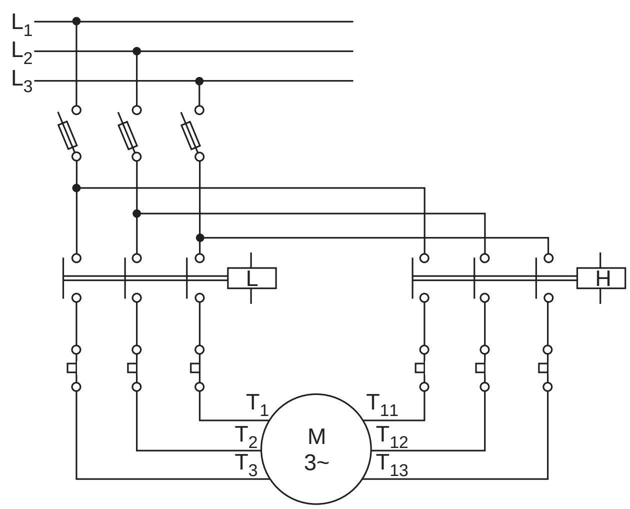


Fig. 3.34 (b) Power diagram for star connected winding for two-speed operation of motor

It is clear from the power diagram that separate overload relays are required for low speed and high speed. While making connections proper care should be taken that phases between high and low speed windings are not reversed. Machines may get damaged if the direction of rotation is changed. Three types of control circuits for the starter are shown in Fig. 3.35.

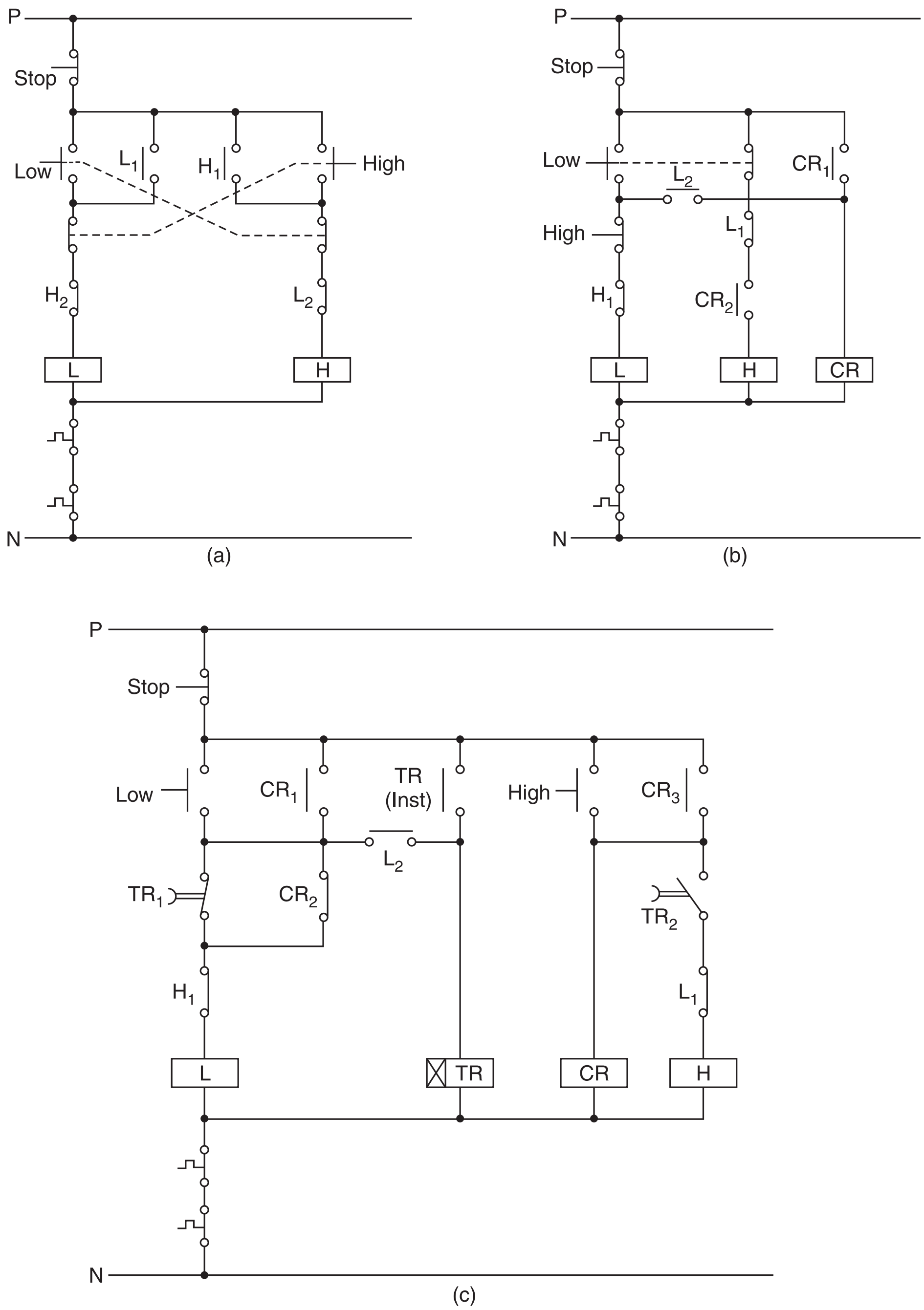


Fig. 3.35 Control circuit for two speed, two winding motor

In the control circuit of Fig. 3.35 (*a*) change over from low to high speed and high to low speed can be done by pressing the respective push buttons. Push button interlocking as well as contact interlocking have been incorporated in the control circuit design. This type of control, however, results in rapid speed transfer which may activate the overload relays.

To prevent this the control scheme can be equipped with time delay relays that will provide time lag between the speed changes.

For some drives the starting torque of the high speed winding is too low, requiring the motor to run on low speed first before being switched over to high speed. This is achieved through a control scheme using a compelling relay as shown in Fig. 3.35 (*b*). It may be observed that pressing of high speed push button does not have any result. To run the motor at high speed first the low speed push button is to be pressed which would energise contactor L and the compelling relay CR. Contactor L gets hold through contacts CR_1 and L_2 while compelling relay CR gets hold through its own contacts CR_1. Its another contacts CR_2 also closes. For running the motor on high speed, pressing of the high speed push button de-energises the low speed contactor L while the compelling relay CR remains hold. The de-energisation of L leads to closing of its normally closed contact L_1. Thus high speed contactor H is energised through the normally closed contact of LOW-push button, contact L_1 and closed contact CR_2. Switching back to low speed can be done by pressing the LOW-push button which would de-energise contactor H and energise contactor L. This control scheme has the disadvantage that both the push buttons, LOW and HIGH have to be pressed for selecting high speed operation. This shortcoming can be removed by using a timer as shown in the control scheme in Fig. 3.35 (*c*).

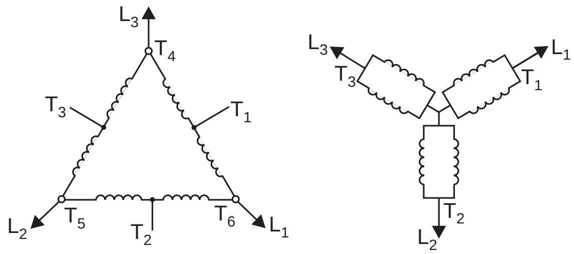
In this circuit, when the high speed push button is pressed the compelling relay CR gets hold through its contact CR_3. Its contact CR_1 also closes and energises contactor L through closed contacts TR_1 and H_1. This in turn energises timer TR through contact L_2. Timer TR gets hold through its instantaneous contact TR (Inst). Thus even when the high speed push button is pressed the motor starts in low speed and runs in low speed till timer TR times out and opens its delayed contact TR_1, de-energising contactor L and at the same time closing contact TR_2. When contactor L drops contactor H picks up through closed contact CR_3, TR_2 and L_1.

When the motor is desired to be run only on low speed, low speed push button is to be pressed. Contactor L and timer TR would get energised. Both the contactors get hold through the instantaneous contact of timer TR. When the LOW-speed push button is released, contactor L gets hold through contact TR (inst), L_2 and CR_2. The operation of timer TR which leads to opening of delayed contacts TR_1 has no effect on contactor L. The motor can be shifted to high speed instantaneously by pressing the HIGH-push button.

It may be noted that when the motor is running on high speed it cannot be brought to low speed by pressing the LOW speed push button. First the STOP-push button has to be pressed and only then the motor can be run on low speed by pressing the LOW speed push button.

3.8.2 Two Speed One Winding (Consequent Pole) Motor Starter

A three phase squirrel cage induction motor can be wound so as to bring out six leads for external connections. By making suitable connections of these leads (T_1, T_2, T_3, T_4, T_5, T_6) the three phase windings can be connected either in series delta or in parallel star as shown in Fig. 3.36.



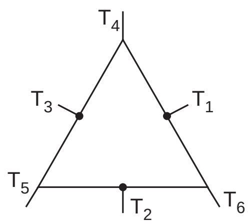
(a) High speed (b) Low speed

Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	—	T_4, T_5, T_6
High	T_6	T_4	T_5	All others	—

(c) Connection table for two-speed one winding constant H.P. motor

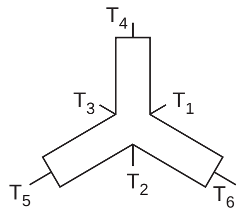
Fig. 3.36 Winding connections for one winding, two speed induction motor

Constant horse power



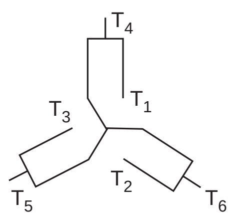
Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	—	T_4, T_5, T_6
High	T_6	T_4	T_5	All others	—

Constant torque



Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	All others	—
High	T_6	T_4	T_5	—	T_1, T_2, T_3

Variable torque



Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	All others	—
High	T_6	T_4	T_5	—	T_1, T_2, T_3

Fig. 3.37 Typical motor connection arrangement for three phase-two speed one winding motor

If the windings are designed such that series delta connection leads to high speed as shown in Fig. 3.36 (*a*), then the horse-power rating would be the same for both high as well as low speeds. On the other hand if series delta connection is designed for low speed and parallel star connection for high speed then torque rating of the motor would be same at both low as well as for high speeds. Typical motor terminal connections, for constant horse-power, constant torque and variable torque are shown in Fig. 3.37.

The power diagram for a constant horse-power, two speed, one winding motor is shown in Fig. 3.38.

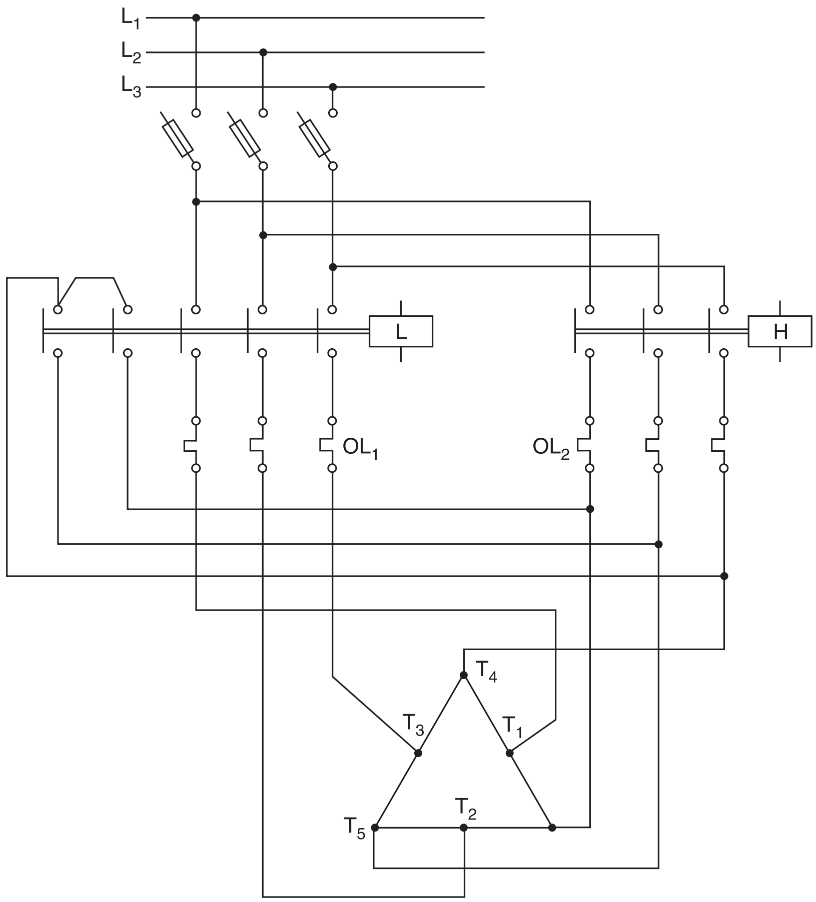


Fig. 3.38 Power diagram for constant horse-power, two speed, one winding induction motor

It is clear from Fig. 3.38 that the low speed contactor *L* requires 5 poles. The control scheme for the starter may be any of the control circuit discussed in the previous section using Figs. 3.35 (*a*), (*b*) and (*c*).

We may have three speed consequent pole motors by having one winding which is reconnectable and the other an ordinary winding. Four speeds may be obtained by having two reconnectable windings.

3.9 REVERSING THE DIRECTION OF ROTATION OF INDUCTION MOTORS

In a three phase induction motor, the rotor tends to rotate in the same direction as the revolving magnetic field produced by the stator windings. The direction of the revolving field depends upon the phase sequence of the supply voltage. If the phase sequence of supply to the motor windings is changed by interchanging two phase leads, the direction of the revolving fields is reversed. Thus the direction of rotation of a three phase induction motor can be reversed if the two supply phase leads to the motor terminals are interchanged. This phase reversal to the motor terminals is accomplished by two contactors.

The power diagram for reversing the direction of rotation of the motor and the associated control circuits are shown in Fig. 3.39.

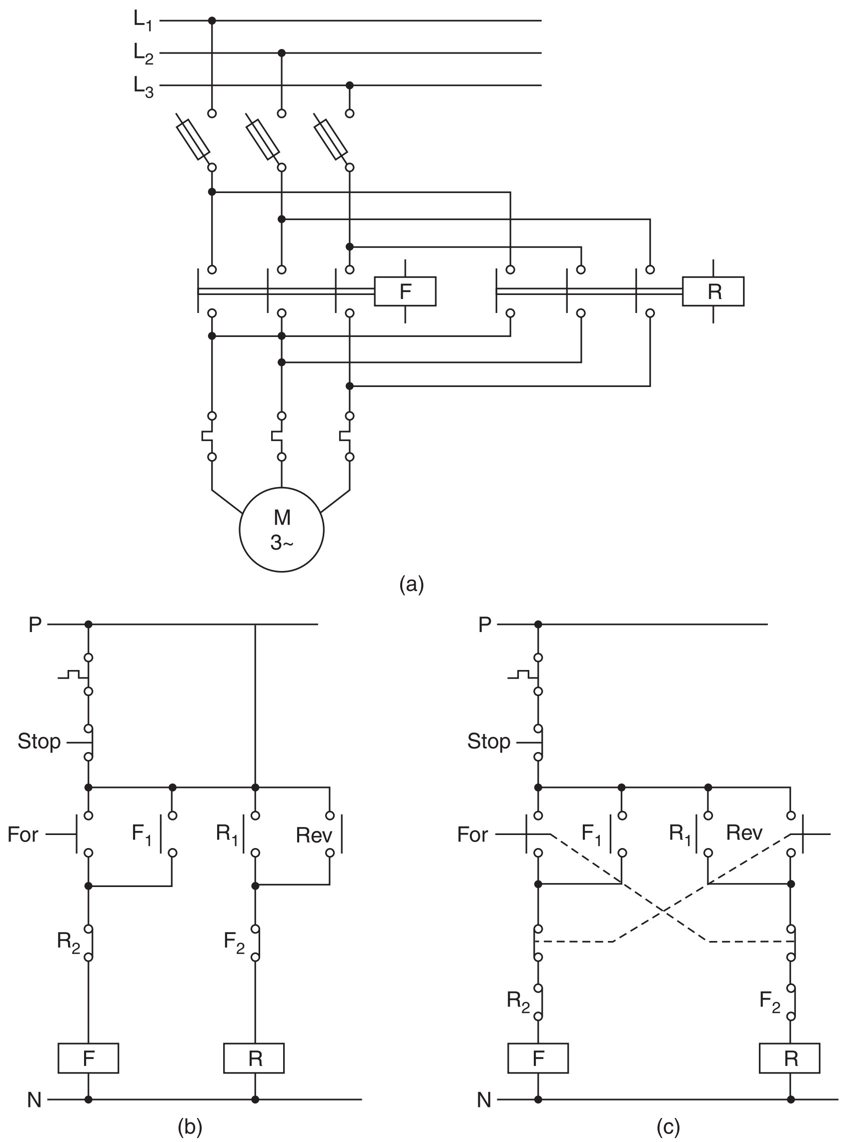


Fig. 3.39 Reversing direction of rotation of a three phase induction motor (*a*) Power diagram (*b*) and (*c*) Control circuit diagrams

It may be seen from 3.39 (*a*) that phase reversal to motor terminals has been done by interchanging phase L_2 and phase L_3 leads at the upper terminals of the reverse contactor *R*. The forward and reverse contactor are mechanically interlocked *i.e.,* if one of them is closed the other cannot close. This is done to avoid dead short circuit in case both the contactors closing simultaneously. Electrical interlocking has also been provided, by using control contacts. Electrical interlocking is essential even if mechanical interlocking of contactors is provided. This is because, if the coil of contactor which is mechanically interlocked not to close, is energised, its coil gets burnt. The coil gets burnt as it draws large current due to less reactance in this case. Reactance of coil is less as reluctance to flux path increases due to large air gap between the electromagnet and the locked armature of contactor. Forward reverse starters may be designed for either Forward-Reverse Operation or Forward-Off-Reverse Operation.

The control diagram in Fig. 3.39 (*b*) is a simple circuit for Forward-Off-Reverse operation. The motor can be run in forward or reverse direction by pressing FOR or REV push buttons. When say the FOR-push button is pressed contactor *F* gets energised and is held energised through its auxiliary contact F_1. As the interolocking contact F_2 is now open the reverse contactor *R* can not be energised even if the REV-push button is pressed. When the motor is to be reversed, the motor is to be stopped first by pressing the STOP-push button which de-energises contactor *F*, only then the motor can be run in reverse direction by pressing the REV-push button. Control circuit in Fig. 3.39 (*c*) is for direct reversing of the motor. In this circuit, for reversing there is no need to first press the STOP-push button. Direction of rotation of the motor can be changed by pressing the respective push button. This is accomplished by using interlocking through *NC* contacts of the push button in the coil circuits of the contactors. Assume that motor is running in forward direction when contactor *F* is energised through closed contact F_1, NC contact of reverse push button, and normally closed contact R_2 of reverse contactor *R*. When it is desired to reverse the motor direction, REV-push button is pressed, its NO contact closes whereas its *NC* contact which is in series with coil of contactor *F* opens. Contactor coil of *F* is thus de-energised and its holding circuit is also released. De-energisation of *F* also leads to closing of its auxiliary contacts F_2. The reverse contactor *R* is thus energised through NO contact of REV-push button, *NC* of FOR-push button, and *NC* contact F_2 of contactor *F*. The contactor *R* remains energised through its auxiliary contact R_1. Similar action takes place when the motor is to again run in forward direction by pressing FOR-push button. Induction motors can be safely reversed by direct reversing method as the inrush current is not significantly more than when it is started direct from rest. Direct reversing is also used for bringing a motor to standstill quickly using reverse torque acting as a brake.

3.10 PLUG STOPPING OF MOTOR

Plug stopping or plugging of a motor means bringing the motor to standstill quickly by applying reverse torque on the rotor. Reverse torque for plugging of a motor to standstill is obtained by changing the direction of the revolving magnetic field (interchanging any two stator leads). When the rotor reaches zero speed and attempts to reverse, supply to the motor is disconnected with the help of a zero-speed plugging switch.

Control circuit for plugging a small squirrel cage motor from either direction with zero speed plugging switches has been discussed in this section. Here two zero speed plugging switches are required for the control operations. The forward plugging switch contact, FOR-PS close when the motor runs in forward direction and remains closed till the motor comes to standstill or zero-speed. Similarly reverse plugging switch contact, REV-PS close when motor starts in reverse direction. Control diagram of a Forward-Reverse starter with plug-stop facility has been shown in Fig. 3.40.

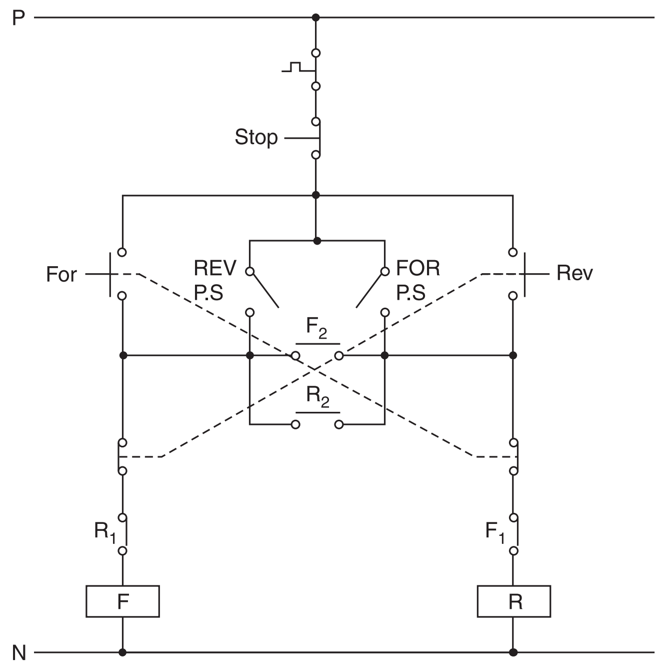


Fig. 3.40 Control circuit for Reversing of an induction motor with plugging facility

In this control circuit auxiliary contact as well as push-button contact (NC contact) interlocking have been provided between Forward and Reverse contactors. The operations of the circuit is as follows.

When the FOR-push button is pressed, contactor *F* gets energised and the motor starts rotating in forward direction. Forward plugging switch contact closes and contactor *F* gets hold through closed contact of forward plugging switch and auxiliary contact F_2. When the motor is stopped by pressing STOP-push button contactor *F* gets de-energised, the holding circuit breaks due to opening of contact F_2. But the contactor *R* gets energised through forward plugging switch, back-contact (NC contact) of FOR-push-button, and normally closed contact F_1. Thus a reverse torque acts on the motor to bring it to zero speed quickly. Near zero speed the forward plugging switch opens and de-energies contactor *R*. If the motor is to be run in reverse direction the reverse push-button has to be pressed. Similar action, as described above, takes place when the motor is stopped from running in the reverse direction.

3.11 DYNAMIC BRAKING

An induction motor can be brought to rest quickly if ac supply to the motor terminals is removed and instead a dc supply is applied. The dc current flowing through the stator windings would produce the same number of stationary poles as the number of poles of the revolving field produced with ac supply. The rotor would cut the flux of these stationary poles resulting in induced emf and current flow in the rotor windings. This current flow in the rotor would cause I^2R loss in the winding resistance or in the external resistances in case it is a wound rotor motor. The rotor would slow down as a result of the mechanical energy of rotation being converted into electrical energy and dissipated as heat. Energy conversion would be complete when the rotor would reach zero speed.

For a quick stop, dc current fed to the stator winding should be six to eight times the rated current of the motor.

Direct current can be supplied to the 3-phase windings in either of the following two ways:

(1) A pair of stator terminals T_1 and T_2 connected across the dc source and the third terminal T_3 is left open. The same current would pass through the two windings, they being in series.

(2) In this method two winding terminals, say, T_2 and T_3, are joined together and supply is given between this junction and the third terminal T_1. This is more popular arrangement as it develops less heating for a given braking torque. This connection arrangement is shown in Fig. 3.41.

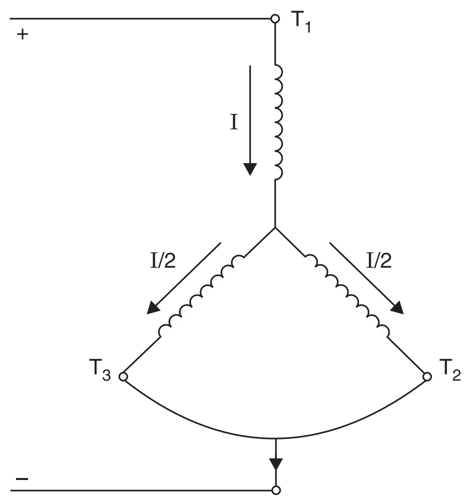


Fig. 3.41 Stator winding connections for dynamic braking

The power diagram and control diagram for dynamic braking of a squirrel cage induction motor is shown in Fig. 3.42 (*a*) and (*b*). It can be seen from the power diagram that dc current to the motor stator is controlled by a variable resistance *R*.

Contactor DB [see Fig. 3.42 (*b*)] has been used to switch on dc supply to the motor terminals during braking. In the control circuit an OFF-delay timer has been used for setting the time for which dc supply is to be given for braking. In an OFF-delay timer, the contact operates after some time from the instant of switching off of the relay coil. In the circuit NC contact of the START-push button has been used in series with the coil of contactor *DB* for interlocking.

This interlocking is to avoid simultaneous energisation of contactor *M* and DB and thereby mixing of ac and dc supply. The working of the control circuit is as follows: When the START-push button is pressed, contactor *M* gets energised and is held through its contact M_1. OFF-delay time *TR* also gets energised, its delayed contact TR_1 closes immediately, and keeps the circuit ready for dynamic breaking. When the motor is to be stopped, on pressing the STOP-push button contactor *M* and timer *TR* get de-energised. Contactor *DB* gets energised through delayed contact TR_1 of the timer and the closed contact M_2. Closing of contactor *DB* applies dc supply to the stator terminals. When the OFF-delay timer operates, its contact opens and de-energises contactor *DB*.

In this type of Dynamic braking, the braking torque varies considerably over the braking period. Depending upon the magnitude of dc excitation, braking torque may be 50% of rated motor torque at the instant the dc is applied, rise to a value of 500 to 600 percent at about 3 to 6 percent speed, and then drop rapidly to zero as the motor comes to rest.

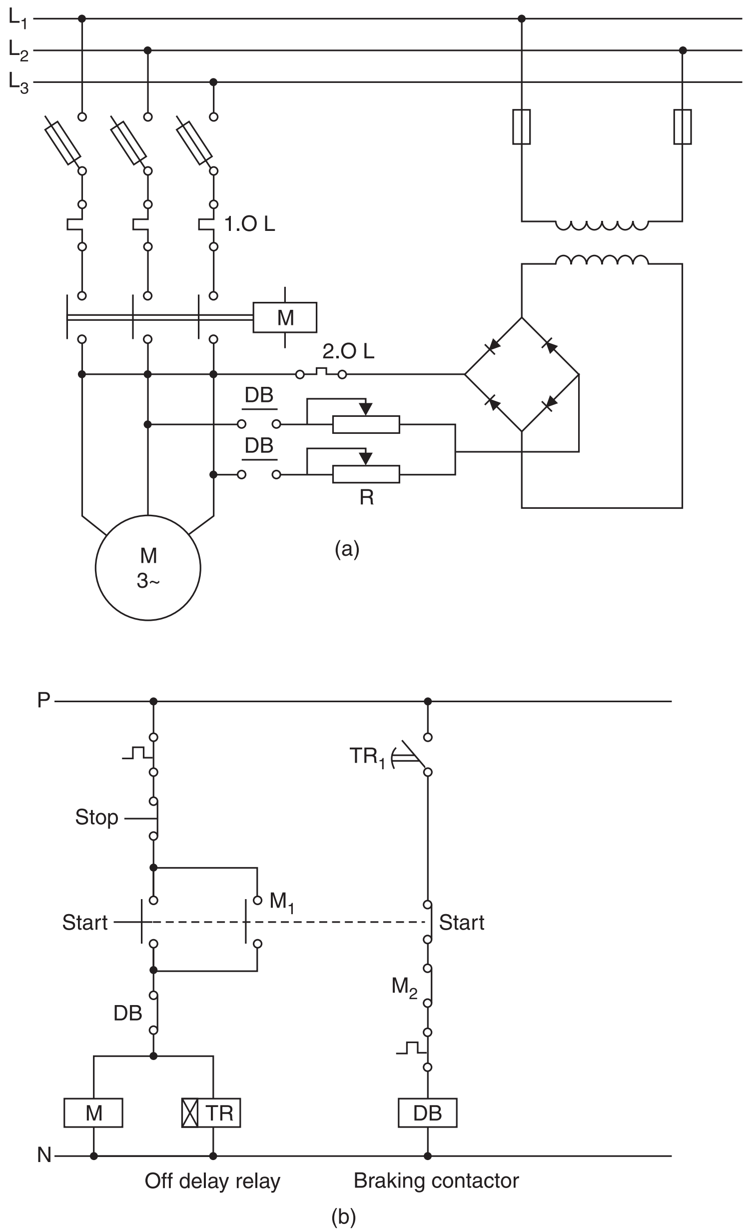


Fig. 3.42 Dynamic braking of a three phase induction motor
(*a*) Power circuit diagram (*b*) Control circuit diagram

The reason for above mentioned variation in the braking torque is explained as follows: It is known that braking torque is developed due to interaction between the rotor current and the total flux ($T_{B_r} = K \phi_t I_r$). The total flux ϕ_t in an ac motor during braking has resultant value that is represented by the constant dc flux and a superimposed flux caused by the rotor emf. It, therefore, becomes clear that the flux-current product ($\phi_t I_r$) at any instant of time will determine the torque at that instant. At the start of braking period, the rotor reactance is high, thus the rotor current has a low-lagging power factor. This current therefore has a large reactive component that greatly diminishes the dc field. Thus under this condition the braking torque is low. When the motor slows down, the rotor reactance becomes low, then power factor of the rotor current increases, and the demagnetising effect on main dc flux reduces. The braking torque thus rises even though the motor speed drops.

REVIEW QUESTIONS

1. Explain why there is a limitation on the use of across the line full voltage starters for starting of squirrel cage motors.

2. Explain why reduced voltage is applied across the motor terminals during starting of an induction motor.

3. What are the basic methods used for achieving reduced voltage starting ?

4. Discuss the working of a semi-automatic stepless resistance starter.

5. How is an increment resistance starter different from other reduced voltage starters ? Draw its power and control diagram.

6. Name the situation where you will prefer a line resistance reduced voltage starter than a line resistance starter.

7. Explain the meaning of open circuit transition and closed circuit transition, with respect to starting of induction motors.

8. Discuss the working of auto-transformer starter (closed circuit transition) with the help of diagrams.

9. Mention the advantages of part winding starter as compared to other reduced voltage starters. Draw power diagram for three step starting of an induction motor.

10. Explain the working of a fully automatic open circuit transition star-delta starter. Also draw its starting current versus time characteristic.

11. Explain working of a closed circuit transition star-delta starter.

12. Discuss the working of two speed one winding (consequent pole) motor starter.

13. How will you reverse the direction of rotation of a squirrel cage induction motor ? Draw power and control diagram for the forward/reverse starter ?

14. Draw diagram for plugging a squirrel cage induction motor to stop from either side using zero speed plugging switches.

15. Explain the principle of dynamic braking of squirrel cage induction motor and draw power and control diagram for the same.

16. Starting current of squirrel cage motors is approximately:

(*a*) two times the full load current (*b*) four times the full load current
(*c*) six times the full load current (*d*) equal to rated current

17. The primary purpose of applying reduced voltage at starting to squirrel cage motor is:

(*a*) to reduce losses (*b*) to attain smooth acceleration
(*c*) to avoid voltage fluctuation of mains (*d*) to obtain high starting torque.

18. At 50% of rated speed during acceleration, the current drawn by an induction motor is almost:

(*a*) equal to rated current (*b*) twice the rated current
(*c*) four times the rated current (*d*) six times the rated current.

19. The starting current of a 20 h.p. motor is approximately equal to

(*a*) 100 A (*b*) 120 A
(*c*) 180 A (*d*) 250 A.

20. In Increment resistance starter, the motor starts accelerating at:
(*a*) the instant of switching on
(*b*) 25% of line voltage
(*c*) 60% of the line voltage
(*d*) full line voltage.

21. For a 120 hp motor which one of the following is the most suitable starter ?
(*a*) Reactor reduced voltage starter
(*b*) Auto transformer reduced voltage starter
(*c*) Star-delta starter
(*d*) Part-winding starter.

22. Dynamic braking for an ac motor is accomplished by
(*a*) reversing the direction of rotation of the motor
(*b*) connecting dc voltage to stator
(*c*) inserting resistance in series with motor leads
(*d*) disconnecting ac power from motor leads and connecting the motor to a load resistor.

4

Starters for Wound Rotor Induction Motors

4.1 INTRODUCTION

The rotor of a wound rotor induction motor is wound with three phase windings. The windings are star connected, the three terminals are taken out and connected to slip rings mounted on the shaft. Connections are then tapped through brushes mounted on the slip rings. This motor is also commonly known as slip ring induction motor. The purpose of taking out the three rotor terminals is to connect extra resistance in the rotor circuit. Connection of resistance in the rotor circuit limits the current drawn by motor and also the torque speed characteristic of the motor changes. Extra resistance in the rotor circuit may be added to obtain high starting torque and also to control the speed of the motor. To see how variation of rotor circuit resistance effects the torque slip characteristic, let us assume that for a particular induction motor its rotor resistance is 1 ohm and rotor reactance is 10 ohm. Let us assume that the rotor resistance is made 1, 2, 6 and 10 ohm respectively. The rotor standstill reactance x_{20} = 10 ohm will remain constant since x_{20} is fixed by the design of rotor. The torque equation for an induction motor is given by :

$$T = \frac{KSR_2}{R_2^2 + S^2 X_{20}^2}$$

where K is a constant.

We assume that value of K = 100 and find magnitude of torque at different values of slip for (R_2 = 1, X_{20} = 10), (R_2 = 2, X_{20} = 10), (R_2 = 6, X_{20} = 10) and (R_2 = 10, X_{20} = 10), the results are shown in Table 4.1.

Torque slip characteristic for different values of rotor circuit resistance are plotted as per values shown in Table 4.1. Torque slip speed characteristic for four different values of rotor circuit resistance have been drawn together for the sake of comparison as shown in Fig. 4.1.

Table 4.1 Calculated values of torque at different slips having variable rotor resistance

SLIP *S*	*Torque for* $R_2 = 1, X_{20} = 10$	*Torque for* $R_2 = 2, X_{20} = 10$	*Torque for* $R_2 = 6, X_{20} = 10$	*Torque for* $R_2 = 10, X_{20} = 10$
0.01	0.99	0.49	0.16	0.09
0.02	1.92	0.99	0.33	0.199
0.05	4.0	2.35	0.82	0.49
0.1	5.0	4.0	1.62	0.99
0.15	4.6	4.8	2.35	1.46
0.2	4.0	5.0	3.0	1.92
0.3	3.0	4.61	4.0	2.75
0.4	2.35	4.0	4.61	3.45
0.5	1.92	3.45	4.92	4.0
0.6	1.62	3.0	5.0	4.41
0.7	1.40	2.64	4.94	4.69
0.8	1.23	2.35	4.8	4.87
0.9	1.09	2.11	4.61	4.97
1.0	0.99	1.92	4.41	5.0

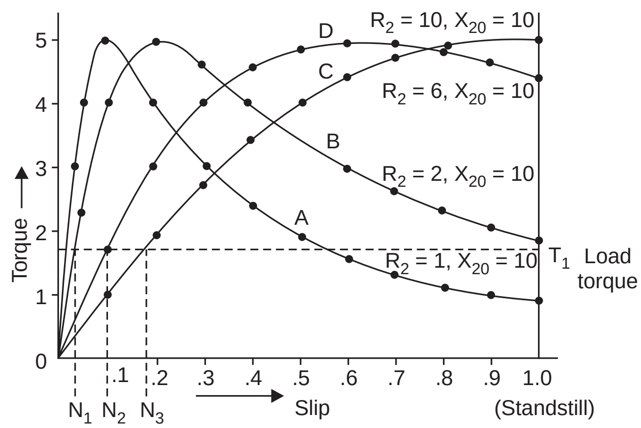


Fig. 4.1 Effect of variation of rotor circuit resistance on torque slip characteristic of an induction motor

Curve *A, B, C* and *D* are plotted by rotor resistance of 1, 2, 6 and 10 ohms. The dotted line shows the load torque required from the motor. This line intersects the characteristic *A, B, C* and *D* at four different points in the stable region of their characteristic. The following observations can be made from the above :

(*i*) The starting torque for rotor resistance of 1 ohm is less than the torque requirement of the load connected on the motor. Therefore the motor will not be able to start from standstill (refer curve *A*).

(*ii*) Starting torque increases with increase in value of rotor resistance. Refer curves *B, C* and *D*.

(*iii*) The slip at which maximum torque occurs varies with the variation of rotor resistance. For rotor resistance of 1 ohm maximum torque occurs near synchronous speed, while for R_2 = 10 ohm *i.e.,* $R_2 = X_{20}$ maximum torque occurs at standstill.

(*iv*) The value of the maximum torque developed remains constant but only the slip at which it occurs varies with the variation of rotor circuit resistance.

(*v*) Torque is maximum when the rotor resistance $X_2 = SX_{20}$ is equal to the rotor resistance R_2. (In graph *A* for example, maximum torque occurs when $S = 0.1$ and for graph *D*, where R_2 = 10 ohm and X_{20} = 10 ohm maximum torque occurs when $S = 1$.

(*vi*) The motor can be run at different speed with a particular load connected on the motor shaft, say T_1 as shown in Fig. 4.1. The motor will run at speed N_1 if rotor resistance is 2 ohms, at speed N_2 if rotor resistance is 6 ohm and at speed N_3 if rotor resistance is 10 ohm.

From the last observation, it is seen that if initially, 10 ohm resistance is connected in the rotor circuit, the motor will develop maximum torque at starting. If the load on the motor is T_1, the motor will quickly accelerate to its final speed N_3. If now it is desired to increase the speed to N_2 rotor resistance is decreased to a value of 6 ohms. Further, higher speed N_1 is possible if the rotor resistance is decreased to 2 ohms. Thus it is seen that variable speed is possible by changing the rotor circuit resistance. The value of resistance to be connected in the rotor circuit is selected depending upon how much starting torque is required, A starting torque of 1.5 to 2 times the connected load is generally acceptable for most drives for smooth acceleration. The resistance to be connected in the rotor circuit should be of continuous rating, if the motor is desired to be run at intermediate speeds for long duration. Resistance of short time rating can be used if the rotor resistance is to be used only for starting where the resistance is cut off rapidly.

4.2 MOTOR ACCELERATION

To accelerate a slip ring induction motor from standstill to full speed with full load, resistance connected in the rotor circuit is cut out in steps. During acceleration it is required that current and torque peaks are restricted to reasonable limit. Limitation of current peaks is necessary to prevent excessive line voltage drop and also overstressing of the switching devices. Limitation of torque peaks is required to prevent overstressing of the mechanical parts of the driven machinery. Figure 4.2 shows connection of a slip-ring induction motor with extra resistance in the rotor circuit.

To accelerate the motor smoothly, first the contacts 1 should close and energise the stator winding with whole of resistance in the rotor circuit. The total value of resistance should be such as to limit the torque and current to 1.5. to 2.00 times the full-load values. These values, however, would depend upon the type of load connected and the permissible current limit. The motor should accelerate according to the torque versus speed curves shown in Fig. 4.3.

When the main contacts 1 close, starting torque equal to 1.5 times full load, equal to *OA* in Fig. 4.3 is developed. The motor will accelerate along curve *AB*. When motor torque balances the full load torque at point *B* the contacts 2 should close and thereby cutting off resistance R_1 from the rotor circuit. As the resistance is cut off the motor should again develop higher torque with resistance $(R_3 - R_1)$ in circuit and the accelerate along curve *CD*. At point *D*, contacts 3 should close to cut off resistance R_2 from the rotor circuit. Motor will now accelerate along curve *EF* and reach about 80% of Synchronous speed at point *F*. At this instant contact 4 should close to cut-off the remaining resistance. Now, the whole of resistance R_3 is cut-off. The motor will now develop torque equal to point *G* and then accelerate along curve *GH*. Now the

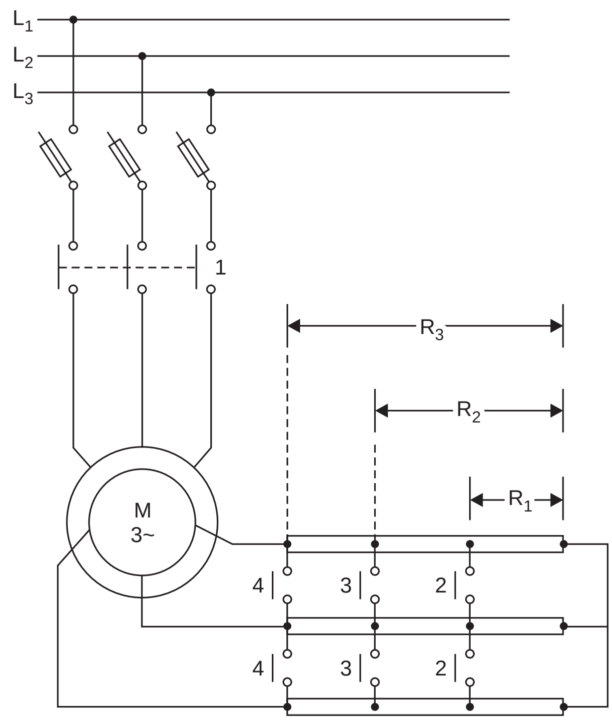


Fig. 4.2 Connection scheme for starting of wound rotor induction motor

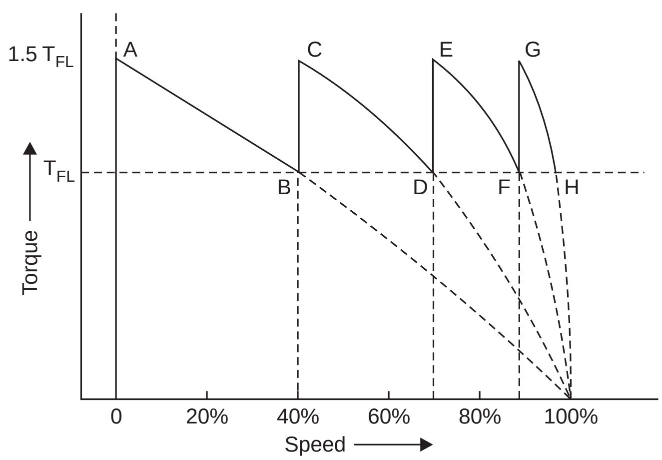


Fig. 4.3 Torque-speed curves during the period of acceleration of a slip-ring

motor has fully accelerated and only rotor winding resistance is in the circuit. The motor runs at a speed near synchronous speed. The Motor can be made to run at any intermediate speed, say at point B, *i.e.,* at 40% of the synchronous speed with resistance R_1 cut off, resistance remaining in the circuit being equal to $(R_3 - R_1)$. The acceleration of motor according to the curves in Fig. 4.3, may be obtained perfectly, by using an automatic magnetic controller. Achievement of acceleration with a drum switch or a face-plate starter should depend upon the judgement of the operator where the operator would cut off the resistance by judging the speed of the motor. The torque or current versus time characteristic and speed versus time characteristics during acceleration are shown in Fig. 4.4.

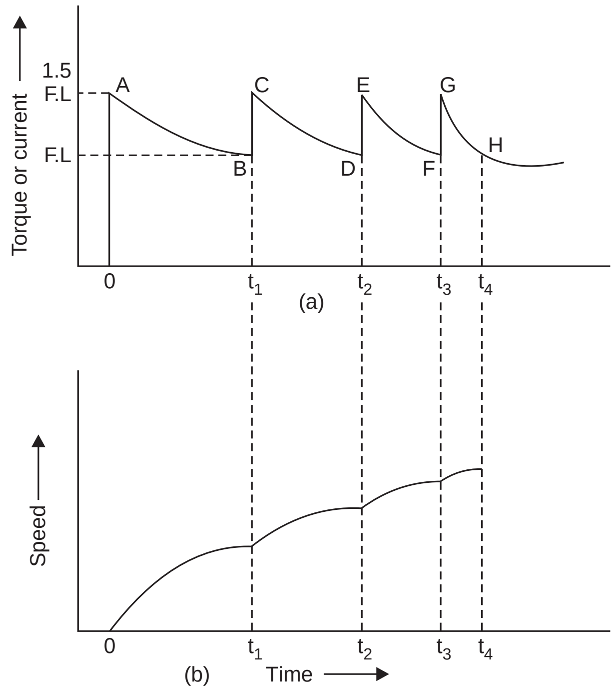


Fig. 4.4 (*a*) Torque/current versus time characteristic during acceleration
(*b*) Speed versus time characteristic during acceleration

In Fig. 4.4 (*a*) the torque or current versus time characteristic has been shown. The motor reaches its final speed in time t_4. The exact shape of the curve *AB*, *CD* etc. depend upon the type of load connected to the motor. In Fig. 4.4 (*b*) the rise of speed with respect to time has been shown. The speed rises exponentially with respect to time as shown. It must be noted from Fig. 4.4 that during acceleration, the motor takes comparatively less time to reach full-load torque from the instant of cutting of a resistance step.

4.3 MANUAL FACE PLATE STARTER

This is the oldest and simplest type of wound rotor motor controller.The rotor resistance consists of three legs which are connected to each of the motor phase windings. The spider like contact arm, also consisting of three legs form the star point (see Fig. 4.5). Turning of the contact arm moves the star point along the resistor sections and thus varies the amount of resistance in each of the rotor phases. The extra rotor circuit resistance used may be of either short time rating or of continuous duty depending upon whether the controller is to be used as a starter only or also for speed control. In this scheme, the time allowed for the motor to accelerate and the resulting current peaks depends entirely upon the skill of the operator *i.e.,* how he manipulates the controller. In this starter the stator winding is energised through a magnetic contactor and an over-load relay. The starter, thus combines the use of magnetic control and manual control. Wiring diagram for the starter has been shown in Fig. 4.5 (*a*) and the control diagram in schematic form in Fig. 4.5 (*b*).

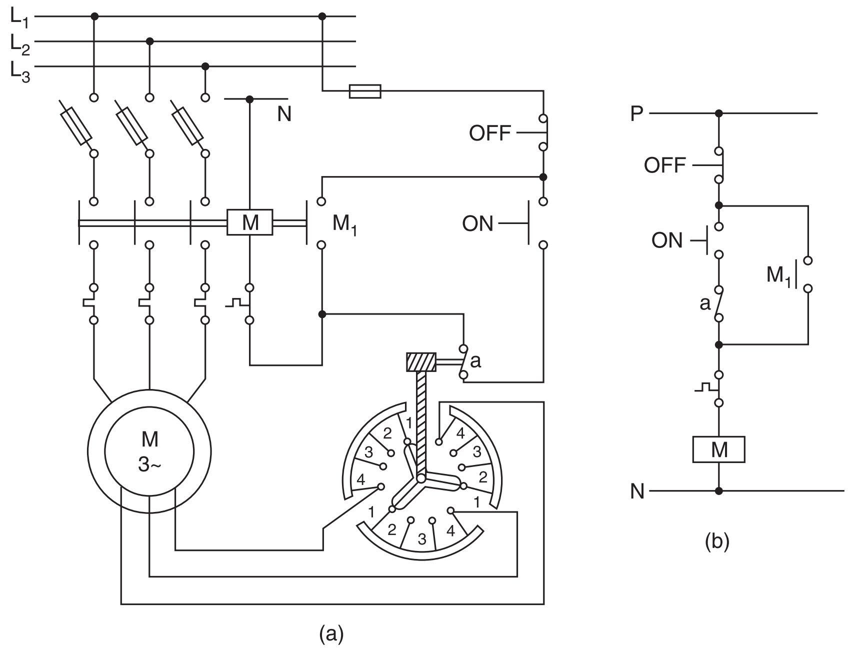
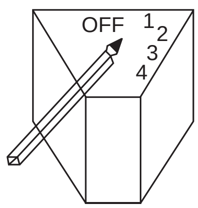


Fig. 4.5 Manual face-plate starter (*a*) Power diagram (*b*) Schematic control diagram

Interlocking provided in the starter permits the motor to be started only when whole of the controller resistance is in the circuit. This is obtained by using an auxiliary contact of controller in series with the ON-push button. When controller handle is in the position shown in Fig. 4.5 (*a*), the whole of controller resistance is in the rotor circuit. At this position the handle keeps the auxiliary contact closed. When the handle is moved in anti-clockwise direction, this contact opens. The operation of starter is explained as follows : When the ON-push button is pressed contactor *M* will get energised if the auxiliary contact '*a*' of controller, which is in series with ON-push button, is closed *i.e.,* if the whole of the controller resistance is in the rotor circuit. The contactor *M* remains energised through its auxiliary contact M_1 bypassing the auxiliary contact interlocking [(see Fig. 4.5 (*b*)]. With the closing of contactor *M*, the motor starts with full controller resistance in the circuit. The controller resistance is now gradually cut out from the three rotor phases by moving the handle in anti-clockwise direction from step 1 to step 4. At step 4, the whole of the resistance is cut out and the motor runs at its final speed. The time for acceleration depends entirely upon the judgement of the operator. The motor stops when OFF-push button is pressed or the overload trips causing de-energisation of contactor *M*. When the motor is to be started again the controller handle has to be brought to initial position again as shown in Fig. 4.5 (*a*). Face plate starters are simple in construction and have low cost but they lack sturdiness and are unsatisfactory for frequent operations. This disadvantage is overcome by drun switches. The rotary sliding contact fingers are mounted on a drum shaft and they make contact with stationary contact fingers when the drum shaft is rotated. The springs of the moving contacts maintain better and more uniform contact force. In a drum switch controller the magnetic contactor for the starter can also be eliminated by having the main contacts on the drum controller itself. Drum switches may be designed for reversing the motor also. Drum switches, are however, often used in conjunction with a magnetic contactor which facilitates inclusion of overload protection or any other pilot device for the control of the motor.

4.4 MANUAL STARTER USING MASTER CONTROLLERS

An important application of slip-ring induction motor controlled by a master controller is in over-head cranes. A master controller, as discussed earlier while dealing with control components, is a switch which has got plastic cams on a rotating shaft. The control contacts are so mounted that cams can activate them. When the shaft containing the cams is rotated by a lever, either in left or right direction particular set of contacts get actuated at different positions of the lever. Master controllers will have lever movement in one direction only if the motor is to be run in only one direction. Figure 4.6 shows in tabular form various positions of the lever (OFF, 1, 2, 3, 4) in the first column. The corresponding state of the control contacts (0, 1, 2, 3, 4) are shown by *X* and *O*. *A X* below a contact denotes that the contact is closed and *O* denotes that the contact its open.



(a)

Lever position	Control contacts				
	0	1	2	3	4
OFF	X	0	0	0	0
1	0	X	0	0	0
2	0	X	X	0	0
3	0	X	X	X	0
4	0	X	X	X	X

(b)

Fig. 4.6 Pictorial view of a master controller and table showing control contact position at various lever positions

Now, we will examine how this master controller is used to run a slip ring induction motor at four different speeds. Control contacts 0, 1, 2, 3, 4 will be used to energise contactors which will ultimately cut off a resistance step from the rotor circuit. The power diagram for the motor to be controlled and associated control scheme have been shown in Fig. 4.7 (*a*) and 4.7 (*b*) respectively. As shown in Fig. 4.7 (*b*), the control relay *CR* can be energised by pressing ON-push button if the lever of the master controller is in OFF-position *i.e.,* contact 0 is closed. In any other position of the lever this contact is open and therefore the control circuit cannot be switched ON. After switching on the control circuit when operator moves the lever to position 1 contact 0 opens and contact 1 closes thereby energising the main contactor *M*. The motor starts with all the resistance in the rotor circuit. A high starting torque is developed and the motor reaches a speed which depends upon the value of resistance in the circuit. When lever is moved further to position 2, contact 2 closes and energises contactor *A*. Contactor *A* cuts off resistance R_1 from the rotor circuit and the motor accelerates to a higher speed. At position 3 of master controller, control contact 3 closes and energises contactor *B*. Closing of contactor *B* shorts another step of resistance resulting in resistance R_2 out of the rotor circuit and the motor accelerating to a further higher speed.

Finally at position 4 master controller contact 4 closes and energises contactor *C* when whole of the resistance is cut out from rotor circuit. The motor thus accelerates to its final speed.

In actual circuits using Master Controllers, time delay relay contacts are also used in series with master controller contact so that even if the operator moves the handle directly from OFF-position to position 4 the resistance shorting contactor *A, B* and *C* would get energised after certain delay of time as set on the time delay relays. The actual control circuit using master controller and time delay relays for an over-head crane will be discussed in a subsequent chapter.

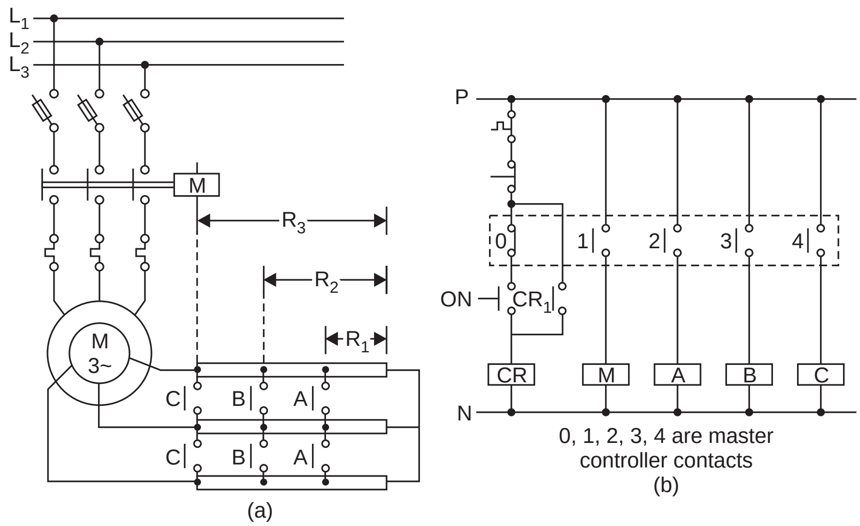


Fig. 4.7 Manual starter for slip ring induction motor using master controller (*a*) Power circuit diagram (*b*) Control circuit diagram

4.5 AUTOMATIC CONTROL OF ACCELERATION

In automatic control the resistance steps in the rotor circuit of a slip ring induction motor are cut off by energising number of contactors in proper sequence, after closing of the line contactor. As discussed earlier, the accelerating contactor should close when motor has accelerated on the preceding step to such a speed that closing of contactor does not cause resulting torque and current peaks to exceed the pre-determined limit. Refer to the curves in Fig. 4.4 (*b*). The accelerating contactors should close at time intervals of t_1, t_2, t_3. There may be three types of magnetic controls depending upon the criterion used for closing of the accelerating contactors. They are :

(*i*) **Definite time control:** The closing of acceleration contactors takes place after definite time period in sequence. The timings are adjusted to restrict current peaks within limits.

(*ii*) **Current limit control:** The accelerating contactors close when the current peak falls back to a pre set lower limit with the help of current limit relays.

(*iii*) **Secondary frequency control:** Frequency response relays are used to close the actuating contactors as the motor reaches pre-determined speeds.

4.5.1 Definite Time Limit Starter

In definite time limit starters, the accelerating contactors close after pre-set delays determined by the timers. The time periods are so adjusted that when a resistance step is cut off, the resulting current peaks remain within limits. The time delay between energisation of successive accelerating contactors can be obtained by using any of the following types of time delay elements :

(*i*) Individual timers, either pneumatic or electronic for each step;

(*ii*) Motor driven cam timer;

(*iii*) Timer heads mounted on contactors; and

(*iv*) Flux decay relays.

Control circuits for all the above are discussed one by one as follows. The power diagram, however, would remain the same for all these control circuits. While studying all these control circuits it would be essential to refer back to the power diagram shown in Fig. 4.8.

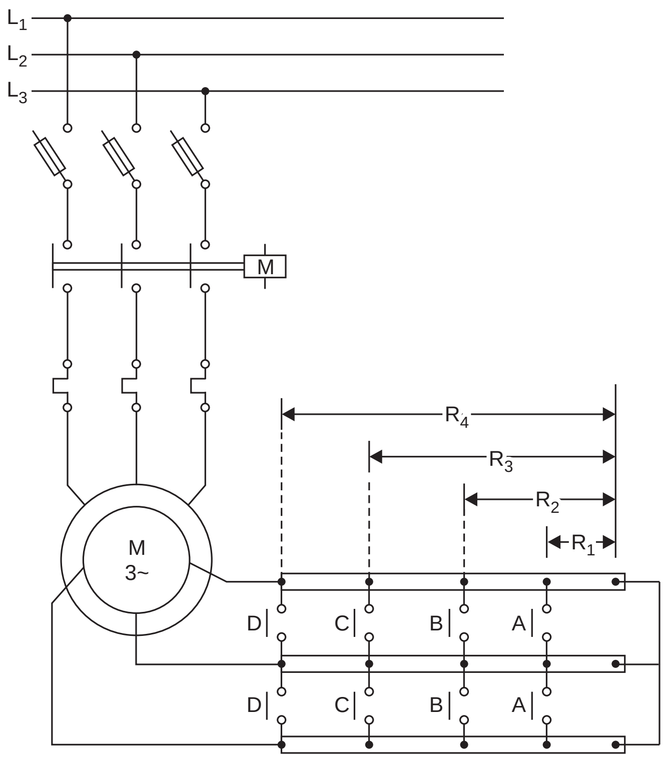


Fig. 4.8 Power diagram for automatic control of acceleration of a slip ring induction motor

4.5.1.1 Control Circuit Using Individual Time for Each Step

Explanation of the control circuit: Pressing of ON-push button energises control relay *CR*. Contactor *M* and timer 1*T* also get energised as contact CR_2 closes. Contactor *M* starts

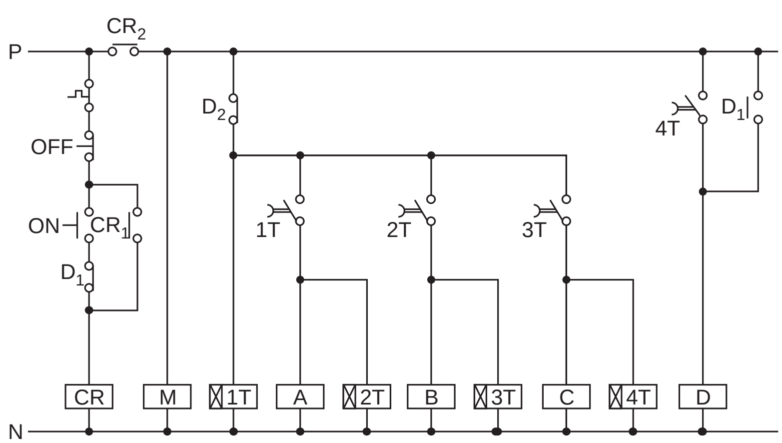


Fig. 4.9 Control circuit for a slip-ring induction motor starter using individual timers

the motor with full resistance in the rotor circuit. When timer $1T$ times out its delayed contact $1T$ closes to energise contactor A and timer $2T$. Energisation of contactor A causes cutting off of resistance R_1 from the three rotor phases. When timer $2T$ times out its contact $2T$ closes to energise contactor B which shorts second step of resistance *i.e.,* R_2 and the motor accelerates further. Along with contactor B timer $3T$ also gets energised which after its pre-set delay energises contactor C. Contactor C shorts resistance R_3. Timer $4T$ gets energised along with contactor C and when it operates, it energises contactor D which shorts the remaining resistance of the rotor circuit *i.e.,* now, the whole of the resistance R_4 is cut off from the circuit. When contactor D energises it gets hold through its contact D_3 while its contact D_2 opens and de-energises contactor A, B and C and timer $1T$, $2T$, $3T$, $4T$.

4.5.1.2 Control Circuit Using a Motor Driven Cam Timer

Explanation of the control circuit: A double element start push button is used to energise the main contactor M and cam timer motor C. Main contactor gets hold through its contact M_1 and contact M_2 connects control supply to the accelerating contactor circuit as shown in Fig. 4.10 (*a*). The starting position of cam timer is as shown in Fig. 4.10 (*b*). In this position contact '0' of cam timer is in actuated position. As normally closed (*NC*) contact of '0' has been used, in starting position contact '0' is open. When START-push button is pressed, the cam timer motor gets energised and it rotates the cam shaft in the direction shown in Fig. 4.10 (*b*). First of all contact '0' gets de-actuated. Supply to cam motor gets hold through' closed contact '0' and therefore push button can now be released. When motor shaft rotates further, cams 1, 2, 3, 4 actuate the respective contacts after fixed time intervals set by protruding portions on the cams. Resistance shorting contactors *A, B, C* and *D* are energised through the closing of contact 1, 2, 3 and 4. Last of all contactor D is energised through closing of timer contact 4 and

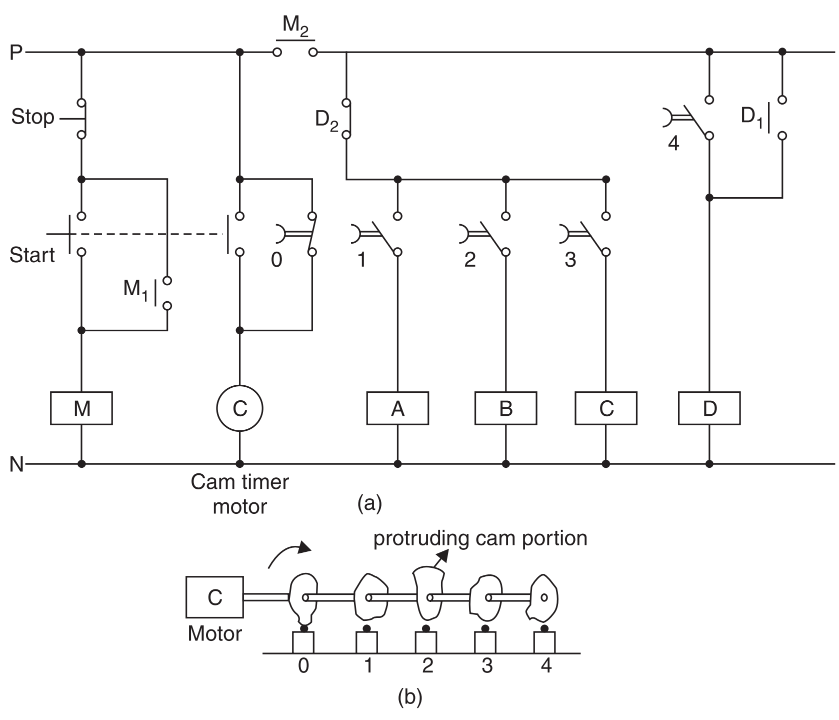


Fig. 4.10 (*a*) Control circuit for a slip-ring induction motor starter using a motor driven cam timer (*b*) Schematic representation of a motor driven cam timer

gets hold through its own contact D_1. At the same time opening of contact D_2 de-energises, contactors *A, B* and *C*. Cam timer motor also gets de-energised when after a full rotation contact '0' is actuated. Contact '0' opens and supply to cam timer motor is cut off. Cam timer rests in this position till the START-push button is pressed again.

4.5.1.3 Control Circuit Using Contactor with Timer Head

Explanation of the control circuit: In this circuit, timer heads (Pneumatically operated) are mounted on the contactors. When a contactor is energised, the plunger of the timer is also attracted along with contactor plunger. Contactor contacts close immediately while timer head mounted on contactors closes its contact after the pre-set time delay, set on the timer head. Variation in operating time obtained is, however, small by using the timer heads. In the above control circuit the motor starts with full resistances, when the ON-push button is pressed. Timer head of contactor *M* operates after pre-set delay and its contact M_1 closes to energise the accelerating contactor *A*. Contactor *A* shorts a set of resistance of the rotor circuit. Timer head *A* closes after some delay and energises contactor *B*. This goes on till the last contactor *D* is energised.

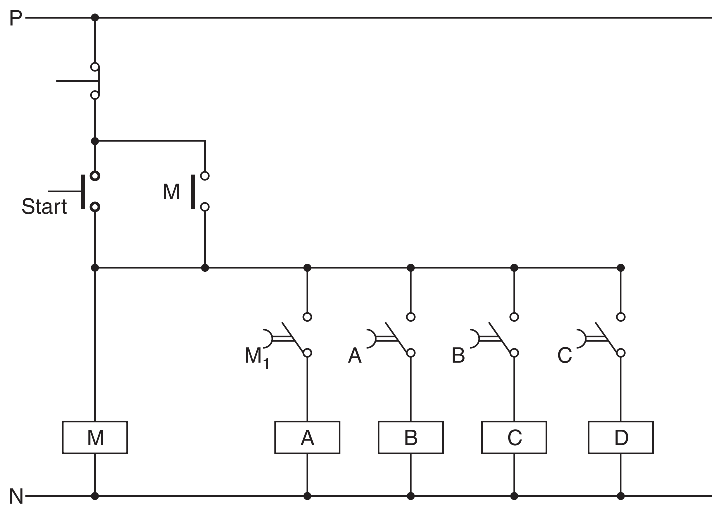


Fig. 4.11 Control circuit for a slip-ring induction motor starter using contactors with timer heads

4.5.1.4 Control Circuit Using Flux Delay Relays

Explanation of the control circuit: When switch *S* is closed the control transformer is energised. The secondary voltage is rectified by a bridge rectifier. D.C. supply so obtained is given to flux-delay relays *AX, BX, CX* and *DX*. In these relays flux decays slowly when their coils are de-energised. The relay contacts come to their normal de-energised condition with a delay of time which depends on the rate of decay of flux. In this circuit, initially all the relays *AX, BX, CX, DX* are in energised condition through normally closed (*NC*) contact of contactor *M,A, B, C* and *D*. The contacts of these relays AX_2, BX_2, CX_2, DX_2 are therefore open. When motor is started by pressing the ON-push button contactor *M* gets hold through its contact M_2 while its *NC* contact M_1 opens and de-energises relay *AX*. Relay *AX* gets de-energised instantly but its contact AX_2 closes, when flux becomes zero after some time delay. Closing of contact AX_2 energises accelerating contactor *A*. Thus first step of resistance gets cut off from the rotor circuit due to closing of contactor *A*. Its contact A_1 opens and de-energises relay *BX*. Also contact A_2 closes in the coil circuit of contactor *B*, After pre-set delay of relay *BX,* its contact

BX_2 closes and energises contactor *B*. Thus second step of resistances is also cut off from rotor circuit. The same sequence of operations follows for energisation of contactor *C* and *D*.

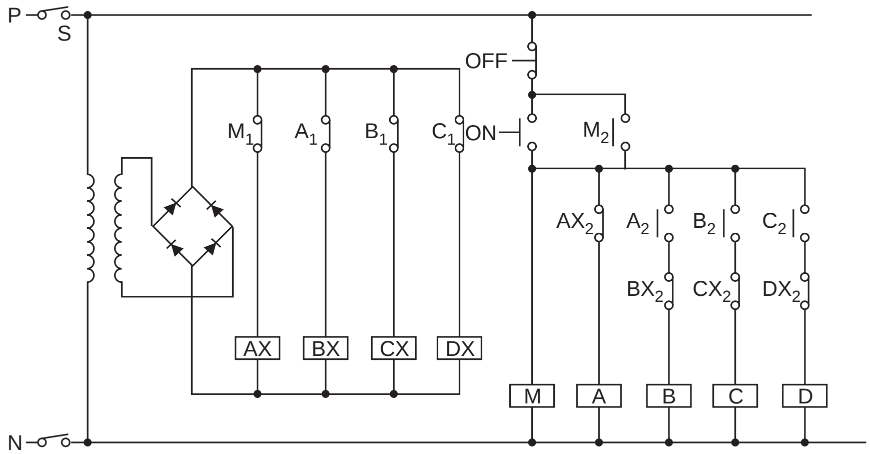


Fig. 4.12 Control circuit for a slip-ring induction motor starter using flux-delay relays

4.5.2 Current Limit Acceleration Starter

In this type of starter, the accelerating contactor closes depending upon the amount of stator/ rotor current. Accelerating contactors are energised when current peak falls to a pre-determined value equal to full-load current. Refer to Fig. 4.4 (*a*) at points *B, D, F* and *H* the acclerating contactors are energised and they cut off resistance in steps.

A current limit acceleration starter uses a special relay known as current limit relay. This relay has two coil viz. a potential coil and a current coil. The current coil restrains the relay from operating when current through the coil is more than the pre-set value. As the current through the current coil drops to the pre-set value, the relay operates provided, however, the potential coil is also energised.If the potential coil is not energised, the relay would not function. The current coil of the current limit relay is energised by a current transformer provided on one phase of the stator line connections. The control diagram is shown in Fig. 4.13.

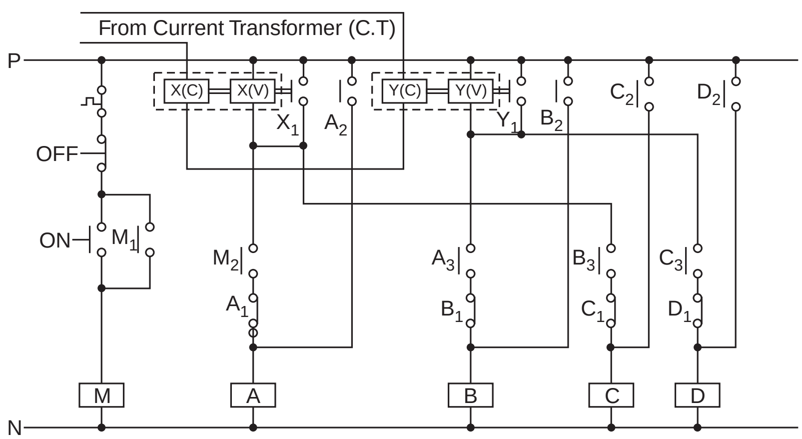


Fig. 4.13 Control circuit for a current limit acceleration starter

One point to be understood before studying this control circuit is that, the auxiliary contacts of contactors are so adjusted that normally open (NO) contact closes before the normally closed (NC) contact opens. This provision is necessary for functinoning of the above control circuit: The motor is energised when the ON-push button is pressed and contactor M closes. Voltage coil $X(V)$ of relay X is energised through closed contact A_1 and M_2. Coil of contactor A and $X(V)$ are in series. Contactor A does not pick up as its coil impedance is high and the current flowing through the coil circuit is not sufficient for the contactor to pick up. Relay X would operate provided the required amount of current through the current coil $X(C)$ flows. Initially when the motor is energised, high inrush current flows and therefore the current coil X (C) restrains the relay from operating. The relay operates when the current falls to a pre-determined lower value. When the relay operates its contact X_1 closes and short the voltage coil $X(V)$ while direct supply to contactor coil A gets applied. Contactor A closes and gets hold through its contact A_2. Little later its contact A_1 opens. Opening of A_1 de-energises the voltage coil of relay X. Its contact X_1 also opens. When contactor A closes, some resistance from rotor circuit gets cut off, now again an inrush of current takes place. Current coil $Y(C)$ of relay Y restrains the relay Y from operating. Due to closing of contact A_3 voltage coil $Y(V)$ which is in series with coil of contactor B gets energised. Contactor B does not pick up as the voltage coil $Y(V)$ is in series. When the motor accelerates, and current through current coil $Y(C)$ comes to a lower pre-set value, relay Y operates and closes its contact Y_1. Closure of contact Y_1 energises contactor B which then gets hold through its own contact B_2. Contact B_1 opens and keeps the relay Y inoperative due to de-energisation of voltage coil $Y(V)$. Contactor B shorts another set of resistance from the rotor circuit. Again there is a current peak. Relay X again comes into action, as its voltage coil $X(V)$ gets energised through closing of contact B_3. The contactor C will close when the relay operates as a result of current falling to a lower pre-set value. As contactor C closes, relay Y comes into operation due to closing of contact C_3. When relay Y operates, accelerating contactor D is energised. These two relays X and Y may be used to energise any number of accelerating contactors.

4.5.3 Secondary Frequency Acceleration Starter

When a wound rotor induction motor accelerates from standstill to final speed the rotor voltage drops from a maximum value at standstill to nearly zero value at final speed. The frequency of the rotor voltage also drops from line frequency at standstill to nearly zero at the final speed. Frequency of rotor induced emf, f_r at any speed is a function of slip s, of the motor and is expressed as:

$$f_r = sf$$

If line frequency is 50 Hz. then frequency of rotor voltage at a slip of 0.02 is, $f_r = 0.02 \times 50 = 1$ Hz. From the above, it is seen that the accelerating contactors may be made to close as a function of motor speed by using some relays which would respond to the rotor voltage and rotor frequency conditions. Frequency responsive relays 1F, 2F, 3F as shown in Fig. 4.14 (a), are connected in the secondary circuit. Each relay coil is connected through a capacitor to a potentiometer resistor, which in turn is connected across one leg of the starting resistor. The inductance of each relay coil in combination with the capacitor forms a series resonant circuit, allowing a high current flow within a certain frequency range, width of the frequency range being determined by the adjustment of the resistor. Frequency control relays 1F, 2F and 3F are tuned so that they would drop at a desired frequency below their series resonant frequency. For example relay 1F is resonant (minimum impedance) at 50 Hz but drops out at 45 Hz, relay 2F is resonant at 45 Hz but drops out at 30 Hz and relay 3F is resonance at 30 Hz but drops out at 15 Hz. The starter shown in Fig. 4.14 will operate in the following manner:

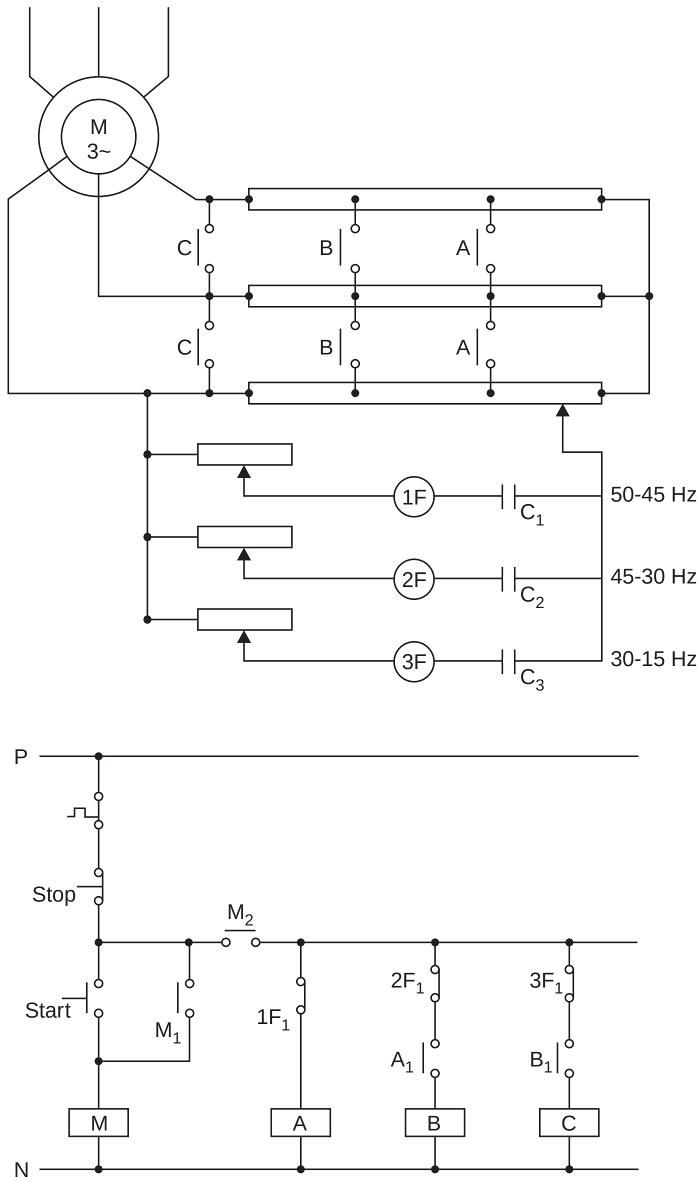


Fig. 4.14 Control circuit for a rotor frequency acceleration starter

(*i*) When the START-push button is pressed, the contactor M energises the stator and motor starts with full resistance in rotor circuit. At starting, relay $1F$ will pick up as its resonant frequency is 50 Hz. Its contact $1F_1$ opens. As the motor accelerates the rotor frequency drops. When the frequency falls to 45 Hz, the relay $1F$ drops, its contact $1F_1$ closes and energises contactor A.

(*ii*) Energisation of contactor A cuts off one set of resistance from rotor circuit and the motor accelerates further.

(*iii*) As the motor gains speed its rotor frequency falls. At 30 Hz the relay $2F$ drops and relay $3F$ picks up. As relay $2F$ drops its contact $2F_1$ closes and energises contactor B

which shorts another set of resistance. At the same time relay $3F$ picks up at 30 Hz and its (NC) contact $3F_1$ opens.

(*iv*) The motor further gains speed and its frequency decreases to 15 Hz. At this frequency relay $3F$ drops. Its NC contact $3F_1$ closes and energises contactor C through already closed contact B_1. Energisation of contactor C cuts off all the resistance from the rotor circuit and the motor accelerates to its final speed.

In this scheme, the resistance steps get cut off quickly if the motor is lightly loaded *i.e.,* if the motor gains speed quickly and thus its rotor frequency falls quickly, the respective relays would drop and the resistance steps would be cut off similarly. When the motor is heavily loaded it would gain speed slowly and the rotor frequency also would fall slowly and therefore the resistance steps would get cut off slowly.

REVIEW QUESTIONS

1. Show the effect of variation of rotor circuit resistance on torque slip characteristic of a wound rotor induction motor.

2. Draw torque speed characteristic during the period of acceleration of a slip ring induction motor.

3. Explain whether wound rotor motors with secondary control or squirrel cage motors with primary reduced voltage starting gives the higher starting torque.

4. Discuss Manual face plate starters for a slip ring induction motor.

5. Discuss working of definite time limit starter using (*a*) Individual timer (*b*) Motor driven cam timer.

6. What are flux delay relays ? How are they used for automatic acceleration of wound rotor motors ?

7. Discuss the working of current limit acceleration starter for slip ring induction motor.

8. Discuss rotor frequency acceleration starter for slip ring induction motor.

9. The rotor windings of a wound rotor induction motor are:

(*a*) Star connected and three terminals taken out

(*b*) Delta connected and three terminals taken out

(*c*) Not connected inside and all the six terminals are taken out

10. In wound rotor induction motors, when rotor reistance is increased, the starting torque:

(*a*) decreases (*b*) increases

(*c*) remains same

11. If rotor resistance of a wound rotor motor is 6 ohms and rotor resistance is 12 ohms, the maximum torque will occur at:

(*a*) starting (*b*) rated speed

(*c*) half the rated speed (*d*) one fourth the rated speed

12. In wound rotor motors as the motor accelerates the rotor frequency:

(*a*) decreases (*b*) increases

(*c*) remains same

13. The starting current of wound rotor induction motor is in the range of:

(*a*) 2.5 to 3 (*b*) 2.5 to 4

(*c*) 5 to 6 (*d*) 1 to 2 times the rated current.

5

Starters for Direct Current Motors

In this chapter brief description of different types of dc motors and their fields of applications have been given. Principles of motor acceleration have been first discussed before dealing with different types of manual and automatic starters.

5.1 TYPES OF DC MOTORS AND THEIR APPLICATIONS

DC motors are classified into three types depending on the way their field windings are excited. Field winding connections for the three types of dc motors have been shown in Fig. 5.1.

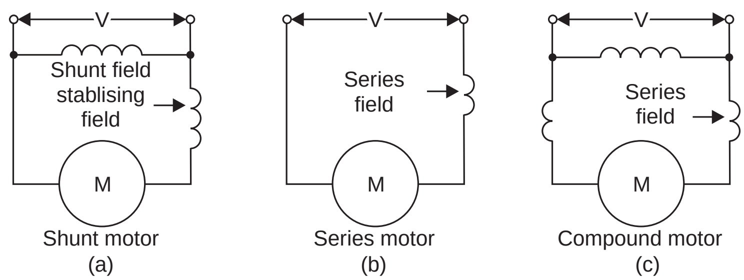


Fig. 5.1 Connections of field windings for different types of dc motors

Brief description of different types of dc motors are given as follows:

5.1.1 Shunt Motor

In this type of motor, the field winding is connected in parallel with armature as shown in Fig. 5.1(*a*). There are as many number of field coils as there are poles. When connected to supply, constant voltage appears across the field windings (as they are connected in parallel with armature). The field current is therefore constant and is independent of the load current. Shunt field winding usually are designed to have large number of turns of fine wire. Its resistance, therefore, is high enough to limit the shunt field current to about 1 to 4 percent of the rated motor current.

A shunt motor operates at nearly constant speed over its normal load range. It has a definite stable no-load speed. The motor is adaptable to large speed variations. The disadvantage of the motor is that it has low starting torque and over-load torque capability.

5.1.2 Series Motor

A series motor receives its excitation from a winding which is connected in series with the armature and carries load current. As the series field has to carry high load current, it is made of a thick wire and a few turns. As the resistance is low, the voltage drop across the series winding is small.

This motor has excellent starting and over-load torque characteristics. The disadvantages are that the motor attains dangerously high speed at no-load. Speed adjustment of the motor is somewhat difficult.

5.1.3 Compound Motor

In compound motors excitation results from combined action of both shunt field winding and series field winding. Fig. 5.1(*c*) shows the winding connections with the series field of the compound motor carrying the armature current(the long-shunt connection). In the short-shunt connection, which is sometimes used, the shunt field is directly connected in parallel with the armature, in which case, the series field current is the same as the line current. Excitation of a compound motor is a combination of series and shunt excitation. The motor, therefore, has mixed characteristic between that of a series motor and a shunt motor. This motor behaves somewhat better than a shunt motor from the point of view of starting and overload torque; and has definite stable no-load speed like a shunt motor. Speed of this motor is adjustable as easily as that of a shunt motor. It's speed, however, tends to change as much as 25 percent between full-load and no-load due to the effect of series winding.

A brief description of some special field windings used in modern motors for corrective influence upon the operation of the motor under load is given as follows.

These field windings are called corrective fields. Their purpose is to reduce the effects of armature reaction such as poor commutation, instability at high speeds, and commutator flashover under conditions of suddenly applied overloads.

Interpole windings are most widely used corrective field windings. Interpole windings are connected permanently in series with the armature circuit. This field maintains the magnetic neutral axis in the same position under all load conditions and thereby permits the motor to commutate well *i.e.,* without sparking at the brushes.

Stabilising field winding is used only in shunt motors that are made to operate at high speeds by shunt-field weakening. This a series field winding placed directly over the shunt winding whose moderate flux tends to prevent run away operation or instability that may result from the demagnetising effect of armature reaction.

Compensating winding is placed in slots or holes in the main pole faces. This winding is also connected in series with the armature circuit. This winding creates a magnetic field that tends to offset the armature reaction which acts to distort the flux-density distribution under the pole faces. If this flux distortion is left uncorrected, it would increase the probability of flashover between brushes under conditions of suddenly applied overloads.

5.2 PRINCIPLES OF DC MOTOR ACCELERATION

In any motor, whether ac or dc both motor and generator action takes place simultaneously. This would become clear when we examine how torque is produced and how the armature current gets regulated automatically depending upon varying load requirements of the motor.

In a dc motor when supply voltage is impressed at the motor terminals current flows through the armature conductors placed in the magnetic field. Interaction of magnetic field and armature conductors carrying current results in development of a force on the armature conductors. As a result the armature starts revolving (motor action). When the armature starts revolving its conductors cuts the magnetic field and an emf is generated in these conductors (generator action). This generated emf is also called counter emf as its polarity is opposite to the polarity of the applied voltage. This generated counter emf exercises a limiting effect upon the armature current and causes the motor to adjust its speed automatically to meet the varying demands of the load. Armature current in a dc motor is directly proportional to the difference between the impressed armature voltage V and the counter emf E and inversely proportional to the armature circuit resistance R_a. The equation for armature current can, therefore, be written as

$$I_A = \frac{V - E}{R_a} \quad ...(1)$$

At the instant when motor is switched on by application of voltage to motor terminals the armature is at rest and therefore the counter emf generated in armature is zero. The expression for counter emf E

$$E = K \phi ZN \quad (2)$$

where ϕ = Field flux

Z = number of conductors

N = speed in rpm

From equation (1) and (2) it can be seen that when the armature is at rest *i.e.,* when N is equal to zero, the armature current, also called inrush current, is

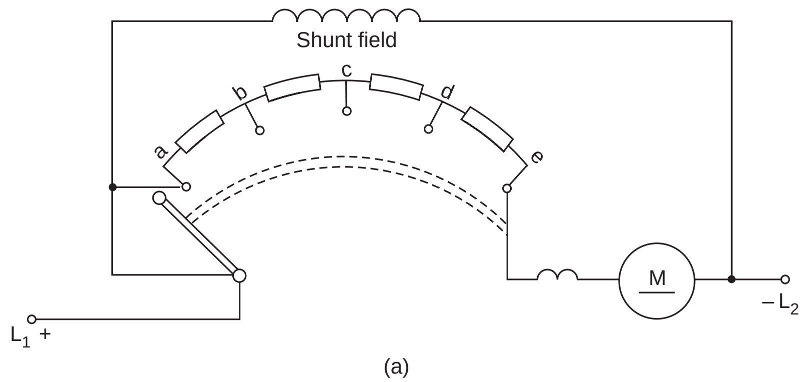
$$I_A \text{ in rush} = \frac{V}{R_a}$$

This inrush current will normally be very high as armature resistance of dc machine is generally very small. For example a 230 V, 10 hp, 500 rpm motor with full load current of 37 A has an armature resistance of about 0.4 ohms. The starting current or the inrush current for this motor is therefore equal to

$$I \text{ inrush} = \frac{230}{0.4} = 575 \text{ A}$$

As the horse-power rating of motor increases, the values of armature resistance decreases resulting in very high inrush currents. A 75 hp motor, having armature resitance of the order of 0.06 ohm will have inrush current of 3833 Amps. Actually, however, inrush current would be somewhat less than the above calculated values because the armature inductance would somewhat delay the current built up and during this time the armature would start rotating and developing some counter emf. Such high currents during starting are undesirable as they may cause damage to the commutator and result in high line voltage drops. Repeated starting and stopping of a motor may also damage the armature winding which is designed for full-load currents. If high inrush currents during starting are to be avoided an external resistance should be connected in the armature circuit of the motor. As the motor accelerates this external resistance also called as accelerating resistance may be cut out (or short-circuited) in steps. When the whole of resistance is cut off, armature of the motor gets directly connected across the line and runs at full speed. Fig. 5.2 (*a, b*) shows how external resistance can be cut off manually in steps in a manual starter and shorted by contactors in an automatic starter.

As seen from Fig. 5.2 the accelerating resistance is cut out (or short circuited) in several steps, each of which is so chosen that the maximum current or the torque peaks during acceleration are adjusted on the basis of good commutation and torque requirements of the driven mechanical load. The value of the total accelerating resistance is so selected as to permit the armature take about 125 to 175 per cent of the rated current so that the motor is capable of starting on load.



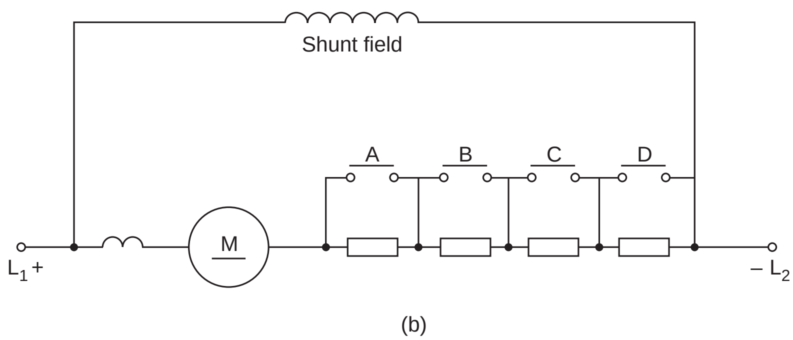


Fig. 5.2 Cutting off of armature resistance of dc shunt motor (*a*) Manually (*b*) Automatically

To further understand the behaviour of a motor during the accelerating period, it would be useful to consider the operating characteristic of a shunt motor. Fig. 5.2 (*a*) has shown a five-step manual starter (with four accelerating resistors). Assume that accelerating resistance steps have been selected such that the inrush current peaks would be limited to 1.5 I_A where I_A is the full load armature current and also that a resistance step would be cut out when current drops to I_A as the motor accelerates. At the instant the starter arm is moved to position *a*, (refer to Fig. 5.2 (*a*)) there will be an initial current inrush of 1.5I_A , the motor will then accelerate along the line *aa* as shown in Fig. 5.3 (*a*) and would theoretically continue to attain 100 per cent speed provided the mechanical load on the motor is zero. However as the motor accelerates due to the opposing induced emf in the armature, currents would drop. When current drops to I_A and the arm is moved to point *b* on the starter, the armature current will again rise to 1.5 I_A and mortor would be accelerating along curve *bb*′. At point *b*′ when motor current again falls to I_A starter arm is moved to point *C*, another step of resistance is cut off and the motor would continue to accelrate along curve *cc*′. Finally when the arm has reached the last position and all the accelerating resitance are cut off, the motor would reach its final speed and draw the normal full load current I_A. Since in a manual starter the movement of the starter handle from one position to another depends upon the skill of the operator, it would be difficult to maintain the operation according to the curve of Fig. 5.3 (*a*). However, this sequence and manner of current change and motor acceleration can be maintained in an automatic starter using four contactors *A*, *B*, *C* and *D* and suitable control circuit associated with these contactors. Several types of control schemes may be designed for this operation. The nature of variation of armature current with time during acceleration has been shown in Fig. 5.3 (*b*) which assumes that the motor would develop rated torque after each accelerating period *i.e.,* when its current falls to I_A at points t_a, t_b, t_c, t_d, and t_e.

The motor will, however, develop more than rated torque while it is accelerating between two consecutive time periods. It is seen from the graph that the time periods decrease gradually *i.e.,* $t_b - t_a > t_c - t_b > t_d - t_c > t_e - t_d$.

The speed time graph of Fig. 5.3 (*c*) shows how the motor accelerated smoothy from zero to final speed without any sudden and violent jerks. This kind of smooth acceleration is particularly desirable on certain installations. In other installations where rapid speed-up is either desirable or permissible and where high current inrushes are not objectionable, comparatively few accelerating setps may be used. Small dc motors up to 2 to 3 hp ratings and in certain special installations motors having ratings as high as 7.5 hp can be started directly from the lines without having any external resistance as high initial current in such installations are of short duration and the coupled loads are capable of withstanding sudden shock due to high torques developed.

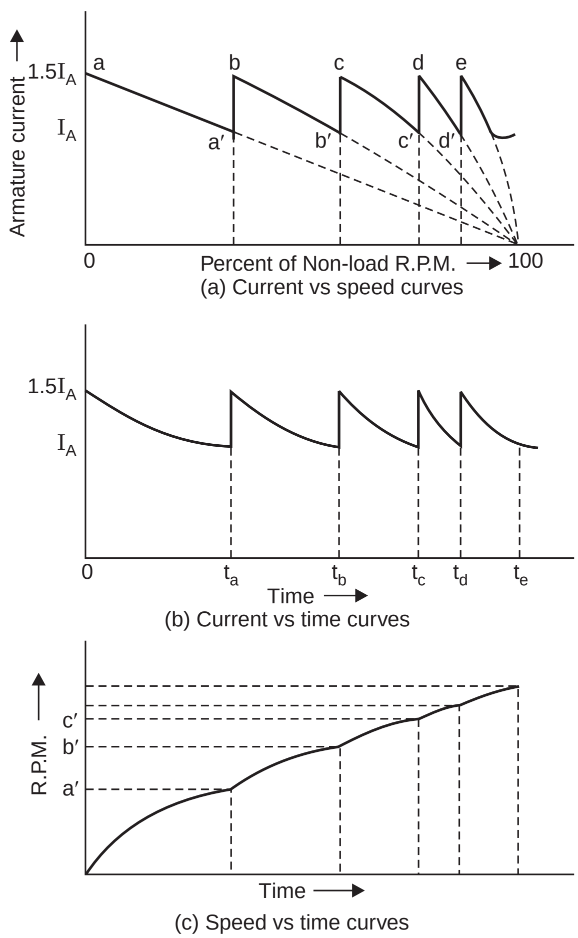


Fig. 5.3 Shunt motor acceleration

5.3 MANUAL STARTERS FOR DC MOTORS

Various types of manual face plate dc motor commonly known as two-point, three-point, four-point starters are available. These types of starters are described as follows: A degree of similarity exists among these starters. All have a face plate rotary switch with a connected group of current limiting resistors. The differences lie in the form of protection they contain.

5.3.1 Two-point Starter

A two-point starter is used for starting a dc motor which has the problem of over-speeding due to loss of load from its shaft. Such a starter is shown in Fig. 5.4.

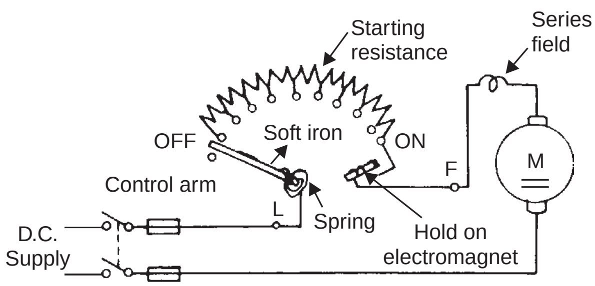


Fig. 5.4 Two-point starter for a dc series motor

Here for starting the motor, the control arm is moved clock-wise from its OFF position to the ON position against the spring tension. The control arm is held in the ON position by an electromagnet. The hold-on electromagnet is connected in series with the armature circuit. If the motor loses its load, current decreases and hence the strength of the electromagnet also decreases. The control arm returns to the OFF position due to spring tension, thus preventing the motor from overspeeding. The starter arm also returns to the OFF-position when the supply voltage decrease appreciably. L and F are the two points of the starter which are connected with the supply and motor terminals.

5.3.2 Three-point Starter

A three-point starter is used for starting a dc shunt or compound motor. The coil of the hold-on electromagnet is connected in series with the shunt-field coil. Such a starter is shown in Fig. 5.5.

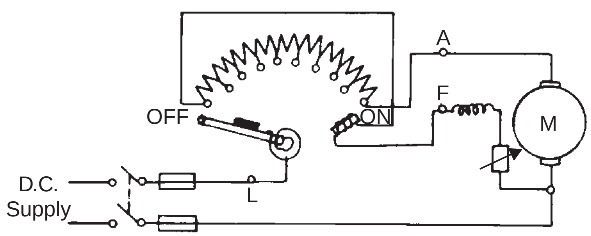


Fig. 5.5 Three-point starter for a dc shunt or compound motor

In case of disconnection in the field circuit due to internal failure or field-rheostat failure, the control arm will return to its OFF position due to spring tension. This is necessary because the shunt motor will overspeed in the same manner as the series motor if it loses its field excitation. The starter also returns to the OFF position in case of low supply voltage or complete failure of supply voltage. This protection is therefore called No Volt Release (NVR). Over-load protection for the motor can be incorporated by connecting another electromagnetic coil in series with the armature. When the motor is overloaded it draws a heavy current. This heavy current also flows through the electromagnetic coil. The electromagnet then pulls an iron piece upwards which short-circuits the coils of the hold-on electomagnet (NVR coil, see Fig. 5.6). The hold-on electromagnet gets de-energised and therfore the starter arm returns to the OFF position, thus, protecting the motor against overload. The complete circuit connection for a three-point starter with NVR and Over Load Release (OLR) is shown in Fig. 5.6. It is to be noted that points L, A, and F are the three terminals of a three-point starter. Use of a brass arc, as shown in the figure, enables connection of the field circuit directly with the supply instead of via the starter resistance.

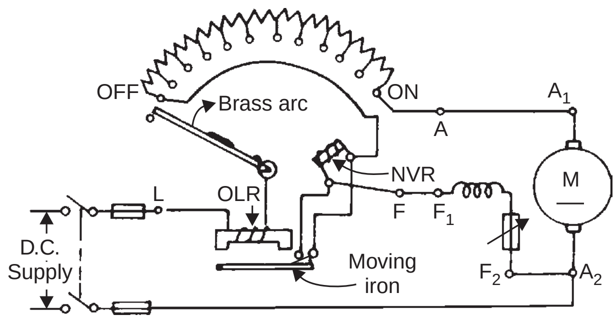


Fig. 5.6 A three-point starter with No Volt Release (NVR) and Over Load Release (OLR) arrangement

A three-point starter may not be suitable where a large field current adjustment by using a field regulator is needed. This may cause weaking of the field current to such an extent that the hold-on electromagnet may not be able to keep the starter arm in the ON position. This may therfore disconnect the motor from the supply when it is not desired. Such a problem is overcome by using a four-point starter.

5.3.3 Four-point Starter

The disadvantage of a three-point starter as mentioned above is overcome in a four-point starter by connecting the hold-on coil across the line instead of in series with the shunt-field circuit. This makes a wide range of field adjustments possible. The connection diagram for a four-point starter is shown in Fig. 5.7. In a four-point starter, therefore, when the starter arm touches the starting resistance, current from the supply is divided into three paths. One through the starting resistance and armature, one through the field circuit, and one through the NVR coil. A protective resistance is connected in series with the NVR coil. Since in a four-point starter the NVR coil is independent of the field-circuit connection, the dc motor may overspeed if for some reason there should be a break in the field circuit. It is, therefore, recommended that before starting a dc motor the field circuit be checked against an open circuit.

A dc motor should be stopped by opening the main switch rather than by throwing back manually the starting arm to the OFF position. If the starting arm is thrown back manually, the field circuit suddenly gets opened. The electromagnetic energy stored in the field gets discharged through the OFF contact button of the starter in the form of an arc, thereby gradually burning the contact. On the other hand if the motor is stopped by opening the main switch, the electormagnetic energy of the field circuit gets slowly discharged through the armature. The starting resistance used in various types of starters is cut out of the circuit in steps while starting a motor. The steps of the starting resistance are so designed that the armature current will remain within certain limits and will not change the torque developed by the motor to great extent.

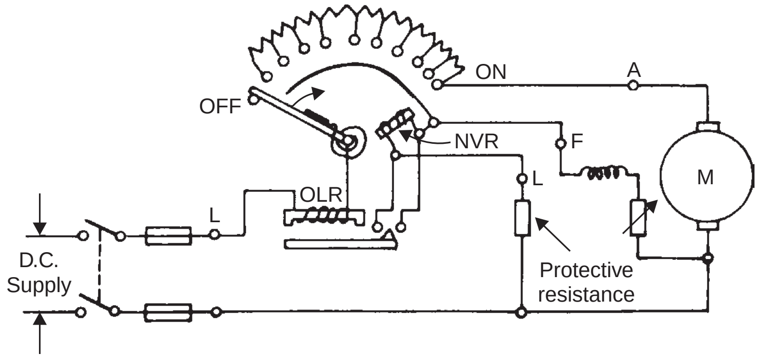


Fig. 5.7 A four-point starter with NVR and OLR arrangement

So far, face plate starters have been discussed. The same type of control as achieved with a face-plate starter can be obtained with a drum-rotary-switch starter. The durm switch has the advantage of being able to handle a large current and therefore is suitable for motors with high ratings. Current-limiting starting resistors are not part of the drum switch and they may be made as large as possible which are rated to carry current continuously. (In a conventinoal starter, the starting resistors are rated to carry current for small durations of time. This reduces the size of the resistances). As a result, the drum switch is able to control the motor continoulsy at intermediate or even at the lowest speed. Drum-rotary-switch starters are suitable for tram car-motor controls and for large crane-motor controls.

Nowadays automatic motor-control starters are also available which can be operated by pressing push-buttons. The working of such automatic starters is as follows: Upon pressing an ON push-button, current-limiting starting resistors get connected in series with the armature circuit. Then some form of automatic control progressively disconnects these resistors unit full line-voltage is available to the armature circuit. On pressing an OFF push-button the system should get back to its original position. Protective devices, such as OLR, NVR, etc. are usually the same as that of a manual starter. Automatic starter circuits are designed using electromagnetic contactors and time-delay relays.

5.4 TYPES OF STARTERS FOR AUTOMATIC ACCELERATION

From the discussions made in the earlier section it is clear that except for very small motors resistance must be connected in the armature circuit during starting period and then be cut-out (or short-circuited) progressively as the motor accelerates to the rated speed. The connection of accelerating resistors becomes necessary due to the following reasons:

(*i*) to limit the inrush current (since high current would produce arcing at the brush sliding contacts and thus damage the commutator surface).

(*ii*) to minimise line voltage drop due to excessive inrush of current; and

(*iii*) to cause smooth acceleration of the driven machinery by avoiding undue mechanical stresses due to sudden application of high torques.

There are many types of automatic starters for dc motors. They can be classified under the heading of three general methods of motor acceleration namely (*i*) Direct-on-line acceleration

(*ii*) Current limit acceleration

(*iii*) Definite time acceleration

Starters designed on the above three methods are discussed as follows:

5.4.1 Direct-on-line Starter

Small dc motors can be started directly by connecting them across the lines as the magnitude of starting current drawn is not very high. Direct-on-line starting of dc motors is similar to ac two wire or three wire control. Some dc contactors have dual windings. These two windings are known as starting winding and holding winding. During closing of a contactor when a large magnetic pull is required, both the windings are energised. When the contactor is closed a small magnetic pull is sufficient to hold the contactor closed and therefore the starting winding is disconnected and only the holding winding drawing a small amount of current is kept energised. This type of design gives a longer life to the contactor as unnecessary overheating of coils is avoided. A direct-on-line starter with dual winding contactor coils has been shown in Fig. 5.8.

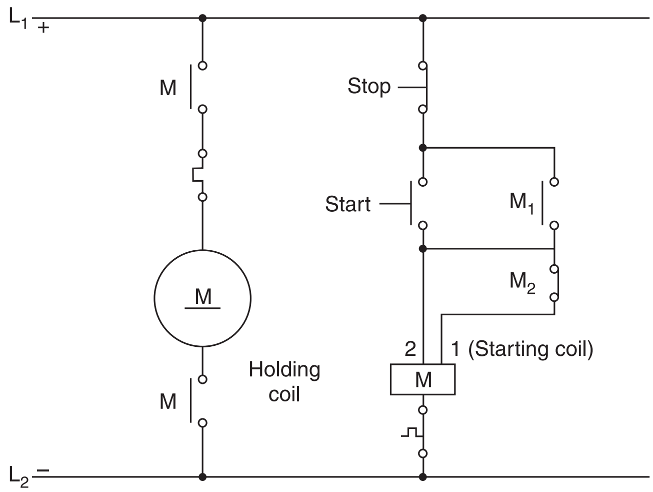


Fig. 5.8 Direct on line starter for a dc motor which uses a dual winding contactor

The armature has been shown connected directly across the lines *i.e.,* without introducing any resistance in the armature circuit. When the START-push button is pressed, both the starting coil (1) and the holding coil (2) of contactor *M* get energised by getting supply through the START-push button and the normally NC contacts M_2 of contactor *M*. As soon as the contactor closes, normally closed contact M_2 will open and disconnect the starting coil 1 while the holding coil will remain enrgised by getting supply through holding contact M_1 which has been connected in parallel with the START-push button. It may be understood that in this type of arrangement setting of NC contact M_2 has to be so adjusted that it would open up when the contactor is almost in closed position. If due to some reason M_2 fails to open the starting coil will aslo remain permanetly energised in which case the coil may get burnt due to over heating since this starting coil is not designed for continous rating.

Another method used to start a dc motor is to connect a limiting resistor in series with the contactor coil when the contactor closes. This would avoid over-heating of the coil as the limiting resistor would allow only a small current sufficient to hold contactor closed. The control circuit for such a scheme has been shown in Fig. 5.9.

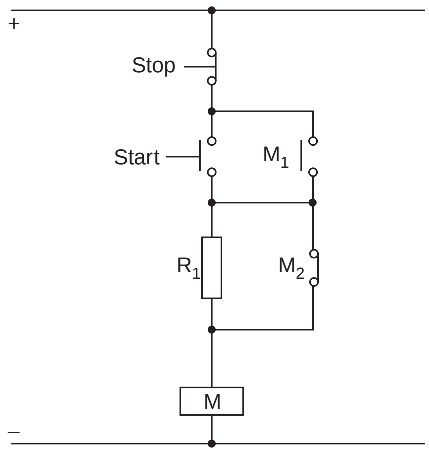


Fig. 5.9 Control circuit for direct on-line starting of a dc motor with a limiting resistor in contactor coil circuit

When the START-push button is pressed, coil *M* receives maximum current required to close contacts through normally closed (NC) contact M_2. When contactor is closed, M_2 opens and M_1 closes. Now coil remains energised through contact M_1 and resistance R_1. Thus the resistance limits the current to a value just sufficient to keep the contactor closed.

5.4.2 Current Limit Acceleration Starters

In this type of starters the load (*i.e.*, the current) will determine how rapidly a motor is to be brought to full speed. A lightly loaded motor may be brought to final speed more quickly than heavily loaded motor. This is made possible by utilizing the fact that rate of current change varies with the load. Inrush current drops faster with a lightly loaded motor and slower with a heavily loaded motor.

In these starters, a set of series or current relays pick up and drop out on changing values of armature current which occurs as the motor accelerates and these relays in turn energise contactors to successively cut out (or short-circuit) resistors from the armature circuit. Current limit starters functioning on the basis of current change are of three types, *viz* (*i*) the series relay type (*ii*) the counter emf type and (*iii*) the lockout type.

5.4.2.1 Series Relay Starter

This starter uses a dc series relay to sense changes in the armature current. The relay consists of a few turns of heavy wire and operates extremely fast as its armature is light in weight and is well balanced having a small air gap. A spring changes the contact position when current through the relay falls below the setting of the relay. Current setting of the relay can be adjusted by varying the spring tension. A series relay starter for a separately excited dc shunt motor has been shown in Fig. 5.10.

In this starter the shunt winding has been shown separately excited and the interpole winding (I.W.) has been shown connected in series with the armature. Three resistances R_1, R_2 and R_3 are also connected in series with the armature. Three series relays 1*AR*, 2*AR* and 3*AR* are also connected in the armature circuit.

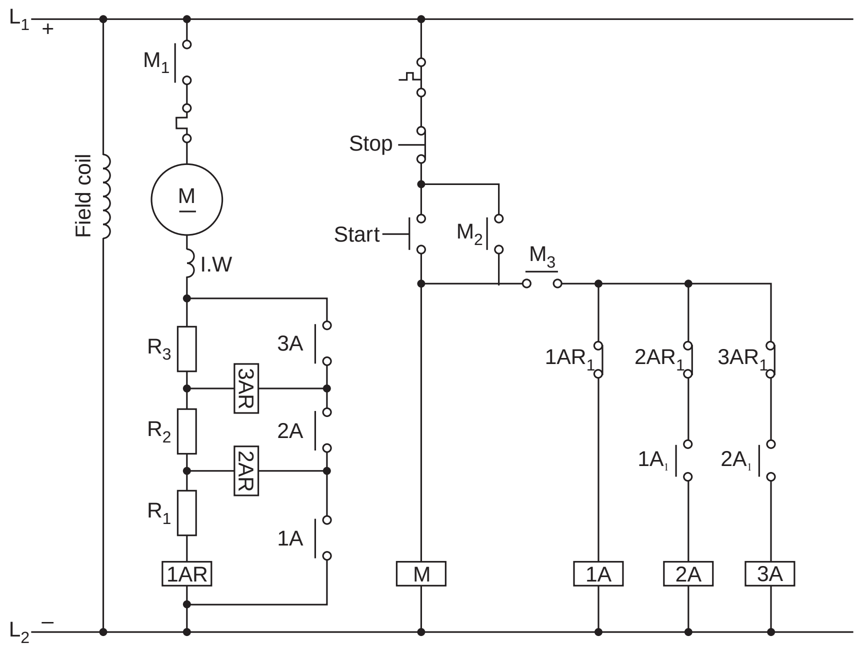


Fig. 5.10 Series relay starter circuit for separately excited dc shunt motor

Before analysing the working of the control circuit of this starter two important points regarding the series relay and the main contactor should be throughly understood and kept in mind while reading the control diagram.

(*i*) Auxiliary contacts (NO) of contactors *M*, 1*A*, 2*A* and 3*A* are set to close after some delay from the closing of their main contacts (*i.e.,* power contacts) and

(*ii*) Operation of series relay is much faster than contactors.

Now we will discuss the working of the control circuit. When the START-push button is pressed, contactor *M* gets energised and first its main contact M_1 closes. Motor starts with armature resistance R_1, R_2 and R_3. The relay 1*AR* picks up and opens its normally closed (NC) contact $1AR_1$ in coil circuit of contactor 1*A*. After the contact $1AR_1$ has opened, auxiliary contacts M_2 and M_3 of contactor *M* would close and therefore contactor 1*A* cannot close. When the motor accelerates sufficiently and the motor current drops to normal value, relay 1*A*R drops, thus closing its contact $1AR_1$ and thereby energising contactor 1*A*. Main contacts of contactor 1*A* closes and shorts resistance R_1. Now, second current inrush takes place as the motor accelerates with resistance R_2 and R_3 and series relay 2*AR* in circuit. Relay 2*AR* picks up and opens its contact $2AR_1$ before interlock contact $1A_1$ closes. As the motor accelerates further, again the armature current falls to normal and relay 2*AR* drops out and thus its contact $2AR_1$ closes and thereby energise contactor *2A*. Main contacts of 2*A* shorts resistance R_2. When resistance R_2 gets shorted a third inrush of current takes place through R_3 and relay 3*AR*.

Relay 3*AR* picks up and opens its contact $3AR_1$ before contact $2A_1$ (interlock of contactor 2*A*) closes in the coil circuit of contactor 3*A*. Finally when the armature current falls again to normal value, relay 3*AR* drops out and closes its contact $3AR_1$ and therefore contactor 3*A* gets energised. Main contact of 3*A* shorts resistance R_3. Now the armature gets connected directly to line and the motor accelerates to its final speed.

5.4.2.2 Counter emf Starter

These starters are economical and perform well for small motors up to 5 hp rating. These starters use voltage relays to cut off resistance from the armature circuit in steps. Voltage relays are voltage sensitive and they can be set to pick up at any desired voltage level. In this type of starter counter emf generated in armature is utilised to energise voltage accelerating relays. These relays are connected in parallel with the armature of the motor as shown in Fig. 5.11.

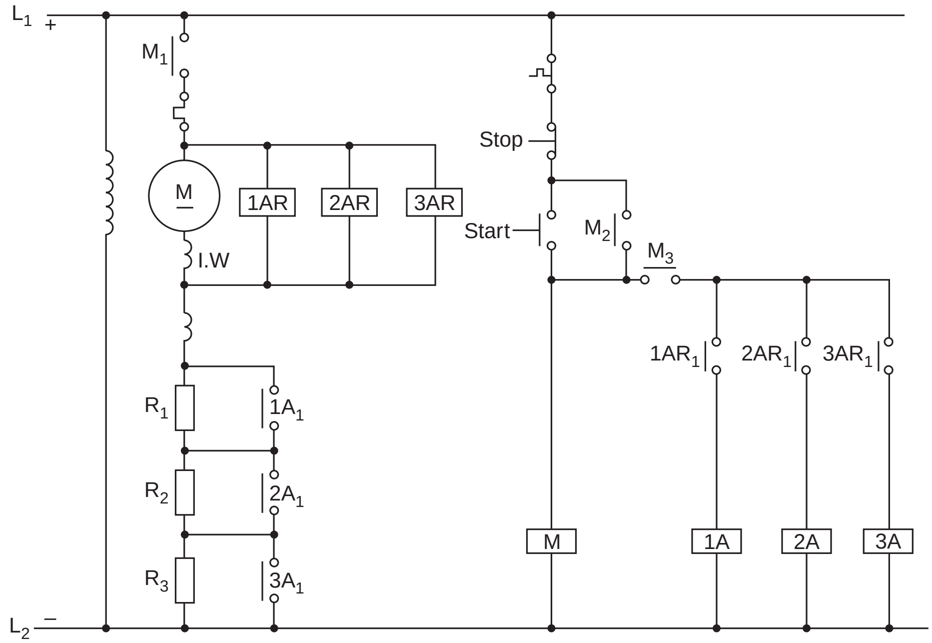


Fig. 5.11 Circuit diagram for counter emf starter for a dc motor

When motor just starts, counter emf in the armature is zero. As the motor accelerates, counter emf also starts building up. The accelerating voltage relays 1*AR*, 2*AR* and 3*AR* are set to pick up at different increasing values of emf and their contacts energise contactors 1*A*, 2*A* and 3*A* to cut off resistance R_1, R_2, R_3 from armature circuit. In the four step starter shown in Fig. 5.11, the voltage accelerating relays may be set to pick up at 50, 75 and 90 percent rated speed. The working of the control is explained as under:

When the START-push button is pressed, contacotor *M* is energised and it gets hold through its own contact M_2. Its main contact M_1 energises the armature with resistance R_1, R_2 and R_3 in the circuit. The motor accelerates and when say 50% of the normal speed is reached, emf generated causes the relay 1*AR* to pick up. Contact of 1*AR* closes to energise contactor 1*A* which shorts resistance R_1 through its main contact $1A_1$. Due to cutting of resistance R_1, the motor accelerates further and at 75% of normal speed counter emf generated makes the relay 2*AR* to pick up. When 2*AR* picks up contact $2A_1$ of contactor 2*A* closes and shorts resistance R_2. Thus the motor accelerates still further and at 90% of the normal speed, relay 3*AR* picks up and thus the third resistance R_3 is short circuited by contactor 3*A*. Now the motor gets connected directly to the lines and reaches its final speed.

5.4.2.3 Lock-out Acceleration Starter

In this starter a special type of contactor known as lock-out contactor is used. This has been explained in detail in the chapter on control components. The contactor has two coils, closing coil and lock-out coil. These coils are connected in series. The magnetic circuit of these coils are so designed that during the inrush current, lock out coil has greater pull than closing coil while at normal current the closing coil has greater pull than the lock out coil. Lock out coil has the tendency to keep the main contact open while closing coil has the tendency to close it. The starter is shown in Fig. 5.12.

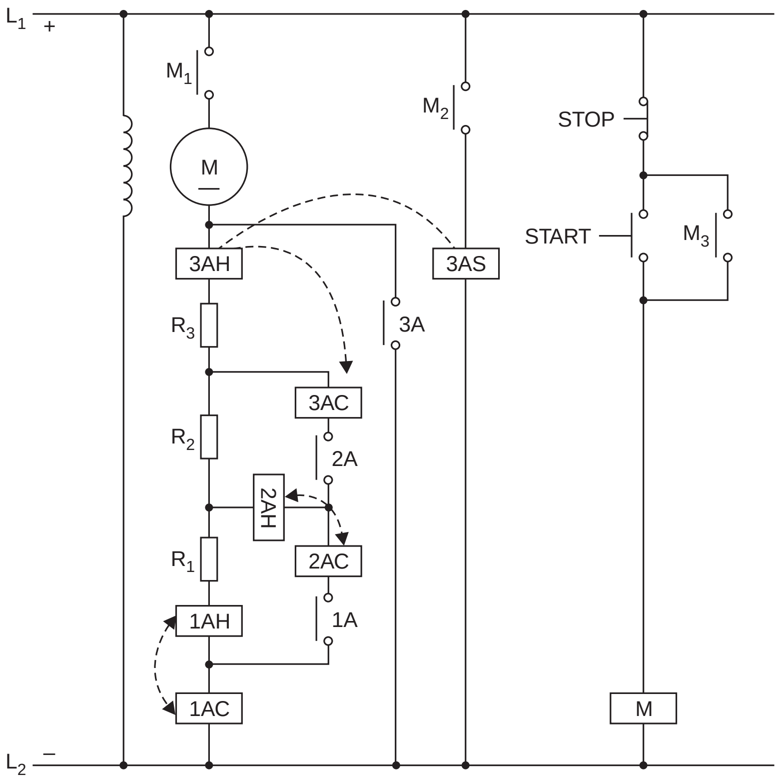


Fig. 5.12 Circuit for shunt motor starter using lock-out type contactor

As seen from Fig. 5.12, the starter has three contactors 1*A*, 2*A* and 3*A*. Each of the contactors 1*A* and 2*A* have two coils *i.e.,* 1*AH* and 1*AC* for contactor 1*A* and 2*AH*, 2*AC* for contactor 2*A*. Contactor 3*A* has three coils holding coil 3*AH*, closing coil 3*AC* and shunt coil 3*AS*. The shunt coil is also wound on the core of the closing coil. The shunt coil cannot close the contactor by itself but can hold the already closed contactor. The working of the starter is as follows:

When the START-push button is pressed, main contactor is energised and it gets hold through its auxiliary contact M_3. Main contact M_1 energises the armature of the motor. Current flows through R_1, R_2, R_3 and the contactor coils 1*AH*, 1*AC* and 3*AH*. Lock-out coil 1*AH* keeps the contactor open during current inrush. When current drops to normal value, closing coil 1*AC* closes the contact 1*A* and thus shorts resistance R_1 and lock-out coil 1*AH*. When contactor 1*A* closes another inrush current flows through R_3, R_2, 2*AH*, 2*AC* and 1*AC*. When this inrush current falls to the normal value, closing coil 2*AC* picks up and closes contact 2*A* which shorts resistance R_2 and coil 2*AH*. At this instant, another inrush current flows through 3*AH*, R_3, 3*AC*, 2*AC* and 1*AC*. Closing coil 3*AC* picks up when current falls to normal value and closes its contact 3*A*, which shorts resistance R_3 along with 3*AH*, 3*AC*, 2*AC* and 1*AC*. Contactor 3*A* is held closed through shunt coil 3*AS* which is energised directly from the lines through contact

M_2. Now the armature gets connected directly to the lines and the motor accelerates to its final speed.

5.4.3 Definite Timer Acceleration Starters

In definite time acceleration starters, resistances from the armature circuit are cut off at fixed intervals independent of the load (*i.e.,* load current). Contacts across accelerating resistors are made to close at successively longer time intervals with the help of special solenoid or motor driven timer, dashpot relays, pneumatic timers, inductive time limit contactors and others. The preset timings of the relays and timer cause the motor to operate on a given acceleration time cycle independent of the load conditions. Definite time acceleration starters are more widely used than current limit starters. This is because timed acceleration is often useful when a driven machine must always repeat the same cycle of operation in manufacturing process or in situations where several motors in a system must perform in a given timed sequence. Several of the above mentioned schemed of definite time acceleration starters are discussed as follows.

5.4.3.1 Starters Using Timers

In the conrol scheme shown in Fig. 5.13, any type of timers *i.e.,* electronic, pneumatic, or a dasphot relay timer may be used for the starter. Three such timers 1*T*, 2*T* and 3*T* have been used as shown in Fig. 5.13.

If we observe the contact connections across accelerating resistors, we will see that they differ from connections made in the earlier described starters. The advantage of using such connections is that when finally contactor 3*A* gets energised, it will short all the resistances along with R_3 and thus the other contactors 1*A*, 2*A* and timers 1*T*, 2*T*, 3*T* can be de-energised. Thus unnecessary energisation of contactors and timers is eliminated.

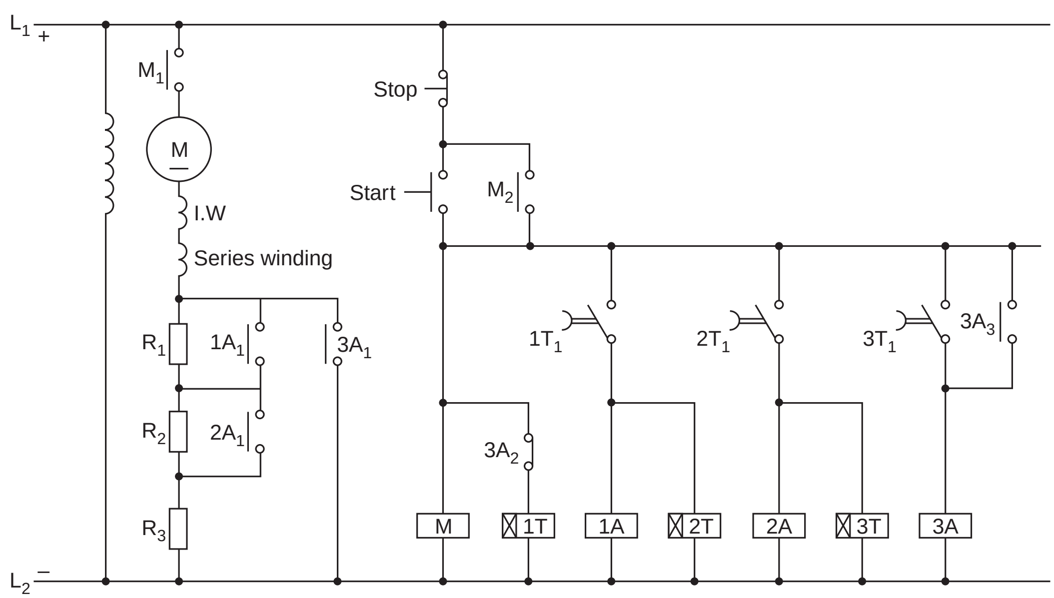


Fig. 5.13 Definite time acceleration starter using timers for a dc compound motor

When the START-push button is pressed, contactor *M* and timer 1*T* are energised and they get hold through contact M_2.Timer 1*T* gets energised with normally closed (NC) contact

$3A_2$ in series. When timer $1T$ operates after pre-set delay its delayed contact $1T_1$ closes and energies contactor $1A$. Contact $1A_1$ of contactor $1A$ closes across resistance R_1 and thereby shorts it. The motor now accelerates further with R_2 and R_3. As soon as contactor $1A$ is energised, timer $2T$, which is connected in parallel with it, also gets energised. After its pre-set delay its contact $2T_1$ closes and energies contactor $2A$ and timer $3T$. Contactor $2A$ closes its contact $2A_1$ across R_2 and therfore the motor now accelerates further with only one resistane *i.e.,* R_3. When timer $3T$ operates after its pre-set delay it closes its contact $3T_1$ and energises contactor $3A$ which gets hold through its contact $3A_3$ connected across the timer contact $3T_1$. Contactor $3A$ shorts resistance R_3 and bypasses R_1, R_2, and contacts $1A_1$ and $2A_1$. Now there is no need for keeping contactor $1A$ and $2A$ energised. This is made possible by using a normally closed contact $3A_2$ in series with the coil of timer $1T$. When contactor $3A$ is energised contact $3A_2$ opens and de-energises timer $1T$. This in turn de-energises $1A$, 2T, $2A$, $3T$ while contactor $3A$ remains energised through its own contact $3A_3$.

Another control circuit using a synchronous motor (or cam timer) which rotates a shaft that closes a set of contacts in a definite and adjustable time sequence has been shown in Fig. 5.14.

Working of this circuit is similar to the circuit given in Fig. 4.10 (*a*). The cam timer figure given in Fig. 4.10 (*b*) also applies to this circuit. The only difference is that the contactors $1A$, $2A$, $3A$ in this case get hold through their contacts $1A_1$, $2A_1$ and $3A_1$.

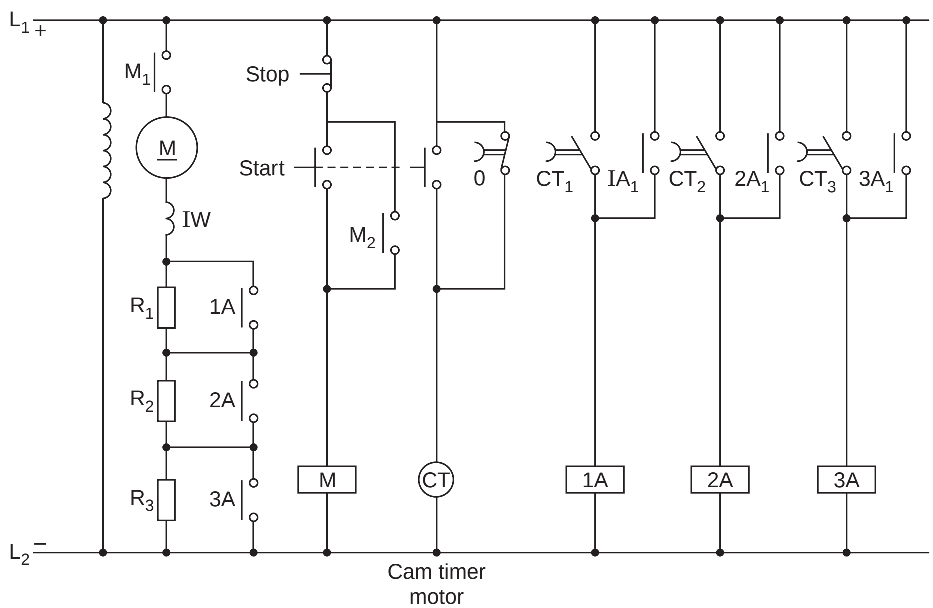


Fig. 5.14 Definite time acceleration starter using synchronous cam type timer

5.4.3.2 Starter Using Time-delay Contactors

This starter uses special contactors which opens with a time delay when its coil is de-enrgised. During energisation of the coil the contactor behaves like a normal contactor and therefore closes instantly. Timer delay during opening is provided by a special copper sleeve which is slipped directly over the core before the exciting coils are installed. During energisation the copper sleeve is electrically idle but when the coil gets disconnected from supply the copper sleeve acts like a short circuited secondary of a transformer. During this period a current flow in the copper sleeve opposes decay of core magnetism. The armature of the contactors, therefore, is released after a time delay. Time delay of such contactors is however fixed and does not depend on any adjustment. The circuit diagram, as in Fig. 5.15, shows how time delay contactors are used for dc motor acceleration. Here the normally closed contacts of the contactors are used across the accelerating resistors.

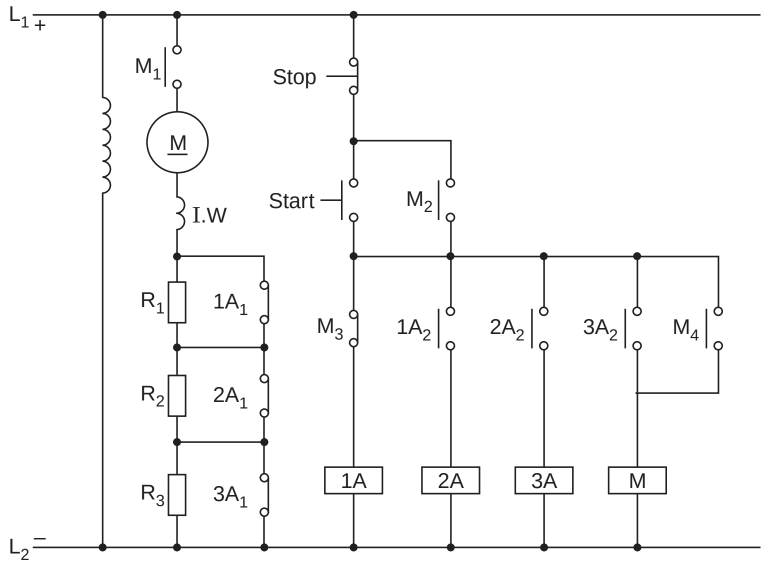


Fig. 5.15 Circuit diagram for a dc motor acceleration starter using time delay contractors

In this starter, during starting the START-push button has to be kept pressed till contactors 1*A*, 2*A*, 3*A* and *M* pick up. First, contactor 1*A* picks up through normally closed contact M_3 and subsequently interlock contact of 1*A*, 2*A* and 3*A* energies respectively contactors 2*A*, 3*A* and contactor *M*. Contactor *M* gets hold through its contact M_4 . Energisation of 1*A*, 2*A* and 3*A* causes opening of $1A_1$, $2A_1$ and $3A_1$ respectively which are connected across resistance R_1, R_2 and R_3.

When contactor *M* is energised, the motor starts with R_1, R_2 and R_3 in its circuit. With the energisation of contactor *M* contact M_3 opens and de-energises 1*A*. However, it drops only after a fixed time delay when it closes its contact $1A_1$ across R_1 and shorts it. Motor accelerates further. As soon as 1*A* drops, its another contactor $1A_2$ opens and de-energises contactor 2*A*. Its contact $2A_1$ closes after a fixed delay and shorts resistance R_2, and at the same time contactor 3*A* gets de-energised because of opening of contact $2A_2$. When contactor 3*A* drops it shorts resistors R_3. Contactor *M* does not drop due to opening of contact $3A_2$, as it remains energised through its own contact M_4. When the STOP-button is pressed contactor *M* gets de-energised and the motor comes to standstill due to opening of main contact M_1.

5.4.3.3 Starters Using Inductive Time Limit Contactors

An inductive time limit contactor is similar in construction to that of a lock-out contactor. It also has two coils whose mmfs simultaneously act on a pivoted armature. Holding coil tends to oppose pick up while the closing coil attempts to pull the armature. The holding coil, whose magnetic circuit is of iron, can prevent pick-up due to the closing coil, even when it is excited at about 1 per cent of the line voltage. As the holding coil is highly inductive its flux decays slowly when it is short circuited. Air gap between the coil plunger and armature is also extremely small. The closing coil, on the other hand has a large air gap. With the line voltage applied across it, the closing coil cannot cause the contactor to pick up when the holding coil is carrying current. It picks up only when the holding coil is shorted and its flux decays to zero. Fig. 5.16 shows the circuit in which three inductive time-limit contactors have been used to provide time delays for short-circuiting the accelerating resistors.

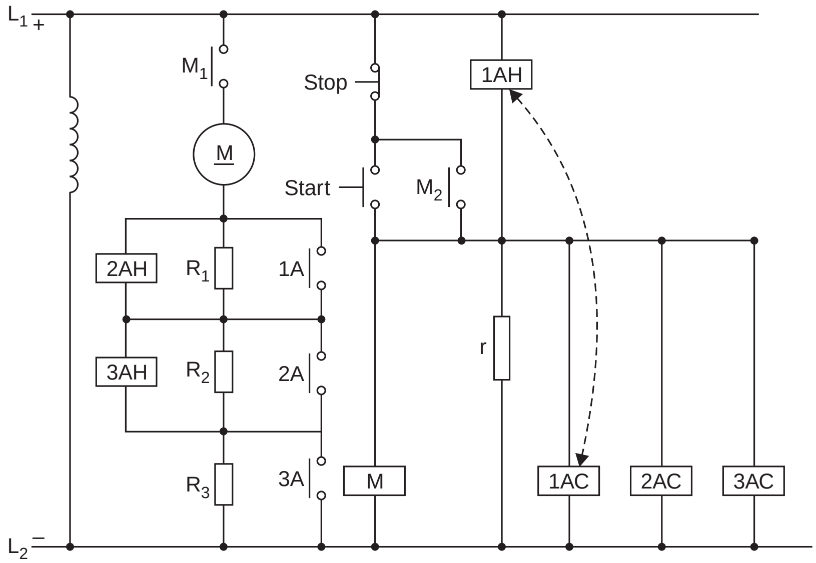


Fig. 5.16 Circuit diagram for a dc motor acceleration starter using inductive time limit contactors

When the line switch is closed, the holding coil 1*AH* is energised, its current being limited by a resistance *r*. Thus the closing coil of 1*AC* cannot pick up and therefore its contact 1*A* across R_1 remains open. When the START-push button is pressed, contactor *M* gets energised and its contact M_1 energises the motor armature with resistance R_1, R_2 and R_3 in series. Voltage drop across R_1 and R_2 also sends current through holding coils 2*AH* and 3*AH*. Thus, contactors 2*A* and 3*A* cannot close even though full line voltage appears across their closing coil 2*AC* and 3*AC* through contact M_2. It may be noticed that as soon as M_2 closes, holding coil 1*AH* of contactor 1*A* gets short circuited. Its current decays to zero within a fixed time. When current in holding coil becomes zero, closing coil 1*AC* picks up to operate the relay contacts. Resistance R_1 gets short circuited due to closing of contact 1*A* across R_1. Simultaneously holding coil 2*AH* of contactor 2*A* gets short circuited. Its current decays to zero after some fixed time and therfore 2*AC* picks up and short resistance R_2 and coil 3*AH* by closing contact 2*A*. When current through 3*AH* decays to zero closing coil 3*AC* of contactor 3*A* picks up and closes its contact 3*A* and short resistance R_3. Armature of the motor now gets connected directly across the lines and the motor attains the final speed.

5.5 REVERSING OF DC MOTORS

The direction of rotation of dc motor can be reversed in either of the two ways:

(*i*) Reversing current through the armature and the interpole windings (if they exist)

(*ii*) Reversing current through the field windings *i.e.,* through shunt and or series windings but not through the interpole windings (if they exist).

Reversing current through the armature is preferred because reversing current through the field windings involves breaking and making highly inductive current of the field windings.

Also field reversal of compound motor requires connections of both shunt and series windings to be changed. In this section only the armature reversal method will be discussed. The basic motor connections for reversal of armature current has been shown in Fig. 5.17.

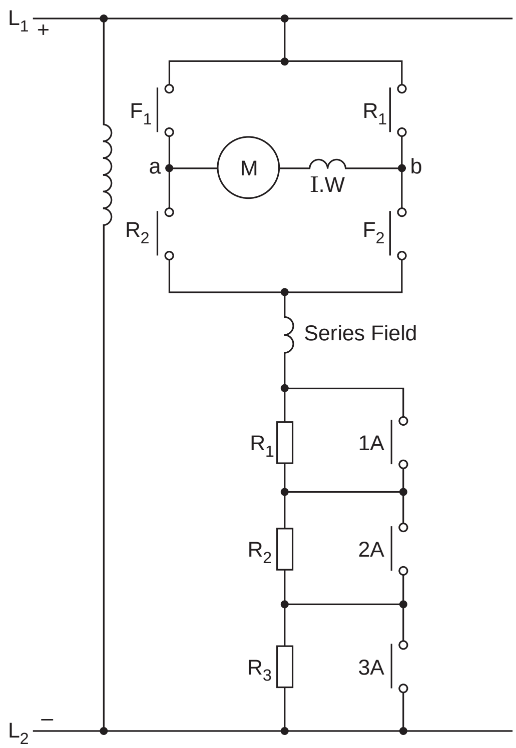


Fig. 5.17 Circuit diagram for reversal of direction of rotation of a dc motor by armature current reversal

In this circuit when forward contactor contacts F_1 and F_2 close, current through the armature flows from a to b and the motor rotates in forward direction. When the motor is to be rotated in reverse direction, forward contactor should get de-energised while the reverse contactor should get energised so that contact R_1 and R_2 close and thereby current through the armature windings flow in the reverse direction *i.e.,* from b to a. In both the above cases, however, current through the series field winding flows in the same direction. The forward and reverse contactor should not get energised simultaneously when the motor is running normally with all the armature resistance out of circuit, as it will cause dead short circuit of power lines and also of the counter emf generated in the armature winding. One method of avoiding this undesired possibility is to interlock both the contactors mechanically. However, more frequently electrical interlocks are provided in the control circuit thereby making it impossible for one contactor to pick up while the other is energised. For double safety sometimes both mechanical and electrical interlocking of contactors is done. A control circuit for direct reversing of dc motor has been shown in Fig. 5.18. Forward and Reverse-push buttons are shown to have back and front contacts.

When the Forward-push button is pressed supply to forward contactor coil reaches through back contact of Reverse-push button and normally close (NC) contact of contactor R. If the motor is to be directly reversed, the Reverse-push button is pressed, its back contact opens and de-energises contactor F. De-energisation of contactor F leads to closing of contact F_2 in the coil circuit of contactor R. Contactor R thus gets energised through front contact of REV-push button and back contact of FOR-push button and normally closed (NC) contact F_2. If the motor is to be brought to rest the STOP-bush button has to be pressed.

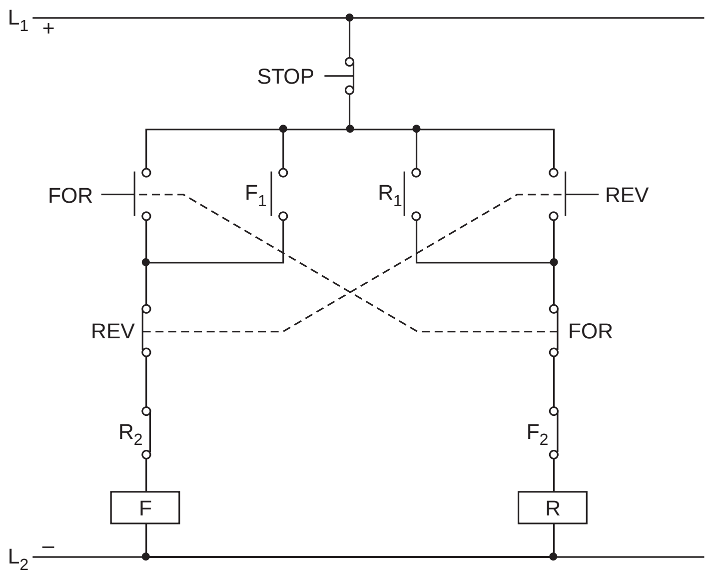


Fig. 5.18 Control circuit for direct reversing of dc motor

In some applications it may be necessary to stop the motor first before it can be run in the reverse direction. This can be accomplished by using a timer relay and zero speed plugging switches. Here, control circuit using an OFF-delay timer for this purpose has been discussed. The control diagram has been shown in Fig. 5.19.

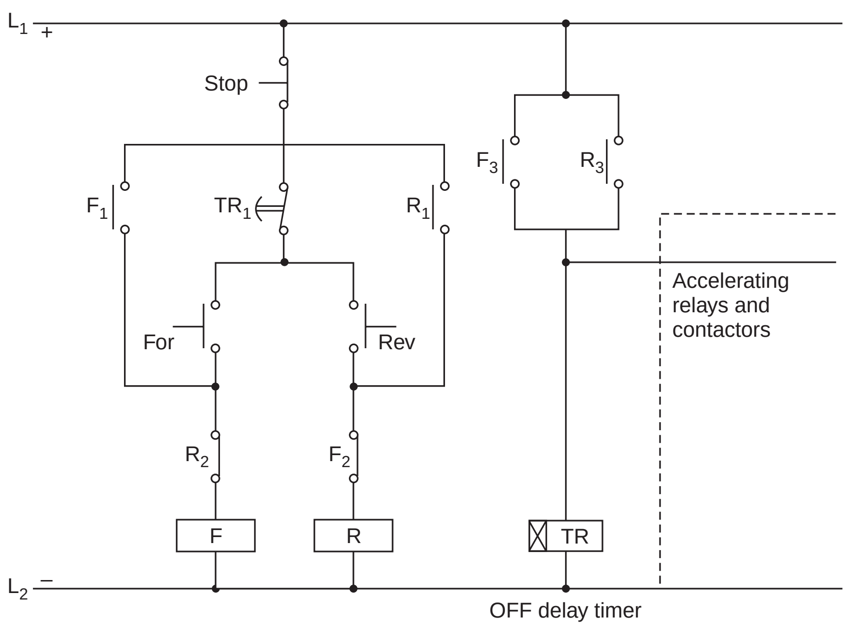


Fig. 5.19 Control circuit for forward-stop-reverse operation of a dc motor using OFF-delay timer

When FOR-push button is pressed contactor *F* gets energised and the motor runs in the forward direction. Its contact F_3 energises the OFF-delay timer *TR* which opens its contact TR_1 immediately. At the same time contact F_3 also energises the accelerating relays and timers which cut off acceleration resistors from the armature circuit of the motor (refer Fig. 5.19). Opening of contact TR_1 makes both FOR and REV-push buttons inoperative thus making it impossible to change the direction of rotation of the motor. When the motor direction is to be reversed, first the STOP- push button is pressed, which de-energises contactor *F*. Timer *TR* is also de-energised due to opening of contact F_3. After pre-set delay from de-energisation of timer *TR* its contact TR_1 will close. This implies that REV-bush button becomes operative only after a pre-set delay from the instant of pressing the STOP-button. Thus forward to reverse operation becomes possible only when the motor comes to stop first.

5.6 JOGGING OPERATION OF MOTOR

The common usage of the word 'Jogging' in our daily life is for slow running. 'Jogging' or 'inching' of a motor also implies the same *i.e.,* to have small movements of the driven machine. In jogging, starting and stopping of a motor is under the direct control of the operator. The primary objective of jogging is generally, to move tools, equipment or processed material into position very slowly. A typical example of jogging is a small portable crane which is moved in small incremental steps to position certain material on a processing line in an industry.

In jogging operation, motors are expected to run at slow speed. Therefore, the jogging control circuits are designed to prevent accelerating resistors from being cut out from the armature circuit. This means when the JOG-push button is pressed, the accelerating contactors do not pick up and therefore the whole of the accelerating resistance remains in the circuit. High resistance in the armature circuit limits the speed of the motor to a low value. A simple control circuit that provides for jogging in one direction only has been shown in Fig. 5.20.

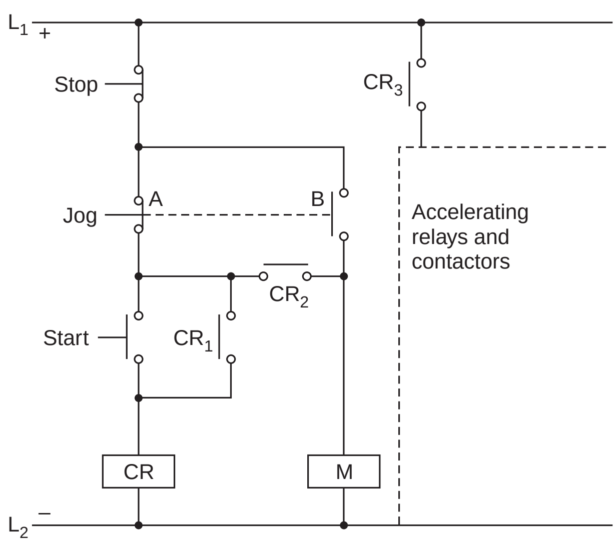


Fig. 5.20 Control circuit for jogging of a dc motor in one direction of rotation

In the above control circuit, when JOG-push button is pressed, the contact *A* opens while contact *B* closes. Contactor *M* is energised due to closing of contact *B* and makes the motor run with all the accelerating resistors in the armature circuit (refer Fig. 5.20). Due to presence of high resistance in the armature circuit the motor runs at a slow speed. Accelerating relays and the contactor circuit are not energised during this operation thus making the motor run at slow speed till such time the JOG-push button is held pressed. When normal operation of motor is required the START-push button is pressed. The control relay *CR* gets energised and is held through its own contact CR_1. Contactor *M* also gets energised and is held through contact CR_2 . Accelerating relays and contactor circuit also gets energised through closing contact CR_3. Accelerating relays and contactors as discussed earlier will cut off the accelerating resistances in the armature circuit step by step and the motor would attain its final speed. The control circuit diagram, Fig. 5.21, shows how a dc motor can be jogged and also operated normally in both the directions of rotation.

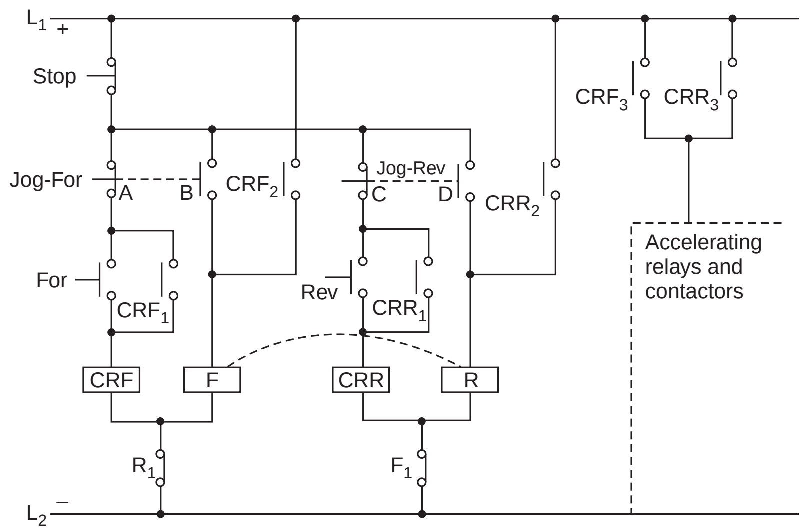


Fig. 5.21 Control circuit for jogging a dc motor in both the directions of rotation

Operation of this circuit is similar to that of the circuit meant for jogging in one direction of rotation only. Forward and reverse contactors are interlocked both mechanically and electrically. When the JOG-FOR or JOG-REV button is pressed the corresponding contactor *F* or *R* is energised due to closing of contact *B* or *D*. Contactor *F* or *R* does not get hold as control relay *CRF* or *CRR* does not get energised. Accelerating relay and the contactor circuit also do not get energised causing the motor to run with all the accelerating resistors in the circuit at a slow speed. For normal running, push button FOR or REV is to be pressed. This will energise either the forward control relay, *CRF* or the reverse control relay *CRR*. The respective relays will remain energised by getting supply through their own contact CRF_1 or CRR_1. Forward or reverse contactor will also get held throuh contact CRF_2 or CRR_2. The accelerating relay and the contactor circuit would also get energised and will be held through either contact CRF_3, or contact CRR_3 .

5.7 DYNAMIC BREAKING OF MOTOR

The principle of dynamic breaking involves utilization of generator action of a motor to bring it to rest quickly. In this method of breaking, the armature terminals are disconnected from the main supply and immediately transferred across a resistor while the field winding is kept energised. Quick stop through dynamic breaking may be explained in following two ways:

(*i*) When the motor armature having counter emf induced in it is disconnected from the supply and is connected across a resistor the counter cemf sends reverse current through the armature. This causes the motor to slow down due to reverse torque developed. Reverse torque is developed due to interaction of field flux and the reverse current flowing through the armature.

(*ii*) When the motor is disconnected from the supply and is connected across a resistor the counter emf sends current through the resistor which is converted into I^2R heat loss. Thus mechanical energy of the rotor is dissipated as heat energy in the resistance. The rapidity with which this energy can be dissipated determines how quickly the motor can be stopped. If a low value resistor is used the motor comes to stop quickly. Control circuit for dynamic breaking of a dc shunt motor has been shown in Fig. 5.22.

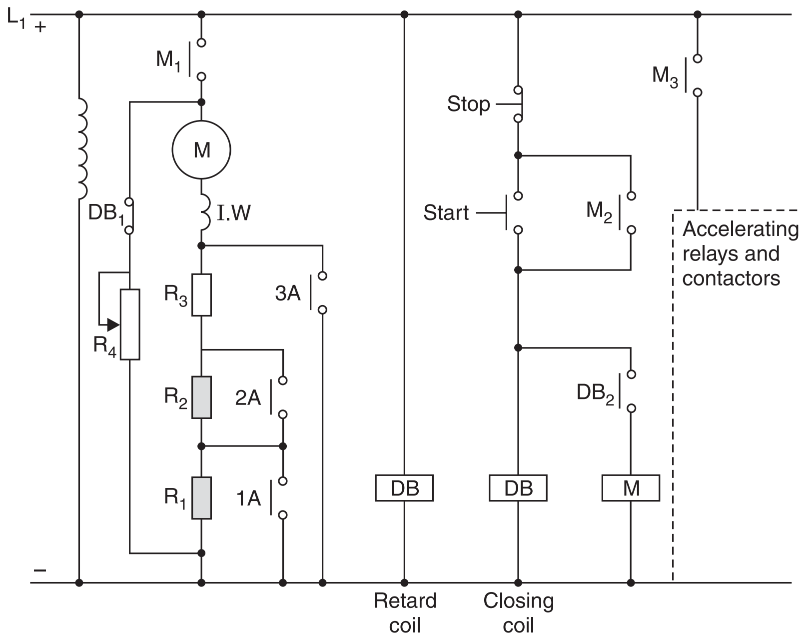


Fig. 5.22 Control circuit for dynamic breaking of dc shunt motor

In this circuit dynamic breaking resistor R_4 is connected across the armature through normally close (NC) conctact DB_1 of the dynamic breaking contactor. This dynamic breaking contactor *DB* is a special contactor having two coils *i.e.,* a retard coil and closing coil. The retard coil exerts an opposite pull on the armature to that exerted by the closing coil. In this circuit the retard coil is kept permanently energised. When the closing coil is energised contactor *DB* closes after a time delay as there is a pull by the retarding coil in the opposite direction. It must be understood clearly here that this delay in closing of the contactor has no effect on the staring operation. However, when the closing coil of contactor *DB* is de-energised by pressing the STOP-push button it opens very fast due to the pull exerted by the retard coil *DB*, which is always energised. Thus the contact DB_1 which is meant for breaking closes with a snap action thereby causing breaking action to start immediately. It is therefore seen that the function of providing retard coil is for achieving a quick stop and it has no specific function during starting of the motor. A brief description for the control circuit is as follows:

When the START-push button is pressed the contactor *DB* is energised first and then the main contactor *M* gets energised through its contact DB_2. Both the contactors are held through contact M_2. Accelerating relays of contactor circuit are energised through closing of contact M_3. Resistances from the armature circuit are cut out in steps by contactors 1*A*, 2*A* and 3*A*. When the STOP-push button is pressed, closing coil of *DB* and contactor *M* are de-energised. Contactor *DB* opens very fast as the retard coil is already energised. Its contact DB_1 closes with a snap action and the armature gets connected across resistances R_4, R_1, R_2 and R_3. The electrical energy of the armature is thus dissipated in resistor R_4, R_1, R_2 and R_3 and the motor comes to stop quickly. If the value of resistance R_4 is decreased the motor can be brought to stop more quickly.

5.8 PLUGGING CIRCUIT FOR DC MOTOR

Plugging or plug stopping of a motor means bringing the motor to standstill quickly by applying reverse torque on the armature. Plugging of a dc motor is done by reversing the supply to the armature while the motor is still running. This develops a counter-torque and motor slows down quickly. When the motor reaches zero speed and tends to reverse, supply to the motor is disconnected by a zero speed plugging switch which opens on zero speed. As during plugging the impressed supply voltage and counter emf in the armature adds up, a plugging resistance is inserted in the armature circuit to avoid excessive current flow.

Plugging is not only used to bring a motor to stop but is also used in drives where quick reversal of drive is required, such as, in cranes and in rolling mills. In a crane plugging is done with the help of master controllers. This is done by moving the handle from full speed forward position to full-speed reverse position or vice-versa. Plugging circuit for a non-reversing shunt motor has been shown in Fig. 5.23.

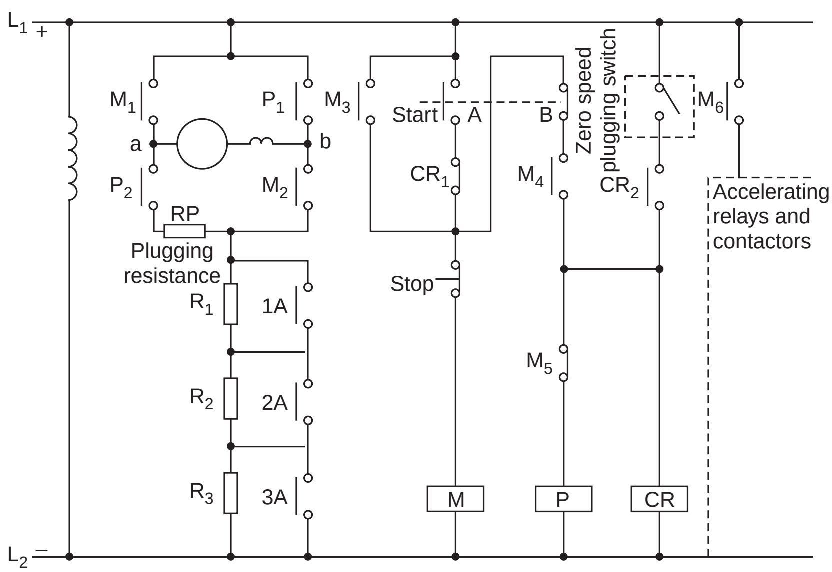


Fig. 5.23 Circuit for plugging to stop a non-reversing shunt motor with a zero speed plugging switch

In this circuit, when the START-push button is pressed, its contact *A* closes and contact *B* opens. Contactor *M* thus gets energised and is held through its contact M_3. When the START-push button is released, contact *B* closes and relay *CR* also gets energised through closed contact M_4. Contactor *P* cannot get energised as M_5 is open. As soon as contactor *M* gets energised its main contacts M_1 and M_2 energise the motor armature with accelrating resistors in the circuit.

Contact M_6 energises the accelerating relays and the contactor circuit. The motor comes to its final speed when all the resistances are successively cut out by accelerating contactors 1*A*, 2*A* and 3*A* respectively. The zero speed plugging switch closes as soon as the motor starts rotating. Control relay *CR* is held through the zero-speed switch and its already closed contact CR_2. Another contact of *CR*, *i.e.,* CR_1 opens and makes the START-push button ineffective till the motor comes to rest. This interlocking prevents simultaneous energisation of contactors *M* and *P*.

When the STOP-push button is pressed, contactor *M* is de-energised and therefore contacts M_1, M_2, M_3, M_4 and M_6 open. The armature gets disconnected from the supply and the accelerating contactors 1*A*, 2*A*, 3*A* also open. Normally closed contact M_5 closes and contactor *P* gets energised. The armature of the motor gets energised through contacts P_1 and P_2 with plugging resistance R_P and accelerating resistors R_1, R_2 and R_3 in the circuit. A reverse torque is developed and the motor comes to zero speed quickly. As the motor reaches zero speed and tends to rotate in the reverse direction, the zero speed switch opens and de-energises relay *CR*. Contactor *P* also gets de-energised due to opening of control contact CR_2. Contacts P_1 and P_2 opens to disconnect the motor from the supply. Control circuit diagram for plugging a reversing motor from either direction of rotation has been shown in Fig. 5.24. In this circuit a zero speed plugging switch with two normally open (NO) contactors has been used. Both the contacts are open at zero speed. The FOR-contact closes when the motor rotates in forward direction while a REV-contact closes when the motor rotates in the reverse direction. Push button interlocking as also auxiliary contact interlocking have been provided between forward and reverse direction of rotation. A plugging resistance R_p which is connected in series with the armature remains shorted through contact P_1 of contactor *P* during normal forward and reverse operation of the motor. This resistance comes into circuit only during plugging operation.

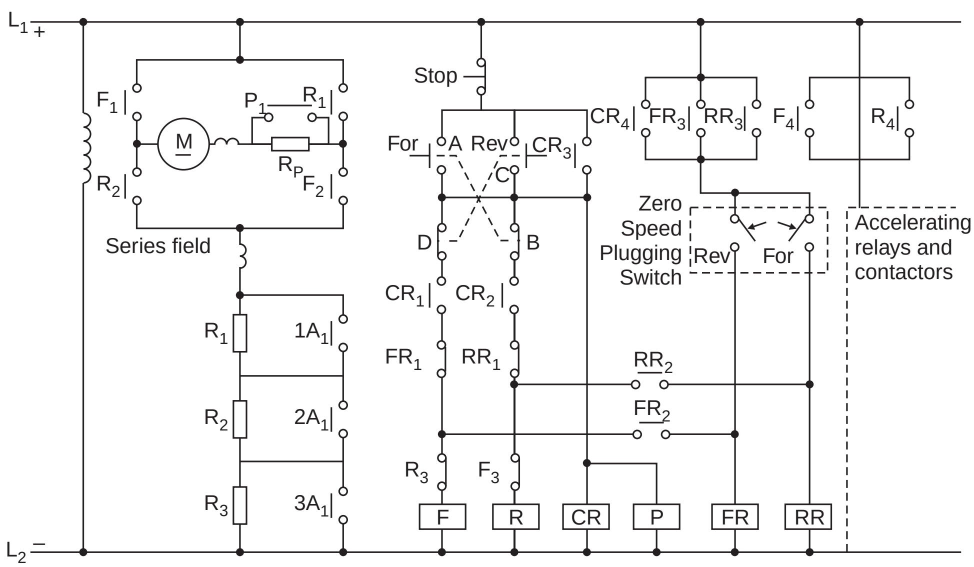


Fig. 5.24 Circuit for plugging a reversing motor from either direction of rotation

To study the operation of the circuit let us assume that the FOR-push button is pressed. Contactor *P* and relay *CR* are energised and gets hold through contact CR_3. Then contactor *F* is also energised and is held through contacts CR_3 and CR_1. Closing of main contacts F_1 and F_2 causes the motor to run in forward direction while closing of contact F_4 helps energise accelerating relays and the contactor circuit and as a result the resistances are cut off in steps. Plugging resistance R_p remains bypassed through contact P_1. When the motor accelerates in the forward direction, relay *RR* gets energised through contact CR_4 and contact FOR of the plugging switch. Relay *RR* gets held through its contact RR_3. Closing of contact RR_2 of this relay prepared the circuit for plugging operation. Now let us see what happens when the STOP-push button is pressed. Contactor *F*, *P* and relay *CR* get de-energised. Due to de-energisation of *F* its contact F_3 closes. Reverse contactor *R* gets energised through contacts RR_3, for-plugging switch contact, and contacts RR_2 and F_3. Energisation of contactor *R* causes the motor to run in the reverse direction with plugging resistance R_p and the acceleration resistors in the armature circuit (as P_1 is open).

When the motor comes to standstill, FOR plugging switch contact open thus de-energising relay *RR*. Due to opening of contact RR_2, the reverse contactor, *R* also gets de-energised. Now, the operation for reverse running and plugging of this circuit can be explained in a similar way as already done for forward running and plugging operation.

REVIEW QUESTIONS

1. Discuss different types of corrective windings used in dc motors.

2. Discuss principle of acceleration of dc motors and draw armature current versus speed and time curves. Also draw speed versus time curves for a shunt motor.

3. Explain the working of four point manual face plate starter for dc shunt or compound motor.

4. Explain the meaning of current limit acceleration. Explain working of series relay starter.

5. Discuss counter emf starter for dc shunt motor.

6. Explain the working principle of lock out contactor with the help of a diagram.

7. Discuss the working of lock out contactor for a dc shunt motor.

8. Explain a definite time limit starter.

9. Explain the method of starting of dc shunt motor using inductive time limit contactors.

10. What is the basic requirement of a reversing starter? Draw fundamental power and control circuit for reversal of a dc shunt motor.

11. Draw control diagram for forward-stop-reverse operation of a dc motor using an OFF-delay timer.

12. Explain the meaning of jogging / inching operation of a motor. Draw control circuit for jogging a dc motor in both the directions of rotation.

13. How is dynamic braking achieved in dc motors?

14. What is plugging? Draw control diagram for plugging a non-reversing shunt motor using a zero speed plugging switch.

15. Can a timer be used for the plugging circuit of a dc motor?

16. Draw control circuit for plugging circuit of a dc compound motor from either direction of rotation.

17. Direction of a dc motor can be reversed by:

(*a*) reversing the supply voltage

(*b*) reversing current through field winding only

(*c*) reversing current through armature winding only

(*d*) reversing current through both field winding and armature winding.

18. Dynamic braking for a dc motor is accomplished by

(*a*) connecting ac voltage to the armature

(*b*) maintaining dc current flow through the armature and connecting a load resistor to the field

(*c*) maintaining dc current flow through the field and connecting the armature to a load resistor

(*d*) disconnecting dc power from the motor and reconnecting the armature to a load resistor.

6

Control of Single Phase Motors

6.1 TYPES OF SINGLE PHASE MOTORS

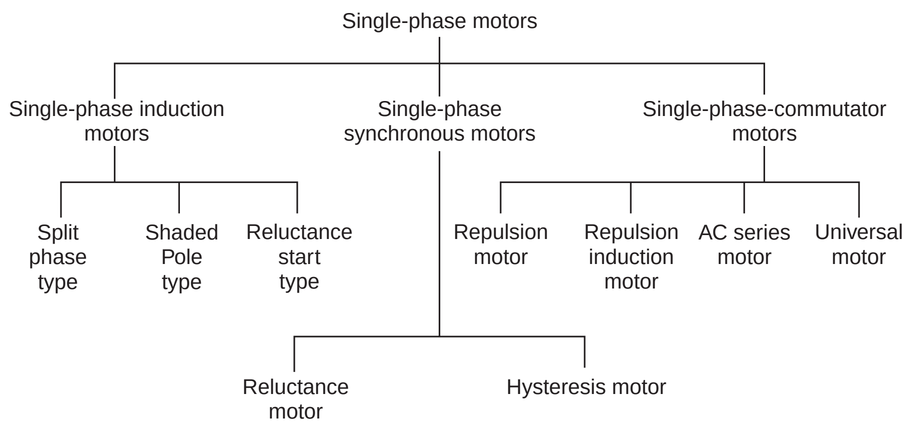
Single phase motors are manufactured in fractional kilowatt range to be operated on single phase supply and for use in numerous applications like ceiling fans, refrigerators, food mixers, hair driers, portable drills, vacuum cleaners, washing machines, sewing machines, electric shavers, office machinery etc. Single phase motors are manufactured in different types to meet the requirements of various applications. Single phase motors are classified on the basis of their construction and starting methods employed. The main types of single phase motors are :

(*a*) Induction motors

(*b*) Synchronous motors

(*c*) Commutator motors

The various types of motors under each class are shown as under:



It is assumed here that the reader has already studied the construction and working principle of all these motors. For review the reader may refer to any standard book on 'Electrical machines'.

Repulsion, repulsion induction and reluctance start motors are not used these days, they have been largely replaced by split phase motors with special capacitors which can be designed to perform equally well as repulsion types. In addition they offer such advantages as lower cost and trouble free service.

Shaded pole motors are extremely popular motors used in low-starting torque applications. Split phase motors are widely used and are designed in several ways to develop different values of starting torque.

Universal series motor is another very popular type of motor which can operate on both ac and dc supply. They generally run at high speed and employ special design features to reduce commutation and armature reaction difficulties on ac supply.

Synchronous motors such as reluctance motor and hysteresis motor operate at synchronous speed for all values of load. They are manufactured in very smal ratings. Practically all single phase motors are designed for line voltage starting and take inrush currents that may be little more than the rated values in some types and six or more times as much in others. Like polyphase motors they are also frequently jogged, plugged, reversed, dynamically braked and plug reversed. When the above mentioned operations are done, contactors of larger ratings than normal are used, as their frequent operations cause overheating and excessive wear of contacts. Control circuits of single phase motors are however simple as few contactors and relays are used.

6.2 UNIVERSAL SERIES MOTORS

The construction and principle of working of a universal series motor are similar to a dc series motor. To enable the motor to work satisfactorily on ac supply also, some modifications are required in its construction. The important modification required are :

(*i*) Field structure should be completely laminated to avoid losses due to eddy currents:

(*ii*) To combat effects of armature reaction and resulting poor commutation the armature is to be designed to have lower voltage gradient between adjacent commutator segments than in an equivalent dc motor;

(*iii*) Poor commutation with ac (due to emf induced by the alternating main field flux in a coil undergoing commutation) is improved by using distributed field windings and compensating field windings that are placed in a slotted stator core. When a universal motor is used with ac supply the armature reactance drop exerts a speed lowering effect with increased loading. At the same time at increased loading the effective flux per ac ampere is less than that produced per dc ampere. This condition tends the motor to run faster on ac supply. Out of the above two factors *i.e.,* of armature reactance drop, and effective flux, the factor which pre-dominates determines the speed of the motor on ac supply.

6.2.1 Reversing Direction of Rotation of Universal Motor

The direction of rotation of a universal motor can be changed by either:

(*i*) Reversing the field connection with respect to those of armature; or

(*ii*) By using two field windings wound on the core in opposite directions so that the one connected in series with armature gives clockwise rotation, while the other in series with the armature gives counterclockwise rotation.

The second method, *i.e.,* the two field method is used in applications such as motor operated rheostats and servo systems. This method has somewhat simpler connections than the first method.

For simple applications like portable drills etc. manual switches are frequently used for reversing the direction of rotation of the motor. Fig. 6.1 (*a* and *b*) shows how a DPDT (Double Pole Double Throw) switch and a three position switch may be used for reversing the direction of rotation of single field and double field type of motors respectively.

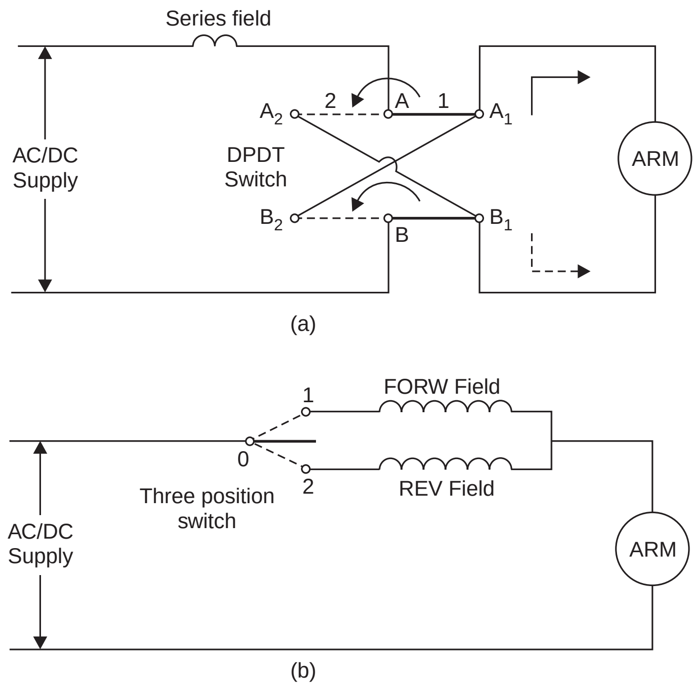


Fig. 6.1 Reversing of a universal motor (*a*) Armature reversing method using a reversing switch (*b*) Two-field method using a three-position switch

In Fig. 6.1 (*a*), when the DPDT switch is in the position shown, the switch blade bridges the switch terminals $A - A_1$ and $B - B_1$, current through series field and armature flows in the direction as indicated by arrows. When direction of rotation of the motor is to be reversed the switch is thrown to position 2.

Now, terminal A gets connected to terminal A_2 and terminal B gets connected to B_2. Current through the armature reverses while direction of current through the series field remains unchanged. This leads to reversal of direction of rotation of the motor. As shown in Fig. 6.1 (*b*) the direction of rotation of the motor is reversed by moving the selector switch in position 1 or 2. In position 1, the FORW-field runs the motor in one direction and in position 2, REV-field runs the motors in the reverse direction. Automatic control circuit for reversal of motor by armature-reversing method is similar to the circuit studied for dc motors in Chapter 5. Power and control circuit for a double field universal motor has been shown in Fig. 6.2.

When the FOR-push button is pressed, the forward contactor F get energised and its contacts F_1 and F_2 close to energise the armature and the FORW-field winding. Similarly when the reverse contactor is energised the REV-field winding and the armature get energised by receiving supply through contacts R_1 and R_2. In the control circuit, push button interlocking, as also auxiliary contact interlocking have been provided to avoid simultaneous energisation of contactors F and R.

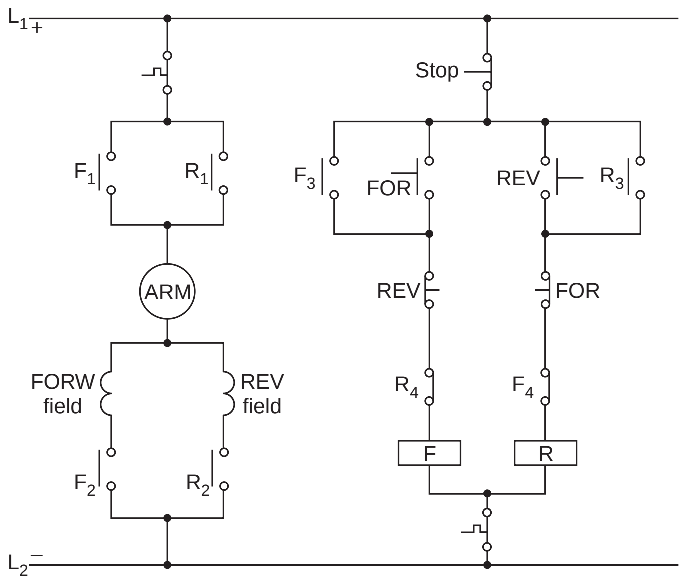


Fig. 6.2 Power and control circuit for reversing of a two-field universal motor

6.2.2 Speed Control of Universal Motor

There are various methods of controlling the speed of a universal motor. A wide range of speed control is possible by inserting a rheostat in the line circuit which causes variable voltage to appear across the motor terminals resulting in reduced motor speed. Another method of speed control, not very commonly used is by brush shifting mechanism. The speed of the motor increases when the brushes are moved backward relative to the direction of rotation. However, only a limited range of speed control is possible by this method. This is because when the brushes are moved further from the magnetic neutral, commutation worsens.

Another speed control method makes use of a tapped field winding. Universal motors are always bipolar. The number of turns on the two poles need not always be the same as the air gap flux is created by series combination of mmfs of the two pole windings.

As shown in Fig. 6.3 the field winding having larger number of turns is tapped at three points thus making possible a total of four operating speeds. For a given value of load, minimum speed will be obtained when the entire winding is used (this gives maximum mmf and flux). Maximum speed will result when the selector switch is on point *H* at which minimum flux is obtained. This method offers possibility of tapping the field winding at appropriate points to permit the motor to run at the same speed on direct current and also on alternating current for a particular input. This, however, does not mean that speeds will be the same on ac and dc supplies for some other values of input currents.

Another popular method of speed control is the governor controlled speed adjusting method. In this method of speed adjustment of a series motor, a governor consisting of an assembly of a spring loaded contacts is mounted on the shaft of the motor. The current enters the governor contacts through carbon brush and slip-ring arrangement. When the motor is running, governor contacts open and close very rapidly depending upon the natural resonant frequency of the moving contacts. For a given spring tension setting, the contacts vibrate at a certain rate. Figure 6.4 shows how a governor is connected to a series motor for non-reversing as well as for two field reversing service.

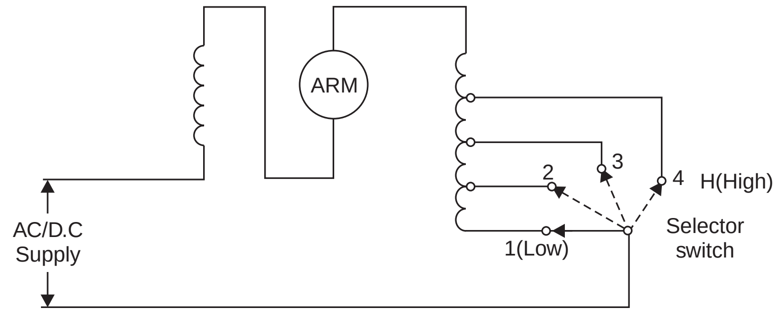


Fig. 6.3 Tapped field winding speed adjustment method for a universal motor

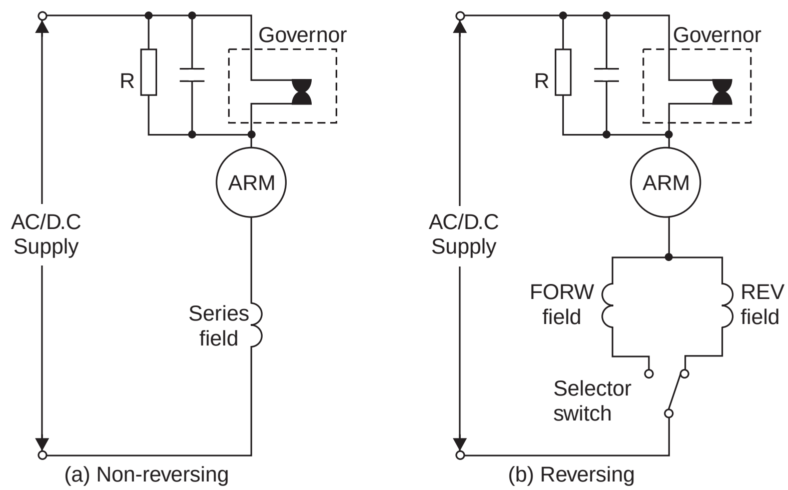


Fig. 6.4 Governor controlled speed adjustment method for a series motor

For a given spring tension setting, contacts vibrate at a certain rate. When the speed rises above the particular value set by the spring tension, the contacts remain open for a relatively longer period of time, than the time the contacts take for closing. This keeps a line resistance R in the circuit a little longer and acts to reduce the speed. The reverse is true when speed falls below the adjusted value. Now the closing time of contact is longer than its opening time and hence the resistance remains in circuit for smaller duration of time and as a consequence the motor speed tends to rise.

In this type of speed adjustment the motor does not run at a constant speed but runs in a narrow range above and below the set speed. A wide range of speed adjustment is thus possible by adjusting the spring tension of the contacts. A small capacitor is used across the contacts to prevent excessive arcing.

6.3 SHADED POLE MOTOR

Shaded pole motors are induction motors manufactured for very small ratings and are used in applications where starting torque requirement of the load is very low. Some of the applications of shaded pole type induction motors are in blowers, fans used in heaters, slide and film projectors, advertising display devices etc. The outstanding features are the low initial cost, small size, and ruggedness. An advantageous feature of such small motors is that the starting current is only slightly higher than the full-load current and therefore the stalled motor condition is not harmful to the motor windings.

Cross sectional view of a shaded pole type motor has been shown in Fig. 6.5. The stator shown are projected type. Short circuited coils known as shading coils (rings) are fixed on one portion of each pole. A pole on which a shading ring is fixed is called a shaded pole. Shading coil can be of thick single turn in the form of a ring or have a number of short circuited turns. The rotor is of conventional squirrel cage type.

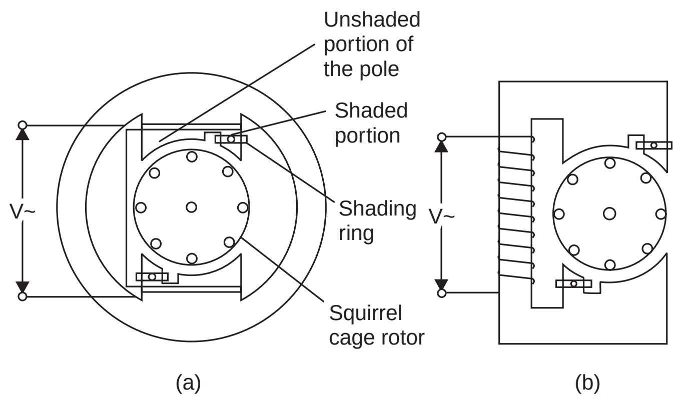


Fig. 6.5 Shaded pole type induction motors of different design

The magnetic field created by the field ampere-turns of a shaded pole motor varies in magnetic strength and merely shifts from one side of the salient pole to the other side for every half cycle of the supply voltage. The direction of rotation of shaded pole motors with a single set of field windings and shading coils can not be reversed. The motor would always rotate in a direction from the unshaded part to the shaded part of the pole. For enabling reversal of direction of rotation, the construction of the stator must be changed to include :

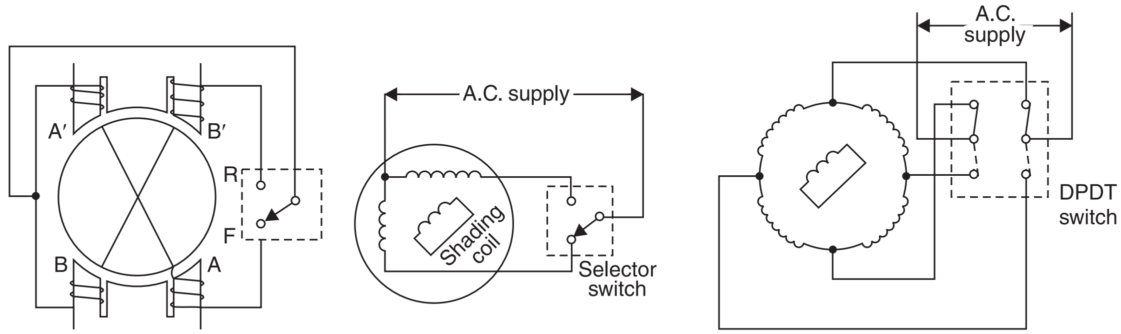
(1) Two sets of shading coils that are normally open circuited and occupy different positions with respect to the main field winding.

(2) Two main windings that occupy different positions with respect to the shading coils.

(3) A special distributed continuous winding that is placed in a slotted stator core and is tapped at appropriate points with respect to the shading coils.

Fig. 6.6 (*a*) shows shading coils placed on both sides of each of the salient poles. With the help of short-circuiting switch either set of shading coils can be made effective. The coils which are short circuited determine the direction of rotation. When the selector switch [Fig. 6.6 (*a*)] is in position *F*, shaded coils *A* and *A′* are shorted while shaded coils *B* and *B′* are open. When the switch position is changed, coils *B* and *B′* are shorted while *A* and *A′* become open.

In Fig. 6.6 (*b*) two distributed windings are placed 90° electrical degrees apart with respect to each other and 45° electrical degrees from the shading coils in a slotted stator. In Fig. 6.6 (*c*) a continuous distributed winding is used and tapped at 90° electrical degrees. Leads from these tappings are connected to a DPDT switch. With alternate position of DPDT switch, the main winding can have either positive or negative 90° electrical degrees relationship with respect to the shading coils. In one case the rotor will turn clockwise and in the other case the rotor will turn counter clockwise.

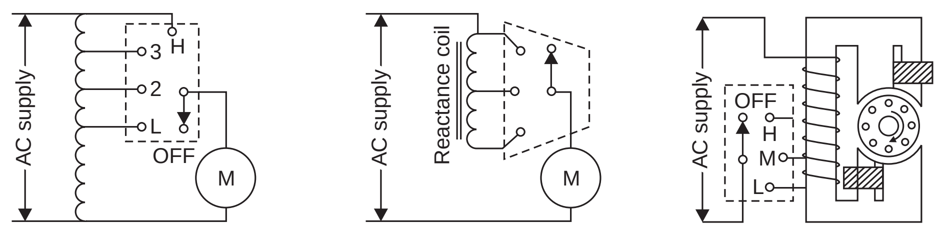


(a) Two sets of shading coil method (b) Two main winding method (c) Tapped distributed-winding method

Fig. 6.6 Method of changing the direction of rotation of a shaded pole type induction motor

The speed of the shaded pole motor can be changed by changing the impressed voltage across the main winding. Three methods are generally employed to vary the winding voltage. They are : (*i*) by using an auto transformer that is tapped for several voltages. (*ii*) by using a tapped reactance coil that incurs a line voltage drop, and (*iii*) by using tapped exciting winding to enable supply voltage to be applied across the whole winding or across a part of it.

Method of speed control illustrated through Fig. 6.7 (*a*) and Fig. 6.7 (*b*) are self explanatory. In the method of speed control illustrated through Fig. 6.7 (*c*), the highest speed results when the smallest portion of the winding is energised.



(a) Auto transformer method (b) Reactance coil method (c) Tapped-winding method

Fig. 6.7 Speed control methods of shaded pole motors

This is because in such a case volts per turn increases resulting in increased speed.

6.4 SPLIT PHASE MOTORS

Split phase induction motors are the most widely used type of single phase motors. They are made in larger sizes than shaded pole type motors. They are used in refrigerators, washing machines, portable hoists, many kinds of small machine tools, grinders, blowers and fans, wood working equipment, centrifugal pumps, etc. Two types of split phase motors are generally available. They are:

(*i*) Standard split phase motor; and

(*ii*) Capacitor split phase motors.

6.4.1 Standard Split Phase Motors

The stator of a standard split phase motor has two windings viz., a main winding and an auxiliary winding. These two windings have different ratios of resistance to inductive reactance. The windings are connected in parallel across the single phase ac supply. The line current is thus split into two parts; one part flowing through the main winding and the other part flowing through the auxiliary windings. Because of different ratio of resistance to inductive reactance of these two windings current flowing through them will have a time phase difference of 30 electrical degrees or more. In some motors, both the windings are energised continuously, while in most of them, the auxiliary winding is used only during the starting period along with the main winding to develop the required starting torque. When the motor reaches final speed the auxiliary winding is disconnected from the supply. The auxiliary windings can be disconnected by using a centrifugal switch in series with it. During starting, the centrifugal switch remains closed. When the motor reaches normal speed the centrifugal switch opens and disconnects the auxiliary winding. This has been shown in Fig. 6.8 (*a*).

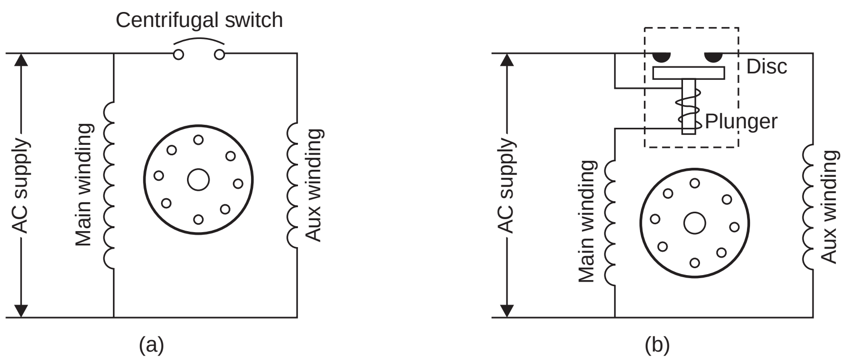


Fig. 6.8 Use of (*a*) Centrifugal switch (*b*) Electro-magnetic relay for connecting an auxiliary winding in parallel with the main winding during starting

Another method of disconnecting the auxiliary winding when the motor has picked up speed is by using an electromagnetic relay as has been shown in Fig. 6.8 (*b*).

During starting the relay picks up due to high starting current and connects the auxiliary winding in the circuit. When the motor reaches normal speed, current drops to normal value and the electromagnetic relay is dropped and therefore the auxiliary winding gets disconnected from supply.

Reversal of direction of rotation of a split phase motor is obtained by interchanging the auxiliary winding terminal connections with respect to the main winding. The motor must be brought to rest or the centrifugal switch must be closed before reversal is attempted. The basic

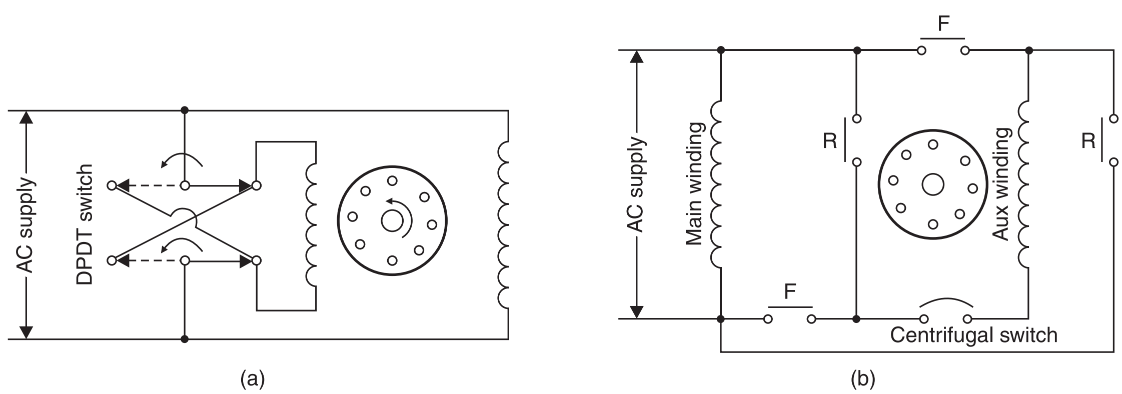


Fig. 6.9 Reversing of split phase motor

circuit for reversal of small split phase motor using a DPDT (Double Pole Double Throw) switch and contactors has been shown in Fig. 6.9 (a and b).

Speed control of standard split phase motors is achieved with difficulty. The usual method is to use two or more windings designed to produce different number of poles. The complications arise as both the main and the auxiliary windings have to be arranged for pole changing. The capacitor type split phase motor which will now be discussed have better possibility of speed adjustments.

6.4.2 Capacitor Type Split Phase Motors

Capacitor type split phase motors are generally similar to the standard split phase construction except for the addition of capacitor and a slightly modified switching arrangement for the two value capacitor type motors. The three types of capacitor split phase motors have been shown in Fig. 6.10.

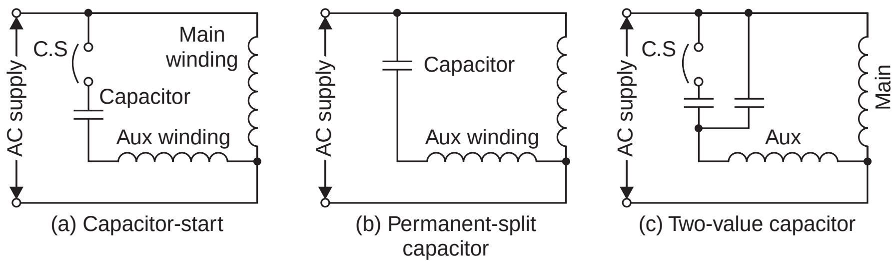


Fig. 6.10 Three types of capacitor type split phase motors

6.4.2.1 Capacitor Start Split Phase Motors

These motors are used where high starting torque is required. To accomplish this, capacitors of large values are to be used. Electrolytic capacitors designed for short duty service are available and used in these motors. The motor should come upto its speed quickly and disconnect the capacitor from the windings, otherwise the capacitor will get damaged. The centrifugal switch or the relay that function in auxiliary winding should be very reliable.

6.4.2.2 Permanent Split Capacitor Motors

These motors are mainly used for low starting torque loads where they are generally shaft mounted. Their particular fields of applications are in air moving equipment such as fans, blowers, oil burners etc. where quiet operation is required.

6.4.2.3 Two Value Capacitor Motors

This type of capacitor motors has the advantage that they develop extremely high locked rotor torque with one value of capacitance in the auxiliary winding circuit and gives quiet running performance of the motor with another capacitor. Electrolytic capacitors are used for starting. Their values are 10 to 15 times as much as the value of the running capacitor.

6.4.3 Starters for Capacitor Type Split Phase Motors

We know that direction of a split phase motor can be reversed if the connection of one of the windings is reversed with respect to the other. In an automatic starter this can be achieved by using two contactors *i.e.,* one for forward direction of rotation and the other for reverse direction of rotation. The connections for control circuit and the power circuit diagrams have been shown in Fig. 6.11. The circuit does not need any further explanation as it is a simple forward reverse starter scheme.

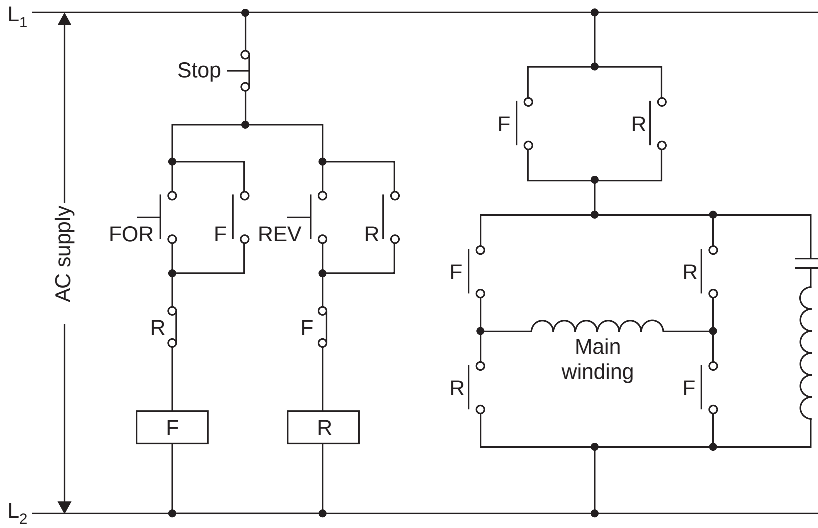


Fig. 6.11 Forward/reverse starter for a permanent split capacitor motor

6.4.4 Starter for Two Value Capacitor Type Split-phase Motors

This type of split phase motors have two capacitors of different values in the auxiliary winding. The motors develop a high starting torque with one capacitor of a higher value and gives a quite running performance with the other capacitor of comparatively lower value. The circuit for forward / reverse operation of a two value capacitor motor has been shown in Fig. 6.12.

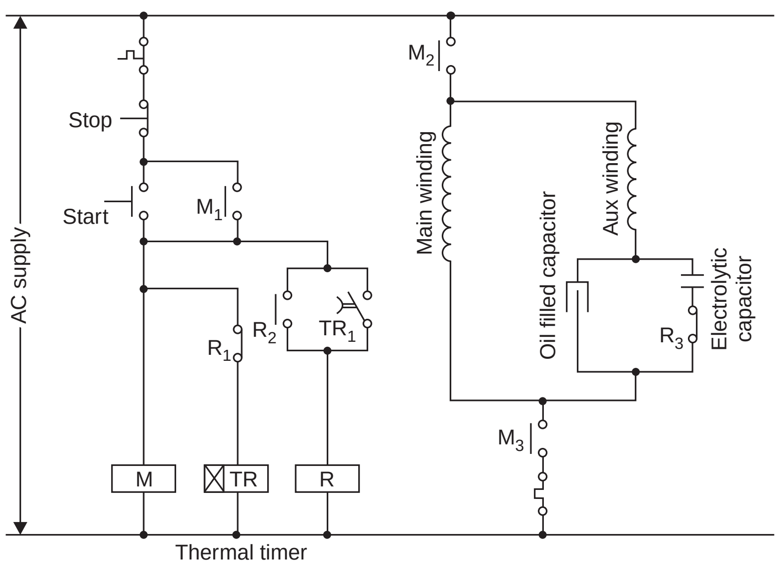


Fig. 6.12 Forward/reverse starter for a two value capacitor motor

In the circuit shown an electrolytic capacitor has been used for starting purpose and an oil filled capacitor has been used for continuous running operation. During starting both the capacitors are in the circuit. When the motor picks up speed the electrolytic capacitor gets disconnected due to opening of a relay contact. The circuit operation is as follows :

When the START-push button is pressed the M contactor is energised which inturn energises both the main and the auxiliary windings (with both the capacitors in the auxiliary winding circuit) due to closing of contacts M_2 and M_3. A thermal timer TR is also energised along with the contactor.

This thermal timer consists of a heater coil wound on a bimetallic strip. After a pre-set delay the bimetallic strips bends and closes contact TR_1. Closing of contact TR_1 causes energisation of relay R which then gets hold through its own contact R_2. At the same time relay R disconnects the electrolytic capacitor from the auxiliary winding circuit due to opening of its normally closed (NC) contact R_3. The thermal timer gets de-energised as soon as relay R is energised due to opening of its contact R_1.

6.4.5 Starter for a Two Value Capacitor Motor Using a Current Relay and an Auto Transformer

This type of starter uses a current relay in series with the main winding and an auto-transformer in the auxiliary winding to increase the effective value of the capacitors in the auxiliary winding circuit. The circuit has been shown in Fig. 6.13.

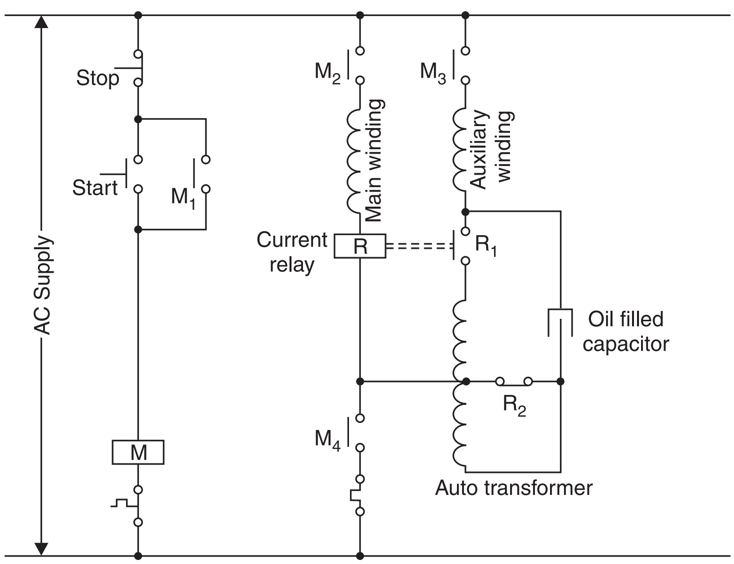


Fig. 6.13 Starter for a two value capacitor motor using an overcurrent relay and an auto-transformer

In this circuit, when contactor M is energised, a high inrush current flows through the main winding which energises relay R. Its contact R_1 closes and contact R_2 opens. Due to closing of contact R_1, the auto transformer winding comes in circuit and the effective value of capacitor is increased. The current relay is designed to pick up at 3 times the full load current and to drop at twice the full-load value. The motor therefore develops high starting torque during starting due to high effective capacitance. When the motor picks up speed, the current drops and the relay R drops out. Due to opening of contact R_1 and closing of contact R_2, the auto-transformer gets open circuited. The auxiliary winding then gets connected through the capacitor only. The relay R can pick up again, if load on the motor causes current to rise to its pick up value and thus re-inserts the auto-transformer. Thus, this increased capacitance permits the motor to develop more torque and prevents stalling at heavier loads.

6.4.6 Dynamic Breaking of Split Phase Motors

The principle of dynamic breaking discussed earlier in connection with polyphase induction motors, also applies well to split phase motors. The procedure, as already explained, is to disconnect the stator windings from ac supply while the motor is running and instead, connect dc supply across the windings. Full wave rectifier is used to obtain dc supply from the available ac source. Precaution must be taken to avoid, simultaneous energisation of the stator windings from both ac as well as dc supply. This is taken care of by providing electrical and/or mechanical interlocking of the contactors. A rheostat is provided in the dc circuit to control the time required for the motor to stop. Less is the value of rehostatic value of resistance, more quickly will the rotational energy get converted to electrical energy and get dissipated as heat and hence less will be the time required for the motor to stop. The control diagram for dynamic breaking of a split phase motor is shown in Fig. 6.14.

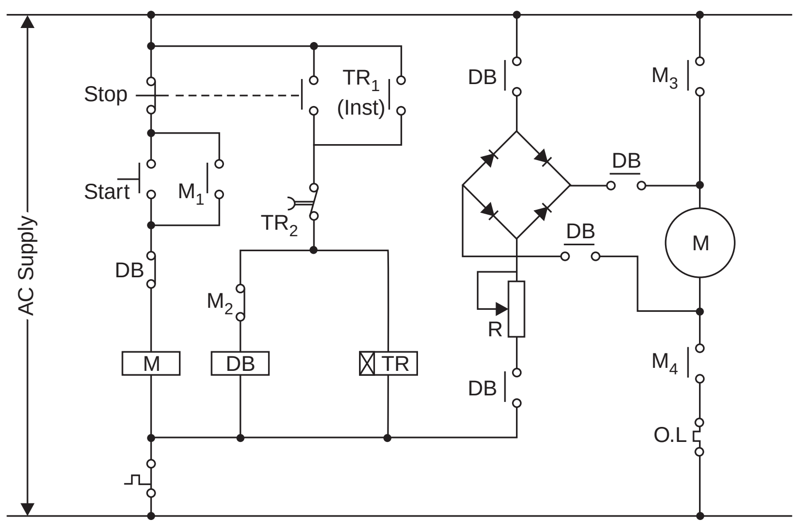


Fig. 6.14 Control circuit for dynamic breaking of a split phase induction motor

When the STOP-push button is pressed, contactor M gets de-energised and closes its contact M_2. Contactor DB gets energised through the back contact of the STOP-push button, closed contact TR_2 and contact M_2. Timer TR also gets energised along with contactor DB. The instantaneous contact of relay TR, *i.e.,*TR_1 closes and thus both contactor DB and relay TR remain energised. Contactor DB energises a bridge rectifier which feeds dc current into the stator winding of the motor. Current to be fed is adjustable through a rheostat, R. Due to feeding of dc current the motor slows down and comes to a quick stop. After a pre-set delay which would match with the time taken by the motor to stop, the timer TR operates and opens its delayed contact TR_2 and thus de-energises contactor DB and gets reset. The time allowed to stop the motor, as explained earlier, can be varied by adjusting the rheostat R.

6.4.7 Plug Reversing of Capacitor Start Motors

The capacitor start motors suffer from the disadvantage that they are not easily reversible due to the centrifugal switch connected in the auxiliary winding. The motor can not be instantaneously reversed by simple control as the auxiliary winding remains disconnected till the motor comes near to zero speed. However, by proper design of the control circuit the motor can be made instantly reversible. This is accomplished by using an electromagnetic relay along with a special two contact centrifugal switch as shown in Fig. 6.15.

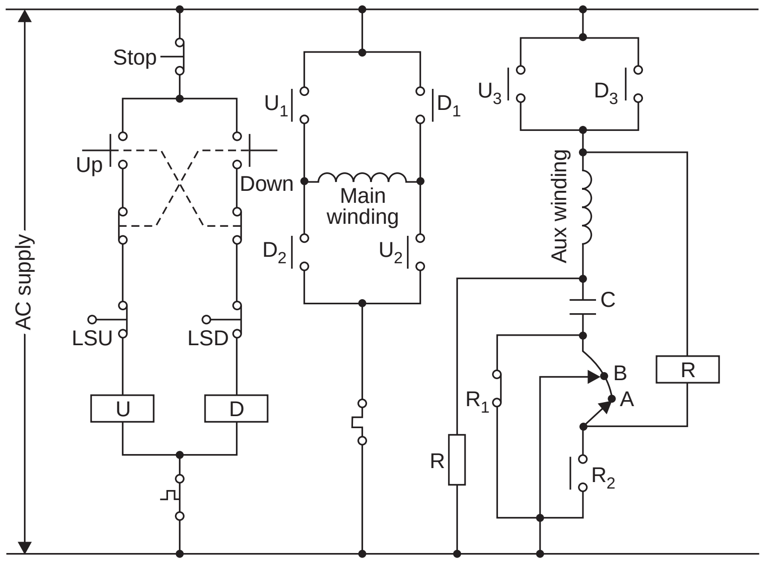


Fig. 6.15 Control circuit for a small hoist using a capacitor start

The circuit shown in Fig. 6.15 is for a small hoist using a capacitor start motor. The upper and lower limits of travel are controlled by two limit switches *viz.* LSU and LSD.

When UP-push button is pressed, contactor U gets energised. Its contacts U_1 and U_2 energise the main winding. Closing of its contact U_3 causes relay R to get energised through the centrifugal switch contacts A—B. After the energisation of relay R auxiliary winding gets energised through capacitor C, the centrifugal switch, and the closed contact R_2 of relay R. When the motor reaches near normal speed, the centrifugal switch opens and the auxiliary winding gets connected to a high resistance R. Under this condition the auxiliary winding is effectively an open circuit and therefore the developed torque is only by the main winding (recall that this is what is required during normal operation of the motor). When the hoist will reach the upper limit the limit switch LSU will be actuated, U contactor will get de-energised, relay R also drops out due to opening of contact U_3. If, to achieve instant reversal, the DOWN-push button is pressed, contactor D would pick-up energising the main and also the auxiliary winding through normally closed (NC) contact R_1 (as relay R will not pick-up because of centrifugal switch being open). The centrifugal switch would close when speed becomes zero, the relay R would then get energised. The auxiliary winding would also get energised through the centrifugal switch contact B. In the downward direction when motor again reaches its final speed the centrifugal switch would open thus connecting the auxiliary winding to the high resistance R.

6.4.8 Speed Control of Split Phase Motors

Speed control of split phase motors (without capacitors) is obtained by either pole changing method or by using special winding arrangements. These methods will, however, increase the size of the such motors and make them expensive.

To obtain two speed operation of a split phase motor, the motor will have two main windings and two auxiliary windings, each set wound for different number of poles. However by special design a single auxiliary winding may also be used. In two speed operation, the centrifugal switch is set to open at the lower of the two speeds. In case of fast speed operation, therefore, the rotor has to accelerate to full speed on the main winding only. No problem would arise on this account if the load on motor is moderate.

Figure 6.16 shows the control circuit for a two speed motor with two main and two auxiliary windings. The control circuit permits starting of the motor at slow or fast speed depending upon the setting of the selector switch. During running condition, transfer can be made from one speed to the other speed.

For the selector switch setting for slow speed, as shown in Fig. 6.16, the motor can be started by pressing the SLOW-push button. A relay CRS first gets energised through contact S_3 and then gets hold through its contact CRS_1. Contact CRS_2 also closes and makes the circuit ready for fast operation. Whenever a change over is required for fast operation, the FAST-push button is to be pressed which would first release the slow contactor S and then energise the fast contactor F. A relay CRF would then get energised and get hold through its own contact. Contact CRF_2 of this relay closes allowing transfer from fast speed to slow speed operation when required. Thus, it follows from the above that the motor can be started for a particular operation, fast or slow, depending upon the setting of the selector switch and then change over to the other operation by pressing the corresponding push button.

6.4.9 Speed Control of Permanent Split Capacitor Motors

The speed of a permanently split capacitor motor can be adjusted by connecting it to a variable voltage source such as an auto-transformer. The limitation of this method is that the starting torque developed is very low, especially when the motor is started on low speed. Another limitation is that speed is sensitive to voltage changes on low speed connections. Further. speed varies considerably for different loading conditions of the motor.

The motor can be started in three different ways using an auto-transformer as shown in Fig. 6.17. In Fig. 6.17 (*a*) the voltage across the main winding and the auxiliary winding are varied simultaneously resulting in low starting torque for low speed operation. This shortcoming, however, can be overcome by first starting the motor on high speed and then stepping it down to low speed as shown in Fig. 6.17 (*a*).

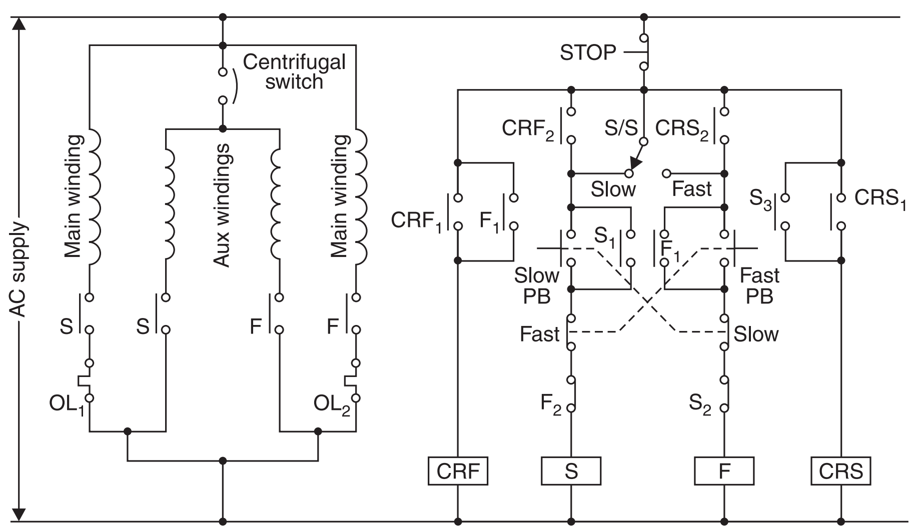


Fig. 6.16 Control circuit for a two speed split phase induction motor having two main and two auxiliary windings

Good starting torque at all speeds can be obtained if the auxiliary winding is connected across the mains supply and voltage adjustment is provided only for the main winding as shown in Fig. 6.17 (*b*).

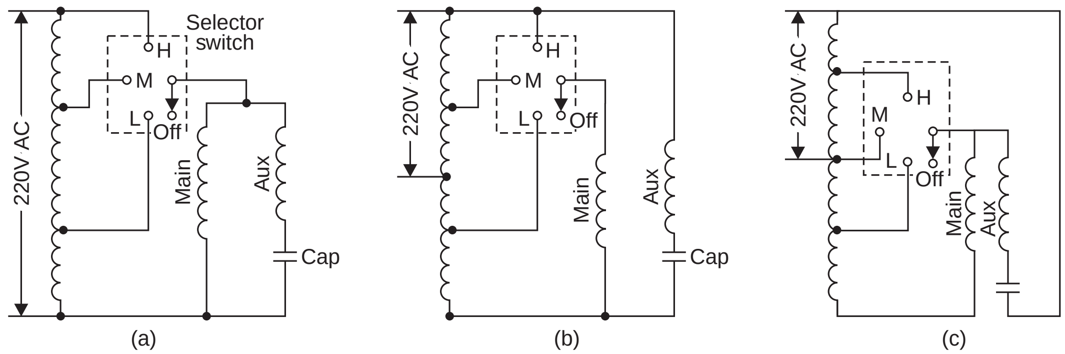


Fig. 6.17 Voltage control method for speed adjustment of split capacitor motors

In the third method of connections shown in Fig. 6.17 (*c*), the two windings are connected to a tapped auto transformer so that any voltage change across the main winding is accompanied by an inverse change across the auxiliary winding. This method with a properly designed motor can be applied to an installation whose speed should not be sensitive to variations of normal line voltage.

In another design of split motor a special winding arrangement is made to eliminate the requirement of an auto tansformer. The motor in this case, in addition to the main and the auxiliary windings, is provided with a so called intermediate winding. The intermediate winding so provided is in space phase with the main winding. The main and the intermediate windings occupy the same slots, the later placed directly over the former. They need not have the same number of turns. The wire of the intermediate winding is invariably smaller in size than the main winding. Two different connections for this type of motor design are shown in Fig. 6.18 (*a* and *b*).

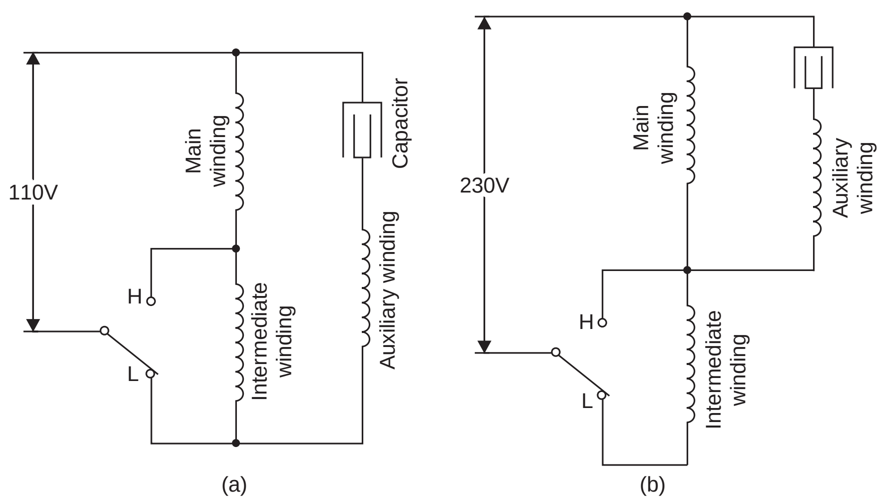


Fig. 6.18 Speed control of split capacitor motor with intermediate winding

The connection scheme shown in Fig. 6.18 (*a*) is generally used for 110 volt motors. The main and the intermediate winding are connected in series across the auxiliary winding and the capacitor. The terminal of SPDT (Single Pole Double Throw) switch *H* and *L* are wired to the intermediate winding as shown in Fig. 6.18 (*a*).

Connections shown in Fig. 6.18 (*b*) are used for 230 voltage motors.

REVIEW QUESTIONS

1. How are single phase motors classified ? Name different types of motors under each classification.

2. What modifications are required to use a dc series motor on ac supply ?

3. Draw connection scheme for armature reversing of a universal motor.

4. Discuss two field method of reversing the direction of rotation of a universal motor.

5. How can the speed of a universal motor be controlled ?

6. Draw power and control diagram for starting a two-value capacitor type split phase motor.

7. Explain with the help of diagram how a current relay and an auto transformer can be utilised for starting a capacitor split phase motor.

8. Discuss dynamic breaking of a split phase induction motor.

9. Discuss plug reversing of capacitor start motors using an electromagnetic relay and a special two contact centrifugal switch.

10. Draw power and control diagram for a two speed split phase induction motor having two main and two auxiliary windings.

11. Explain how you will obtain the speed control of a permanent split capacitor motor.

7

Control of Synchronous Motors

7.1 CONSTRUCTION AND OPERATION OF A SYNCHRONOUS MOTOR

The stator winding of a synchronous motor is similar to that of a 3 phase induction motor. The rotor consists of salient poles excited by dc field windings like that of inward-projecting poles of a dc motor. The rotor field windings are energised by direct current passed through slip rings from an external source or from a dc generator, mounted on the same rotor shaft.

When the stator winding is energised from a 3 phase supply, a revolving magnetic field, the speed of which is given by $N_s = \dfrac{120\,f}{P}$ is produced. This speed is called synchronous speed. To enable the synchronous motor to run at the above mentioned synchronous speed the rotor field winding is energised and at the same time brought near to the synchronous speed, by some other means. The rotor poles, which are always equal to that of the stator poles, are pulled to synchronous speed and the two set of poles lock with each other and the rotor starts rotating at synchronous speed. Thus, to run a synchronous motor, the rotor has to be brought near to synchronous speed first by some means, say by some external prime mover. This is a big disadvantage of this motor. However, a synchronous motor is made self starting by providing a squirrel cage winding (like that of an induction motor) along with the dc field winding on the rotor. In such a case when three phase supply is applied across the stator windings the rotor starts rotating as an induction motor and when it reaches near its final speed (near synchronous speed), dc field winding is energised and the rotor thus pulls into synchronism with the revolving field and continues to run at synchronous speed. At synchronous speed there will be no current in the squirrel cage winding since at synchronous speed slip is zero. The squirrel cage winding therefore is designed only for short duty services. During the starting period the dc field winding has to be kept shorted through a discharge resistance. This is done so as to avoid building up of an extremely high voltage in the winding. If field is left open circuited a high voltage will develop in the open field winding as it has large number of turns and the relative speed of stator flux to the windings of the poles is high during starting. But this induced high voltage will gradually decrease as the motor will be picking up speed. The induced emf in the field winding is kept to a safe value by shorting the winding. This would limit the demagnetising effect on the main flux otherwise caused due to current flowing in the dc field winding as a result of induced emf in it. This demagnetising effect, if allowed to happen will reduce the starting torque of the motor. If in some special applications a higher starting torque is required the field winding can be left open circuited, but should be sectionalised, to have reduced voltage induced across the separated portions.

From the above, it is seen that the primary purpose of the squirrel cage in this motor, is for starting the motor. As mentioned earlier this winding is designed for low thermal capacity. If, however, the motor picks up speed too slowly under some loading condition, it will run as induction motor for extended period of time and as a result the squirrel cage winding may get over heated and get damaged. To overcome this problem a certain protection must be provided which should disconnect the motor from the supply in the event of its failure to get synchronised properly within a certain prescribed time. A timing relay is used for this purpose to open the control circuit if the motor fails to synchronise within the set time.

Synchronous motors, like the induction motors, can be started by applying line voltage, reduced voltage, or using part winding controllers depending upon the kind of load, frequency of starting, and power serivce restrictions. The starters for the motor can be manual, semi-automatic, or fully-automatic using a polarising frequency relay.

From the above it follows that synchronous motor control has two basic functions:

(*i*) To start the motor as an induction motor (the motor can be started by any schemes such as across the line, auto-transformer, primary resistor or any other method) ;

(*ii*) To bring the motor up to synchronous speed by exciting the dc field. Different types of synchronous motor starters are discussed as follows.

7.2 MANUAL PUSH BUTTON SYNCHRONISING STARTER

When the START-push button shown in Fig. 7.1 is pressed contactor *M* gets energised and the motor starts as induction motor. The field winding remains shorted through normally closed contact F_1 and discharge resistance. When the motor has reached its maximum speed, the RUN-push button is closed which energises and holds contactor *F* contacts F_2 and F_3 closed and contact F_1 open. The field winding is thus energised and the motor pulls into synchronism. An ammeter and a rheostat are connected in the field circuit to control the excitation current.

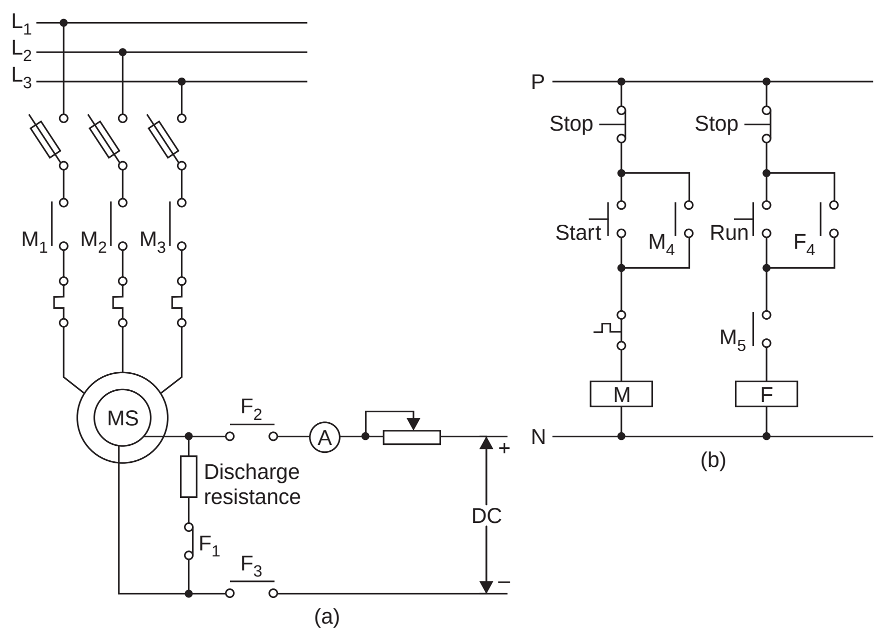


Fig. 7.1 Power and control circuit for a manual push button synchronising starter

Unity power factor of the motor can be obtained by adjusting the rheostat. A leading power factor can also be obtained by increasing the excitation.

The disadvantage of the starter is that synchronisation of the motor depends entirely upon the judgement of the operator.

7.3 TIMED SEMI-AUTOMATIC SYNCHRONISING

In this method the synchronous motor may be brought up to synchronous speed by exciting the field winding with the help of a Definite Time relay instead of a push button. The control scheme is as shown in Fig. 7.2.

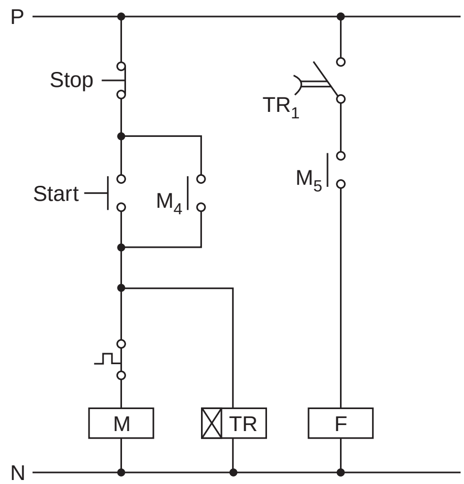


Fig. 7.2 Control scheme for timed semi-automatic synchronising

In this circuit, timer *TR* is energised along with the main contactor. After a pre-set time delay the rotor accelerates to its maximum when the contact TR_1 closes and further accelerates the rotor to synchronous speed by energising the field winding. The setting of the timer is adjusted to the maximum value ever required for the motor to accelerate. This method of starting, like the push button operated synchronising method, is also not satisfactory because of the reason that if the synchronism operation fails, it becomes necessary to depress the STOP-button and repeat the starting cycle. Rotor will however continue to rotate and only the timing cycle will start again. It thus follows that neither the push button nor the timer method of synchronising is a satifactory method of starting.

7.4 AUTOMATIC STARTER USING POLARISED FIELD FREQUENCY RELAY

It is known that synchronous motor is started by first accelerating the rotor with the help of its squirrel cage winding upto near its synchronous speed and then synchronising by applying the dc field excitation. In an automatic starter using polarised field frequency relay, synchronisation is obtained automatically when about 92 to 97 percent synchronous speed is obtained with the help of a Polarised Field Frequency Relay (PFR). Such a PFR has two coils one for ac supply and the other for dc supply. This relay is used in the circuit along with a reactor as shown in Fig. 7.3. The working principle of a PFR will be discussed a little later. First we will discuss the functions of a PFR relay and an Out of Step Relay, TR used in the starter circuit shown in Fig. 7.3.

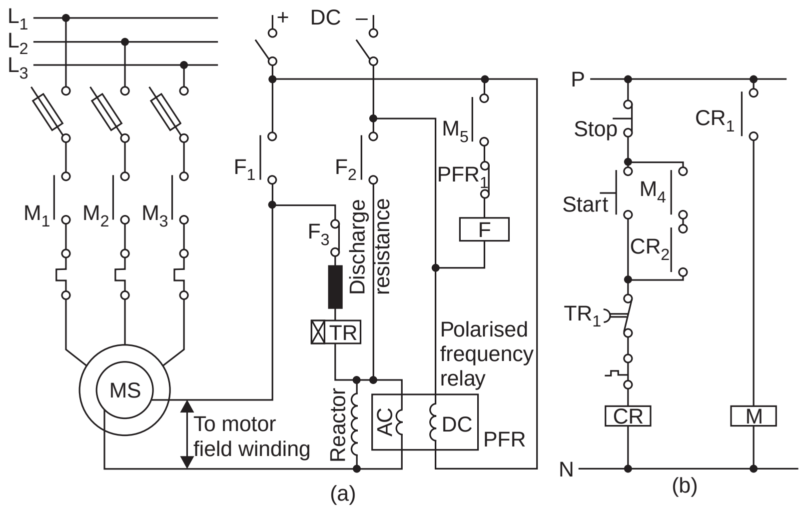


Fig. 7.3 Power and control circuit for an automatic starter for a synchronous motor using polarised field frequency relay

When the START-push button is pressed, *CR* relay gets energised and consequently the main contactor *M*, is energised through its contact CR_1. It gets hold through its contact CR_2 and contact M_4 of the main contactor. Normally closed (NC) contact of the overload relay and the Out of Step Relay *TR* are connected in series with AC coil of relay *CR*.

At the instant of starting when contactor *M* closes and the motor starts on its squirrel cage winding, the polarised field frequency relay (PFR) opens its normally closed contact PFR_1 and thus does not allow the field contactor *F* to get energised. When the motor reaches 92 to 97 percent of its synchronous speed, *PFR* relay closes its contact PFR_1 which causes energisation of the field contactor *F* through already closed contact M_5. A positive interlocking between the normally closed and the normally open contacts of contactor *F* causes the normally open contacts F_1 and F_2 to close earlier than the opening of the normally closed contact F_3. This positive overlap is desired in contactor *F* so that the field winding does not remain open at any instant during starting or running of the motor. An open field winding can cause damage of insulation of the winding due to high voltage developed in it. From the circuit diagram it is clear that as long as contactor *F* is de-energised, the field winding remains shorted through the normally closed contact F_3, the discharge resistance, the Out of Step Relay *TR*, and the reactor. Now, let us consider the instant when the contactor *F* closes. The closing of field contactor *F* applies dc excitation to the field winding and causes the motor to pull into synchronism. Now let us consider the function of Out of Step Relay *TR* which is connected in series with the field discharge circuit. It the motor fails to synchronise or re-synchronise after pulling out of synchronism within the pre-set time delay of *TR* relay and if the amount of current induced in field winding exceeds the value set on *TR* relay, the relay contact opens thereby de-energising the main contactor of the motor.

Let us now discuss the working principle of the polarised field frequency relay and also the function of the reactor in the circuit. Polarised field frequency relay has a direct current coil (*A*), induced field current coil (*B*), and a pivoted armature with its contact PFR_1 as shown in Fig. 7.4. Coil *A* is connected to the source of dc excitation and thus builds up constant magnetic flux in the relay core and polarises it. Alternating flux produced due to current flowing in coil *B* is superimposed on the constant flux of coil *A*. The flux through the armature, thus, depends on the flux produced by both coils *A* and *B*. The resultant wave form of flux through the armature is shown in Fig. 7.4 (*c*).

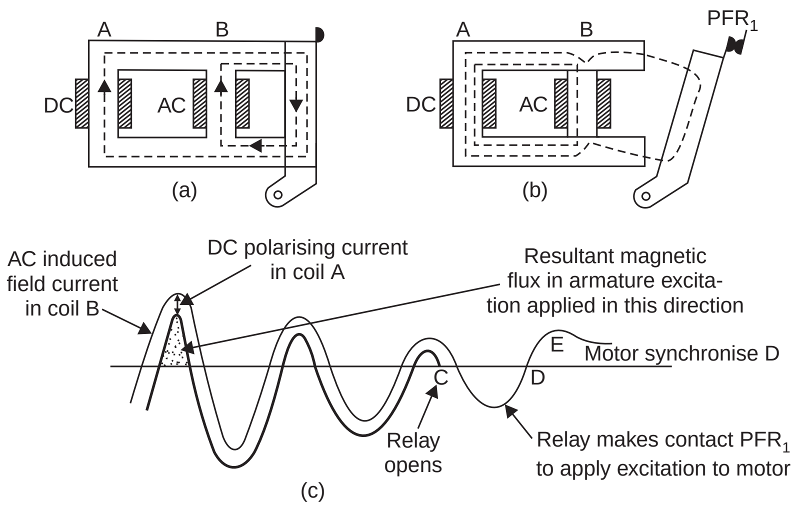


Fig. 7.4 Polarised field frequency relay

As seen from Fig. 7.4 (*c*) coil *B* produces alternating flux of equal positive and negative magnitude. The combined flux through armature will be much larger when coil *B* flux is opposing the dc coil (coil *A*) flux as shown in Fig. 7.4 (*a*). This is so because coil *B* opposes the flux from dc coil *A* and causes it to take a longer path through the armature of the relay. This condition has been shown through darker loops (lower loops) of Fig. 7.4 (*c*). When flux due to coil *B* is in the other direction as shown in Fig. 7.4 (*b*), it does not force much flux from coil *B* to take longer path through the armature. This condition has been shown by darker loops (upper loops) in Fig. 7.4 (*b*). The armature will open when current level falls to a certain low level as shown by point *C* in Fig. 7.4. When armature drops, relay contact PFR_1 closes which energises the field contactor *F*. Contact F_1 and F_2 closes and the rotor field winding is excited by dc supply. F_3 opens and removes the short across the field winding. Excitation is applied in a direction opposite in polarity to that of the induced field current at the point of application to compensate for the time required to build up excitation due to magnetic inertia of the motor winding. The inertia is however such that dc excitation does not become appreciably effective until induced current has reversed (Point *D* on the curve) to the same polarity as the direct current. Excitation then continues to build up until the motor synchronises as shown by point *E* on the curve.

Now we come to the function of the reactor across the rotor field winding and AC coil of PFR relay. When the motor is accelerating the slip frequency is high and therefore the current induced in the field winding will have higher frequency. Thus the reactor would offer a high impedance, the induced current would be diverted to AC coil of *PFR* relay and the relay would pick up. When the rotor would gain speed, the frequency of induced current would get reduced and therefore reactor impedance would decrease. At 92 to 97 percent of the synchronous speed, reactor impedance will be quite low and thereby allowing more current. Current flow through AC coil *B* or *PFR* relay will be reduced. The relay thus would drop precisely at the right moment when rotor speed frequency and polarity of induced current are most favourable for synchronisation. As already explained, when the relay drops, its contact PFR_1 closes and completes the control circuit for field contactor *F*.

During running of the motor, if an overload or a voltage dip causes the motor to lose synchronism, slip frequency currents are immediately induced in the field winding which flows in the AC coil of *PFR* relay. Relay armature gets attracted and opens the PFR_1 contact. This leads to de-energisation of contact *F* and thus dc field excitation to rotor is cut off. If the normal conditions of line and load are restored within the preset time of the Out of Step Relay, and if the motor has enough pull-in-torque, the motor will automatically re-synchronise. If, however, the abnormal conditions continue, either the over load relay will operate or the motor will get disconnected from the supply by the Out of Step Relay.

REVIEW QUESTIONS

1. Explain in brief the construction and working of a synchronous motor.

2. Discuss Manual push button synchronising circuit for a synchronous motor.

3. Draw the control scheme for timed semi-automatic synchronising.

4. Explain the construction and working of a polarised field frequency relay.

5. Discuss starting of synchronous motor using a polarised field frequency relay.

6. The speed of a synchronous motor is fixed by

(*a*) Stator supply voltage

(*b*) Rotor supply voltage

(*c*) Frequency of power supply and number of poles in stator

(*d*) Starting winding

7. To make the synchronous motor self starting a winding is placed.

(*a*) in the stator pole faces

(*b*) in the rotor pole faces

8. A synchronous motor can be used to increase the power factor of an electrical system by:

(*a*) increasing the speed

(*b*) over exciting the rotor field

(*c*) under exciting the rotor field

(*d*) applying dc to the rotor field

9. Mention the disadvantage of a manual push button operated synchronising starter. Show and explain with the help of a schematic diagram how this is overcome in an automatic starter.

8

Protection of Motors

8.1 PROTECTION OF AC MOTORS

Contactors, fuses and over-load relays are used for control of motors upto 150 hp while for larger high voltage motors circuit breakers along with protective relaying are used. Moulded Case Circuit Breakers (MCCB) are used for LT (low tension *i.e.* low voltage) motors of high ratings. MCCBs are available for range settings upto 800 A. In general two basic protections are always provided for every motor ;

(*i*) Over-load protection.

(*ii*) Short-circuit protection.

In addition to these, protection against unbalanced supply voltages, under voltage, reverse phase, over temperature, stalling, etc. are provided in motors used in special applications.

8.2 CO-ORDINATION OF FUSE, OVER-LOAD RELAY AND CONTACTOR/ CIRCUIT BREAKER OPERATING CHARACTERISTICS

While studying starters for induction motors it has been seen that the fuses and the overload power contacts are connected in series with the motor supply lines. An over load protective device provides protection to a motor against carrying sustained over current which may be due to mechanical over-loading or under voltage supply. Fuses on the other hand, provide protection against any earth fault or short circuit in the motor winding or at its terminals. The characteristic of fuse should be co-ordianted with the starting current of the motor. An induction motor draws 6 to 7 times the full load current during starting period and this current approximately remains at this high value upto about 80% of the rated speed. The fuse characteristic and the starting current characteristic of the motor should be matched as shown in Fig. 8.1.

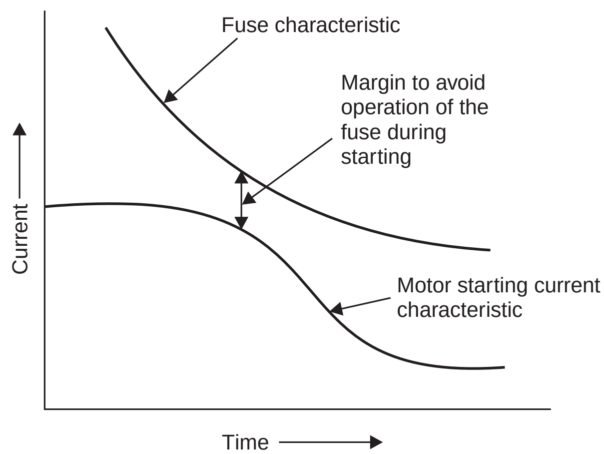


Fig. 8.1 Co-ordination of fuse and motor starting current characteristics

It is clear from Fig. 8.1 that sufficient margin should be there between the starting current characteristic and fuse characteristic to avoid blowing of the fuse during starting. When starting current of a motor is not known, the following approximations may be made :

Type of Starting	*Motor starting current times the rated load current*
Direct-on-line	6 to 8
Star-delta	2.5 to 3
Auto-transformer	2.5 to 4
Slip-ring starter	1 to 2

In a starter the breaking capacity of contactor or circuit breaker should be fully exploited. For this purpose the overload characteristic, which is responsible for switching off the contactor/circuit breaker, should be co-ordinated with fuse in such a way that for the value of fault current upto the breaking capacity of contactor/circuit breaker, the circuit breaker should operate and for current higher than rated value of contactor/circuit breaker, the fuse should blow. To obtain this co-ordination the characteristic of over-load relay should lie below the characteristic of the fuse as shown in Fig. 8.2.

These characteristic should intersect at a point, preferably above the breaking current capacity of the contactor/circuit breaker. As seen from Fig. 8.2 it is clear that for any fault current greater than I_A, the operating time for fuse to blow is smaller than the overload tripping time, and, for current lower than I_A the over-load tripping time is less than the blowing time of the fuse. For currents smaller than I_A, the fuse will however provide back-up protection, that is, it will blow if the over-load fails to strip. Referring to Fig. 8.2 it is observed that for current $I_B > I_A$ fuse operating time $t_1 < t_2$ *i.e.*, of the overload tripping time and for current $I_C < I_A$ fuse operating time $t_4 > t_3$ *i.e.,* of the overload tripping time.

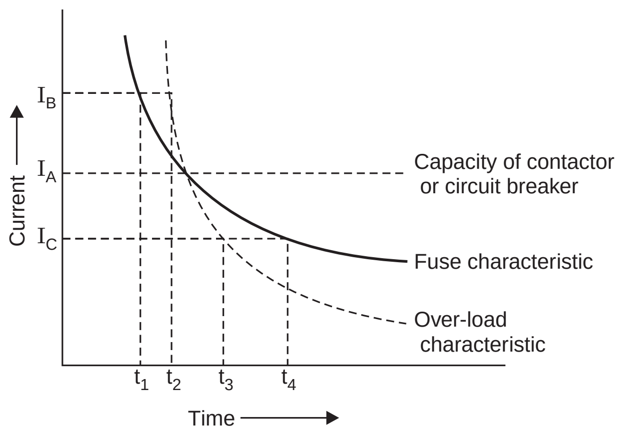


Fig. 8.2 Matching of fuse and overload relay characteristic for motor protection

8.3 OVERLOAD, SHORT CIRCUIT, AND OVER-TEMPERATURE PROTECTION

8.3.1 Overload and Short Circuit Protection

Motors are designed to operate under definite temperature rise limitation which depends upon the class of insulation used. The most serious effect of overload on motor is the temperature rise of the motor which tends to weaken the insulation and thus shorten its life. The expected life of insulation is halved for every 10°C rise in temperature above the recommended upper limit. Temperature rise depends on heating and heating is caused due to one or more of the following reasons:

(*i*) Types of load (continuous or intermittent)

(*ii*) Mechanical overloading

(*iii*) Reduced line voltage

(*iv*) Higher ambient temperature

(*v*) Inability of the machine to cool itself.

All the above reasons do not cause over current. For example, higher ambient temperature will not cause excessive current to be drawn by the motor but will cause over-heating. It is therefore clear that protective devices must be designed to trip the motor on the basis of temperature rather than on the basis of only over-load current. Operation of a circuit breaker is however an exception to this practice which operates to trip instantly to avoid damaging effects of a short circuit or a sudden current increase of extremely high value. Moulded Case Circuit Breakers, now being extensively used in L.T. installations, however, have both the over load and short circuit tripping facility. In MCCBs, currents greater than 10 times the rated current are broken instantly by magnetic release while currents less than 10 times are broken by thermal overload element having inverse time characteristic.

Although many designs and constructions of overload relays are used in control circuits for motors, they can however be classified on the basis of two general principles of operation viz.

(*i*) Thermal principle

(*ii*) Electromagnetic principle

In thermal overload relays (this has been explained in details earlier) the temperature sensitive element such as bimetallic strip of low melting point is used. The relay has inverse time characteristic *i.e.*, it responds more rapidly to increased current and vice-versa.

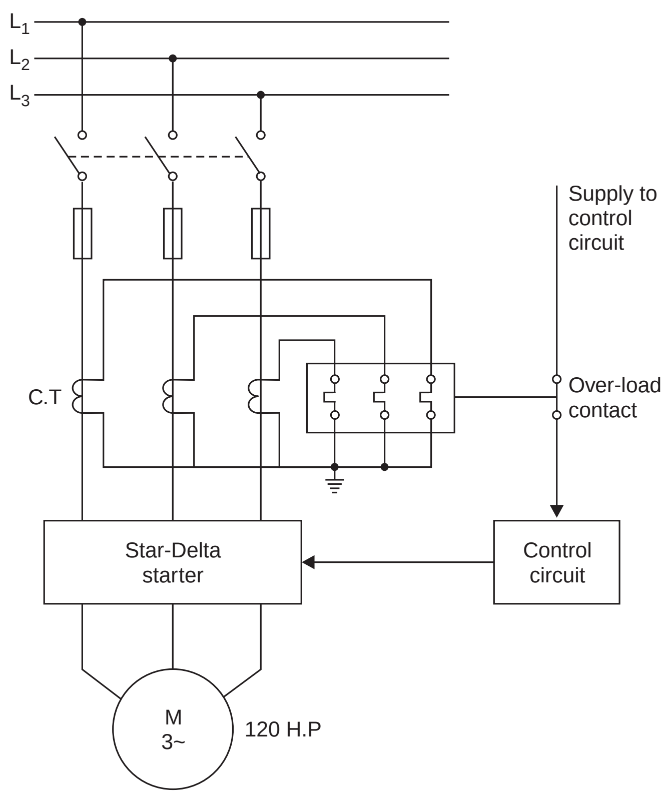


Fig. 8.3 Overload relay connection through CTs for overload protection of a motor of high rating

The electromagnetic type of relay operates instantly when over-current reaches some definite value. Time delay is obtained by using dashpot or magnetic varying assembly. Overload can be auto reset or hand reset. In hand reset, a knob has to be pressed to reset the relay.

For larger motors upto 1500 hp, overload relays are connected indirectly through current transformers, as heat dissipation becomes a problem in higher rating of overload elements. For example, for a 120 hp motor having a rated current of 170 amps, current tansformer of 200/5 A are connected to an overload relay of 3-6 range. Connection of an overload relay through current transformers has been shown in Fig. 8.3 in block diagram form.

For full load of 170 amps the overload needs to be set at $\frac{5}{200} \times 170 = 4.3$ A. For this overload setting at 4.3 A, the overload would protect the motor for rated current.

For still larger LT motors, as already explained, MCCBs are used which are available with thermal settings up 800 A.

For high voltage motors above 1200 hp, Circuit Breakers along with protective relays are used as shown in Fig. 8.4.

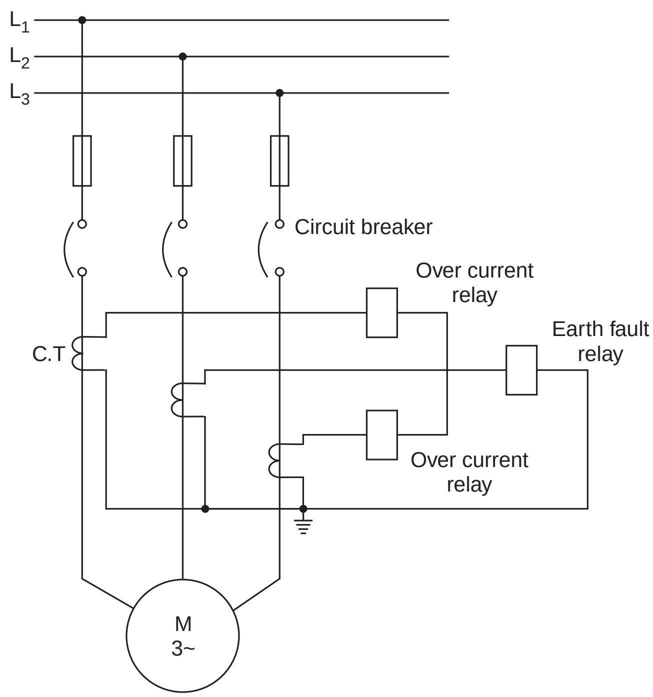


Fig. 8.4 Protection of H.T. motor using over current relays and earth fault relay

In this circuit two over current relays and one earth fault relay have been connected. Over current relay has instantaneous element as well as inverse time element. Inverse time element is set at somewhat less than 4 times the rated current of the motor allowing sufficient time delay so that the motor does not trip during starting.

Instantaneous element is set so as to pick up at little above the locked rotor current and provide short circuit protection. The earth fault relay also has instantaneous as well as inverse time delay elements. Its inverse-time delay element is adjusted to pick up at not more than about 20% of rated current or about 10% of the maximum available ground fault current whichever is smaller.

The instantaneous element should pick up at current ranging from about 2.5 to 10 times the rated current.

For larger motors, Percentage Differential Relaying is provided for short circuit protection. The advantage of this protection is that it provides faster and more sensitive protection than over current relaying and at the same time it does not operate on starting or on other transient over currents.

For continuous rated motors without short time overload ratings, the protective relays or devices should be adjusted to trip at not more than about 115% of rated motor current. For motors with 115% short time overload rating, tripping should occur at not more than about 125% of rated motor current. The tripping current should not exceed 140% of rated motor current even if the motor has high short time overload ratings.

8.3.2 Over Temperature Protection

For over temperature protection a special type of semiconductor device known as thermistor is used. It is also known as thermistor type overload relay. This makes use of a special semiconductor resistor, chemically similar to ceramic oxides. The unique property of the material is that the resistance is comparatively low at normal temperature, remains nearly constant upto some critical value, and has an extremely large positive temperature co-efficient of resistance within a narrow range above the critical temperature. Moreover, by varying the composition of doping of the ceramic disc which is about the size of a small tablet, the critical range can be controlled to permit selection of the temperature at which protection is required. Another good feature is that its power carrying capacity is self-limiting since the device has the tendency to increase its resistance as the temperature rises.

Since the device is small enough to be placed in direct contact with the motor winding and has good thermal response, it eliminates the delay factor in transferring heat to the actual sensing elements. The element is encapsulated in an epoxy resin having compatable thermal, electrical and mechanical properties and is generally capable of carrying the coil current of industrial type relays. In the circuit diagram of Fig. 8.5 three thermistors are shown placed at the surfaces of three stator windings of a motor.

During starting sufficient current will flow through the *CR* relay to actuate it as the temperature and resistance of the thermistors are low. When the START-push button is pressed the primary winding of control transformer T_1 gets energised and therefore the secondary winding sends direct current to *CR* relay through diodes D_1 and D_2. With the closing of *CR*, contact CR_1 closes and hence coil *M* gets energised. The three main contacts close and the motor is energised. Whenever there is excessive motor temperature due to some reason, the thermistor resistance increases and causes reduction in the current flowing through *CR* relay coil. Thus the *CR* relay drops, which in turn drops contactor *M* and therefore the motor stops.

The motor can be started again only when temperature and hence resistance of the thermistors drop to low values. For this, the relay is adjusted such that its pick up current is more than twice its drop out current.

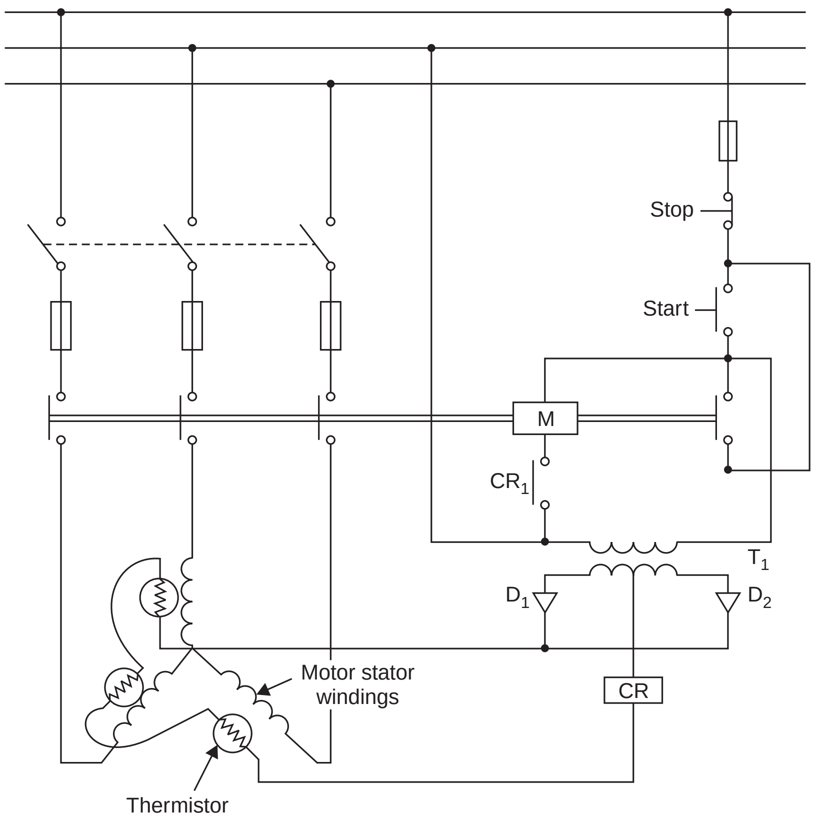


Fig. 8.5 Three phase motor protected by thermistor overload relay

8.3.3 Under Voltage Protection

If the starter of a motor is controlled by a maintained contact control device, the contactor will drop out when supply fails and will get energised again when supply is restored. This type of control can be used where the operator is not required to be near the machine. If, however, an operator is there on the machine, such unpredictable restarting of the motor may cause accident to the operator.

Motors are mostly controlled by push buttons and spring returned master switches which provide under voltage protections. Contactors do not pick up when supply is restored. *AC* contactors have a short drop out time. A system disturbance resulting in a voltage dip for a very short time will shut off the motors. In continuous process industries it is desired that the plant should not stop for such small duration of voltage dips. To achieve this, undervoltage protection as shown in Fig. 8.6 is used.

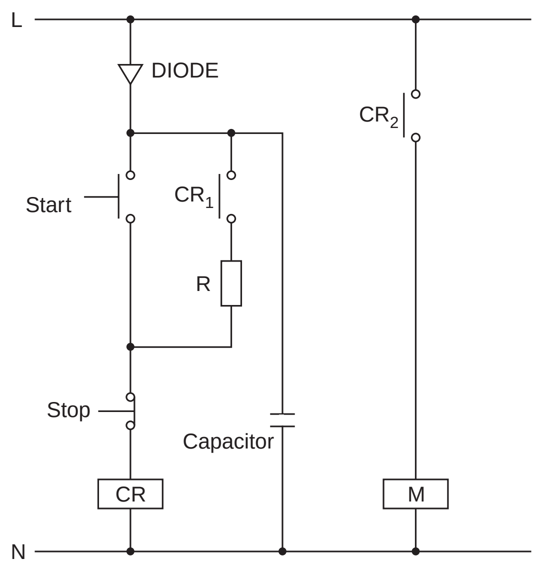


Fig. 8.6 Under voltage protection circuit

Main contactor *M* is controlled through normally open contact of under voltage relay *CR*. Relay *CR* is a dc relay fed through a rectifier. A capacitor gets charged to supply voltage. When power supply fails, capacitor discharges through the *CR* coil and keeps the relay closed for some time. If during this period supply is restored contactor *M* will automatically get energised due to already closed contact CR_2 of relay *CR*.

Careful judgement has to be exercised while using this protection scheme. High switching transients may result in automatic starting of the motor due to the magnetic flux remaining entrapped, especially in larger motors. It may be understood that undervoltage protection may not be provided to all motors as simultaneous starting of all motors on restoration of power supply will result in drawing of high current from the mains which can cause large voltage drop in the system.

8.3.4 Phase Failure and Phase Reversal Protection

If a fuse blows or a wire carrying supply to a motor breaks while the motor is running, the motor will continue to run on two healthy phases but will draw higher currents. This is known as single phasing of a 3-phase motor. The current in the two healthy phases would increase by 1.73 times. This would cause severe overheating of rotor due to negative phase sequence currents flowing as a result of unbalanced voltages. On the other hand, if two phases of supply to a three phase induction motor are interchanged the motor will reverse its direction of rotation. This action is called phase reversal and it can cause injury to people and damage to equipment in many applications. To protect a motor against these conditions, phase failure and phase reversal relays are used.

Many types of design of phase failure and phase reversal relays are available. One type of relay which provides protection for both phase failure and phase reversal consists of four magnetic poles the coil of which are excited by the currents of the two stator phases of the motor. These coils set up a rotating flux which intersects a disc pivoted at the centre. A torque is produced due to interaction of flux and eddy currents induced in the disc. Torque is made of two components: A clockwise rotating torque is produced by the normal polyphase supply and a counter clockwise torque is produced due to the action of the shaded poles.

When balanced three phase currents are flowing through the windings, clockwise torque is pre-dominant and it tends to turn the disc in clockwise direction. The turning of the disc, however, is prevented beyond a certain point when a projection on disc comes to rest against a stopper. If one line opens the polyphase clockwise torque disappears while counter clockwise torque due to pole shaders remains and rotates the disc in the counter clockwise direction. The projection on the disc actuates a contact which is connected in series with the contactor coil. In case of phase reversal, the polyphase torque helps the counter clockwise torque to turn the disc and actuate the contact disconnecting the motor from the line.

Another very common type of relay being used nowadays is based on detecting negative phase sequence currents during single phasing and during unbalanced voltages. This relay has two built in current transformers which sense currents of the motor. The secondary of *CT*s feeds a negative sequence filter. The output of this filter is proportional to the negative sequence component of currents. This output is fed to a sensor which detects the level of negative sequence components of the currents and thus trips the motor starter by opening its control contactor.

8.4 PROTECTION OF DC MOTORS

Like ac motors, dc motors are also protected against short circuit and overload faults. For overload protection, the thermal relay used however will have only one element as against three elements connected in series with the three phases in ac motors. In addition to these basic protections, field failure protection in shunt motors is provided by a field failure relay. When a shunt motor is run on variable speed by inserting a rheostat in series with the shunt field winding, two more protections namely Field Acceleration and Field De-acceleration protections are also provided. All these three types of field protections are discussed as follows:

8.4.1 Field Failure Protection Circuit for dc Shunt Motors

If the main field of a shunt motor or a compound motor is extremely weakened or if there is complete loss of main field excitation, a serious damage to motor can occur under certain conditions of operation. Since the speed of a dc motor is inversely proportional to flux, its speed tends to rise rapidly when the flux is decreased. If the field failure occurs on a motor which is coupled to a load, which can neither be removed nor be reduced to a very low value, the residual flux due to the open field will develop a torque which will not be able to sustain rotation. Thus the motor will stall, heavy current will be drawn from the mains and the overload relay will trip. On the other hand if field failure occurs on an unloaded motor or if the application is such that it permits the motor to be unloaded or overhauled as in the case of a hoist, the motor will not stall but instead its armature will accelerate quickly to a mechanically dangerous high speed or there will be destructive commutation. To prevent the above situation of over speeding, a field failure relay is used. This relay consists of a low voltage coil which is connected in series with the shunt field. The relay has a normally open (NO) contact which is connected in series with the main contactor coil circuit as shown in Fig. 8.7.

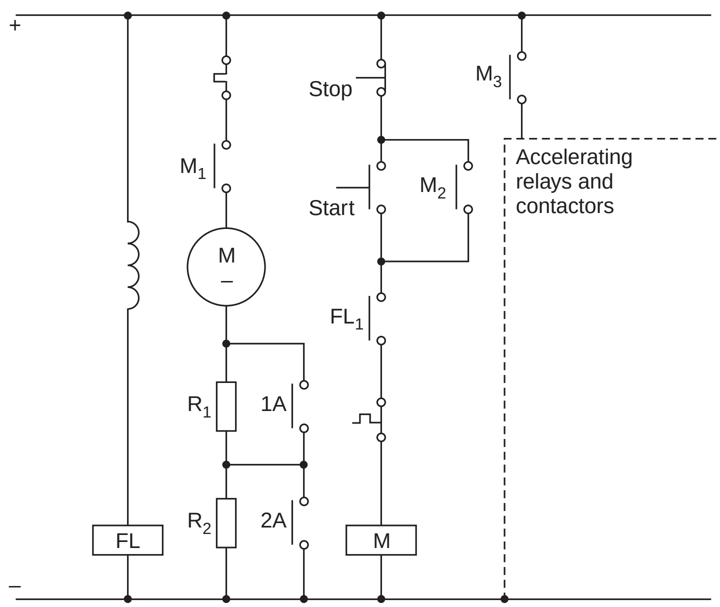


Fig. 8.7 Circuit diagram for the field failure protection of dc shunt motor

As seen from Fig. 8.7, the relay coil *FL* has been connected in series with the shunt winding. Normally, the relay remains picked up and its contact FL_1 in series with the overload contact remains closed. Whenever the field opens, relay *FL* drops and its contact FL_1 opens to de-energise main contactor *M*. Thus the *FL* relay prevents overload tripping or overspeeding of the motor, as the case may be.

8.4.2 Field Acceleration Protection Circuit

This protection scheme is provided in shunt motors, where speeds higher than the base speed (rated speed) are desired to be achieved by inserting resistance in the field winding. For a motor which is to be operated at speeds higher than the base speed, two difficulties are faced which are as under:

(*i*) If the resistance in field is inserted during starting, field current will be low and, therefore, the motor will draw heavy inrush current to produce the required torque (as torque developed depends upon fiux and armature current). To minimise the inrush current it is therefore desired that the motor should be operated on full field strength while it is accelerating *i.e.,* while accelerating resistors are being cut out and the speed is increasing. This means, the field regulating resistance should be inserted only when the motor has reached the base speed.

(*ii*) When the field regulating resistance is inserted, an extremely high armature current is drawn because motor must develop considerable additional torque to speed up. This excessive current peak can be avoided if resistance is inserted slowly or in multiple steps.

Both of the above requirements that is (*i*) short circuiting the field rheostat until the motor reaches base speed, and (*ii*) weakening the field slowly above the base speeds are fulfilled by a field accelerating relay. This relay limits the armature current peaks, prevents tripping of overloading relay, prevents commutator flash over and makes the motor accelerate smoothly to the desired higher speed.

Field acceleration relay *FA* is constructed with a series exciting coil having an intermediate tapping. Its contact is provided with magnetic blowout and an arc shield for efficient arc extinction. Pick-up value of relay is adjusted by varying the air gap between magnetic core and plunger by a slotted nut. The drop out value can be adjusted by varying the tension of a spring. The double coil design of the relay not only permits it to pick-up at higher currents when acceleration proceeds above the base speed but also at low currents when the motor is accelerating up to base speed with the accelerating resistances in circuit. Figure 8.8 shows the connection of a field accelerating relay in the control circuit.

In the control diagram shown in Fig. 8.8 it is seen that the tapped exciting coil is connected in series with the armature circuit. When the motor is started, armature current flows through all the turns of the accelerating relay and the relay closes its *NO* contact FA_1 across the field rheostat. Thus the field rheostat is short-circuited during the acceleration period. When contactor 3*A* gets energised it short circuits a portion of the field acceleration relay winding in addition to the accelerating resistance R_3. Now *FA* relay has fewer ampere turns for a given value of armature current. When the motor reaches base speed and armature current falls to normal value, the relay will drop and its contact FA_1 will open and resistance *RA* would come into the field winding circuit. Insertion of rheostat *RA* in the field winding will accelerate the motor further and in doing so armature current would rise sufficiently to acturate relay *FA*. The rheostat *FA* would be short circuited second time. The armature current will again decrease and same action of relay *FA* will be repeated. The relay may open and close its contact FA_1 several times before the motor reaches its final speed.

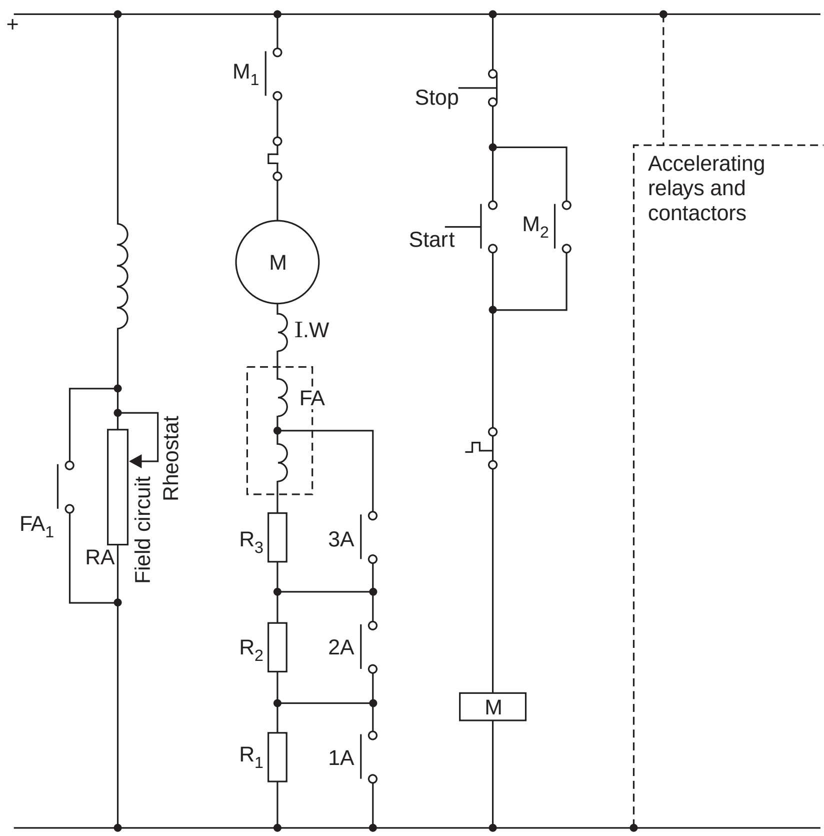


Fig. 8.8 Field accelerating protection circuit for a dc motor

The above operation can also be obtained by another type of field acceleration relay which has a shunt coil of many turns and a series coil of a few turns of heavy copper. The polarities of coil are additive *i.e.,* their mmfs produce fluxes in the same direction during acceleration. This relay is used in a circuit which uses delay type contactors for cutting out acceleration resistance. Connection of this type of relay when used in the starter with delay type contactors, has been shown in Fig. 8.9.

In this circuit when the START-push button is pressed contactors 1*A*, 2*A* and 3*A* are energised, their contacts $1A_1$, $2A_1$ and $3A_1$ open and therefore resistances are inserted in the armature circuit. Contactor *M* closes after energisation of contactor 3*A* by its contact $3A_2$ and is held energised through its own contact M_1. Energisation of contactor 3*A* in turn causes energisation of shunt winding of relay *FA*. Its contact FA_1 opens to insert rheostat R_A in the shunt winding of the motor. As soon as contactor *M* is energised its contact M_3 opens and de-energises contactor 1*A* which drops after its pre-set delay. Its contact $1A_1$ closes and shorts resistance R_1. Interlocking contact of 1*A* in the circuit of contactor 2*A* opens and thereby contactor 2*A* de-energises after the pre-set delay. When finally contactor 3*A* drops and cuts off resistance R_3, it also de-energises shunt winding of relay *FA* due to opening of contact $3A_3$. Relay *FA* thus drops and its contact FA_1 opens and rheostat *RA* gets inserted in the circuit. As already explained, inrush of current takes place which generates sufficient ampere turns in the series coil and this causes the relay to pick up and hence rheostat *RA* is shorted a second time. Thus relay *FA* closes and opens its contact several times before the motor reaches its final speed.

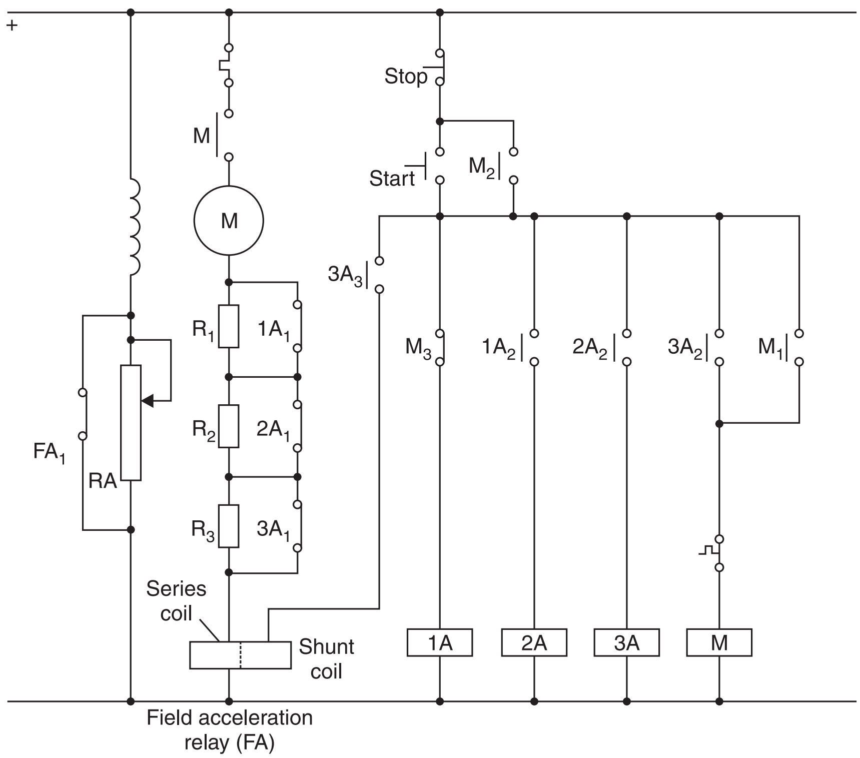


Fig. 8.9 Protection for dc shunt motor using field acceleration relay having series and shunt coil

8.4.3 Field Deceleration Protection Circuit

This protection is required when a shunt or a compound motor running at high speed is to be brought down to a low speed by cutting down field circuit rheostat resistance. When the field circuit resistance is suddenly cut out or decreased the flux would rise suddenly while the speed of motor will still remain high. It thus gives rise to high counter emf (cemf is proportional to flux and speed), induced in the armature which may exceed the impressed supply voltage. Under such conditions cemf will send back current into the mains and this increase in current will be so quick that flash over may occur at the commutators. This abnormal condition can be avoided by using a field deceleration relay which would automatically weaken the field during the slow down period.

Field deceleration relay *FD* is similar in the construction to the field acceleration relay *FA* having shunt and series exciting coils. The shunt and series coils are so connected that the polarities of their mmfs are oppositely directed. The *NC* contact of the relay is connected across a separate field deceleration resistor *RD* as shown in Fig. 8.10.

To understand the working of the circuit, let us assume that under normal conditions the motor is running at a higher speed with rheostat *RA* in series with field, winding. In this condition deceleration relay *FD* will get dropped out (as mmfs of two coils cancel each other) and its contact FD_1 will short resistance *RD*. When the portion of Rheostat resistances *RA* is cut out of the circuit to decrease the motor speeds the counter emf becomes more than the impressed supply voltage and thus armature current flowing through the series winding suddenly reverses. This causes the mmfs due to shunt and series coils to be additive and therefore the relay *FD* picks up and opens its contact FD_1 across resistance *RD*. Insertion of *RD* in series with the field winding reduces the field flux and thus the counter emf is brought down quickly so that normal current flows through the armature. This normal current flow causes relay *FD* to drop. Its contact FD_1 recloses across resistance *RD* and the motor settles down to its reduced speed setting.

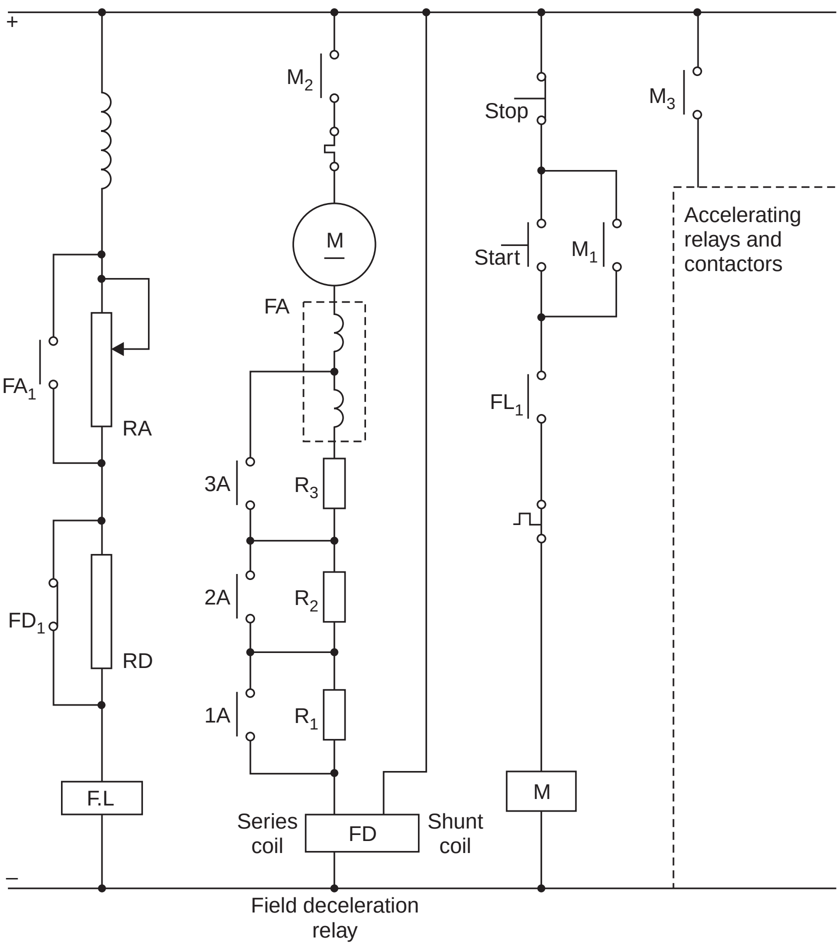


Fig. 8.10 Circuit diagram showing field failure, field acceleration and field deceleration protection for a dc shunt motor

REVIEW QUESTIONS

1. How will you match the fuse characteristic with the starting current characteristic of a motor ? Explain with the help of a diagram.
2. Explain how the contactor rating, fuse and overload relay characteristic are matched for motor protection.
3. What are the different possible causes of over heating of a motor ?
4. Show how an ordinary overload relay of 2-5 A range can be used for protection of a 150 hp motor.

5. Draw protection circuit for a H.T. motor using current relay and earth fault relays.
6. What is a thermistor ? Show how it can be used for over-temperature protection of a motor.
7. Why under voltage protection is not provided for all motors in industries ?
8. Draw under voltage protection circuit for an induction motor.
9. Disuss field failure protection circuit of dc shunt motor.
10. Disuss field acceleration protection for dc shunt motor using field acceleration relay having two coils in series and intermediate tapping.
11. Discuss field acceleration protection for dc shunt motor using a relay having series and shunt coils.
12. When do we require field deceleration protection ? How is this achieved in dc shunt motors ?
13. Temperature rise of a motor depends on:
    (*a*) mechanical overloading (*b*) reduced line voltage
    (*c*) higher ambient temperature (*d*) all of these.
14. When the temperature of motor rises above the prescribed upper limit, the life of its insulation is halved for every:
    (*a*) 5°C rise in temperature (*b*) 10°C rise in temperature
    (*c*) 15°C rise in temperature (*d*) 20°C rise in temperature.
15. As the temperature rise above the critical temperature of a thermostat, its resistance;
    (*a*) decreases (*b*) increases (*c*) remains constant.
16. If one fuse of a motor gets blown during running, the current in the healthy phases will rise to .... times the normal current.
    (*a*) 1.70 (*b*) 1.73
    (*c*) 1.75 (*d*) 2.00.

9

Industrial Control Circuits

9.1 INTRODUCTION

In industry a control engineer is frequently called upon to design and modify control circuits as per specified requirements. He is also expected to slove unusual problems occurring in control circuits. Considerable amount of knowledge and experience is required to accomplish the above mentioned tasks.

In modern industry very few machines operate from a single motor. Most of machines have a number of operations. These operations are controlled by different motors or by a number of cylinder piston assemblies powered by hydraulic (oil) or pneumatic (air) pressure. The specific sequence of operations are obtained through relay contacts, timer contacts or through actuation of sensing devices like limit switches, pressure switches, temperature switches etc. As the number of components used on a machine increase, the circuit becomes more and more complex.

This chapter includes study of a number of industrial circuits of varying degrees of complexity. Most of the machines discussed here are general purpose machines found in most of the industries. For each circuit discussed, first a brief description about the machine operation has been given and then the working of its control circuit has been discussed in detail. Working of complex circuits has been explained in steps. Having thoroughly understood the working of all the circuits given in this chapter one should be able to read and analyse any industrial control circuits that he may encounter in practice.

9.2 PLANER MACHINE

Planer machines (also called a shaper) is one of the basic machines used in all mechanical workshops. This machine is used for shaping a job/work piece to required dimensions by a cutting tool. This machine can be of two types, *viz.,*

(*i*) Where the job or the workpiece is fixed and the cutting tool moves to and fro to remove the extra material from the job.

(*ii*) Where the cutting tool is fixed and the job or the workpiece moves to and fro.

Here, we will study the second type of machine in which the cutting tool is stationary and the job fixed on a table (also known as bed) moves to and fro. The to and fro movement of the bed is achieved by forward and reverse rotation of the motor. Rotational motion of the motor is converted into longitudinal motion with the help of rack and pinion arrangement. Rotational motion of the motor is transmitted to the load with the help of an electrically operated clutch. When the dc coil of this clutch is energised the motor pulley gets coupled to the bed side pulley. When the coil is de-energised the motor pulley gets decoupled from the bed side pulley and the bed comes to standstill quickly. The clutch coil is energised along with the motor irrespective of whether the motor is to run in forward direction or in reverse direction. The limit of forward and reverse movement of the bed is determined by the positions of two limit switches as shown in Fig. 9.1. This figure also shows the rack and pinion arrangement for obtaining to and fro movement of the bed.

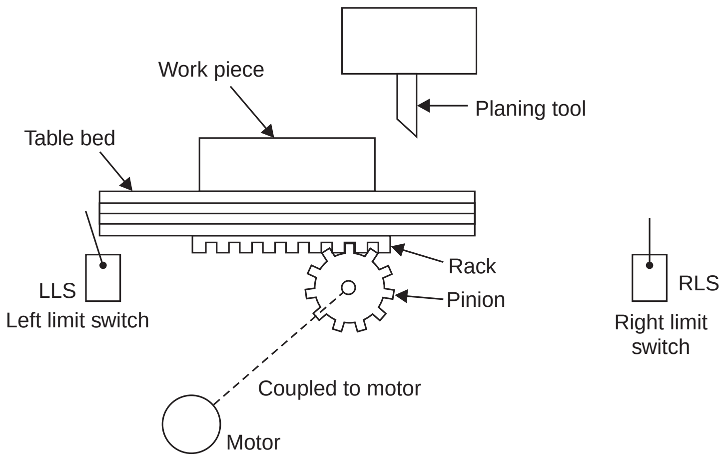


Fig. 9.1 Planner machine arrangement

When bed moves towards right side the work piece placed on table bed is worked upon by the cutting tool. Forward movement towards the right direction will be stopped due to actuation of a limit switch RLS. Actuation of this limit switch will also initiate bed movement in the reverse direction *i.e.,* from right to left direction. Reverse motion of the bed would stop when the left side limit switch LLS gets actuated, and immediately will start another cycle of bed movement. It may be understood that the cutting tool works on the job only in forward movement of the bed. No material is cut from the job in the reverse direction. To start with, the cutting tool is given a fixed depth of cut. After one cycle of bed movement the tool gets horizontal feed (*i.e.*, step movement perpendicular to the direction of bed movement) automatically through mechanical gear arrangment. The starting position for the machine is that the bed should be in the extreme left position with the limit switch LLS actuated.

If the bed is stationed in between the two limit switches the machine can be started by pressing any of the Forward or Reverse-push buttons. The drive for the machine movement is a 3 phase squirrel cage induction motor which is controlled by a forward/reverse starter. The forward/reverse starter of this motor is controlled through two limit switches namely, the left side limit switch LLS and the right side limit switch RLS. These two limit switches restrict the movement of bed or the motor in either direction. The power circuit of the motor includes simple connections for forward reverse operation of the motor. In Fig. 9.2 only the control circuit has been shown.

Working of the control circuit of Fig. 9.2 is explained as follows:

(*i*) As discussed earlier, the pre-condition for starting the machine in Auto mode is that the bed should be in extreme left position actuating the limit switch *LLS*;

(*ii*) When the bed is at extreme left position and the limit switch *LLS* is actuated, normally open (*NO*) contact LLS_1 will be closed and normally closed (*NC*) contact LLS_2 will be open. In this position of the bed the right side limit switch *RLS* will be in unactuated condition, its contact RLS_1 being open and RLS_2 being closed.

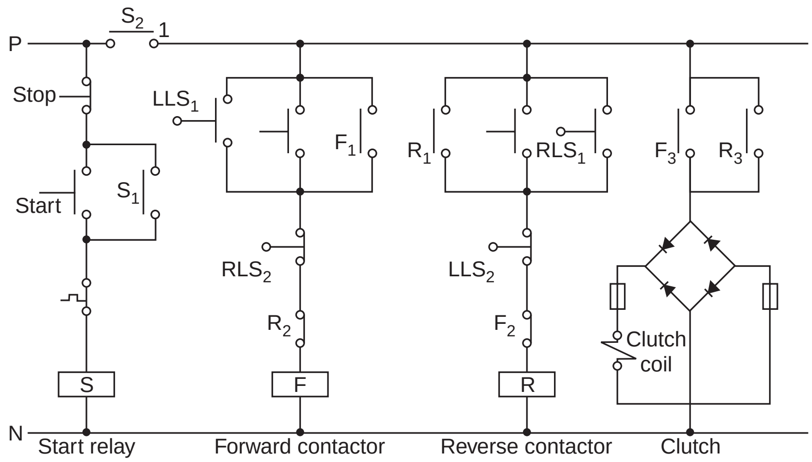


Fig. 9.2 Control diagram for planner machine

(*iii*) Now, when the START-push button is pressed starting relay S gets energised and is held through its contact S_1. Supply then reaches the control bus through contact S_2.

(*iv*) With the energisation of control bus contactor F which runs the motor in the right (forward) direction will get energised through closed contact LLS_1 and normally closed contacts RLS_2 and R_2. Contactor F will now get hold through its own contact F_1 since LLS_1 will open as soon as the bed starts moving in right direction.

(*v*) Electrically operated clutch will get engaged as soon as contactor F is energised (the clutch coil will get energised through Contact F_3). Clutch coil will get energised again when the reverse contactor R will be energised, contacts F_3 and R_3 being connected in parallel. DC current is fed to the coil by a rectifier bridge to have a strong magnetic action;

(*vi*) When the bed reaches extreme right position limit switch RLS is actuated, its contact RLS_1 closes while RLS_2 opens and causes de-energisation of contactor F and thus supply to the motor is cut off and the clutch is also disengaged. The bed comes to stop quickly.

(*vii*) Due to closing of limit switch RLS, contactor R will be energised when contactor F drops. Contactor R will get energised through closed contact RLS_1 and normally closed contacts LLS_2 and F_2, and will be held through its own contact R_1. Its contact R_3 will energise the clutch coil. Closing of contactor R will therefore cause movement of the bed towards the left till left side limits LLS is actuated.

(*viii*) When the limit switch LLS is actuated contactor R will get de-energised due to opening of contact LLS_2 while contactor F again will get energised through closed contact LLS_1 and normally closed contact RLS_2 and R_2. Thus it is seen that after completing one cycle of movement, the bed again starts automatically for the second cycle and so on without having any need to press the Cycle START-push button. This to and fro motion will continue till the STOP-push button is pressed to de-energise the start relay.

(*ix*) If the bed stops in between due to power failure, the machine would not start in Auto mode when Cycle START-push button is pressed after the supply is restored. This is because when both the limit switches LLS and RLS are in de-actuated condition their contacts LLS_1 and RLS_1 are open. Thus neither contactor F nor contactor R picks up when the start relay is energised. In this condition to start the machine the bed has to be moved to the extreme left or to the extreme right by pressing the respective Reverse or Forward push buttons. These push buttons are connected in parallel with the limit switch contacts LLS_1 and RLS_1 as shown in the control diagram.

9.3 SKIP HOIST CONTROL

Skip hoist is used in industry for shifting material from floor level to some higher altitude. Skip hoist consists of a trolley which moves on rails on an inclined plane. On reaching the top of the incline the trolley tilts and drops the material into a large container called silos. The material from silos is then utilised as per requirement. Tilting of trolley at the top is done by mechanical means. The trolley is tilted only upto a particular angle and it remains in that position for a preset time to allow all the material to fall into silos. After the preset halt at the top the trolley returns down the incline. See Fig. 9.3.

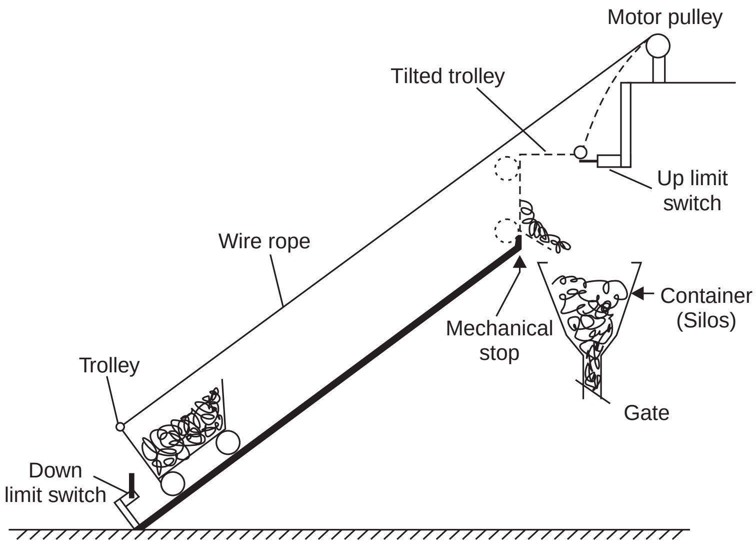


Fig. 9.3 Schematic representation of a skip hoist

The hoist is operated by a rope wound on the drum attached to the shaft of an induction motor. Two limit switches are provided, one for stopping the trolley at bottom of the incline, and the other at the top of the incline. The motor is stopped quickly by an electromagnetic brake which is not shown in the figure. Normally, when power is off, the brake remains engaged and it opens when the motor is energised.

The movement of trolley in the skip hoist is governed by a 3 phase, 415 volt induction motor. This induction motor is controlled by two contactors U and D. The power diagram is similar to Forward/Reverse starter. When contactor U is energised the motor runs in forward direction and the trolley is pulled up the incline. When contactor D is energised the motor runs in reverse direction and the trolley moves down in the incline. Thermal overload relay is provided for the protection of motor.

The control circuit for the skip hoist has been connected between phase (P) and neutral (N), as shown in Fig. 9.4. When the START-push button for upward motion is pressed, contactor

U gets energised through normally closed contact D_2 and LSU_1 the upper limit switch. As the U contactor closes the motor runs in forward direction and the trolley is pulled up. When trolley reaches the top of the rail, its front wheel is stopped at the mechanical stop provided on the rail while the motor is still pulling the trolley. As a result, the trolley is tilted as shown through dotted lines in Fig. 9.3. The motor stops when *UP* limit switch *LSU* is actuated and its *NC* contact LSU_1 opens and de-energises contactor U. At the same time normally open contact LSU_2 of the upper limit switch closes and energises time delay relay T. The motor remains off and the trolley stays tilted for a period, as set on the time delay relay T. This delay is provided so as to allow all the material in the trolley fall into the silos. When the relay operates, its contact T_1 closes and energises contactor D (responsible for downward motion) through normally closed contact U_2 and normally closed contact LSD_1 of the limit switch. As the contactor D closes, motor runs in the reverse direction and the trolley starts moving in downward direction. When the trolley reaches the down position, limit switch *LSD* is actuated and thus its normally closed contact LSD_1 opens and de-energises contactor D.

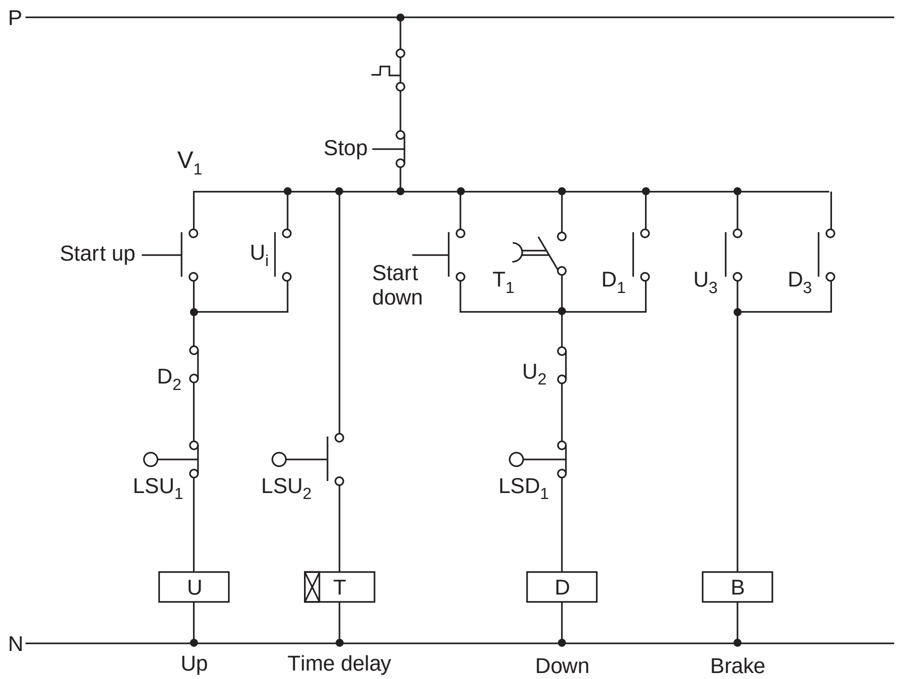


Fig. 9.4 Control circuit for a skip hoist

For the next cycle of hoist, the START-push button for up motion is pressed when the trolley has been filled with material to be taken up. For manual operation of the downward motion, the DOWN-start push button can be pressed. This push button is necessary for bringing the trolley to down position in case of power interruption during the downward motion of the hoist. The brake coils of the motor are controlled by contactor B. The brake opens when brake coils are energised through closing of contactor B. Contactor B is energised by the normally open contacts U_3 and D_3 of Up and Down motion contactors. The brake remains engaged when both the contactors are in de-energised condition.

9.4 AUTOMATIC CONTROL FOR A WATER PUMP

The control operations discussed in this section are of a water pump which pumps water from a storage tank into a pressure tank. The pump is allowed to run until the tank is full upto a certain level. To maintain sufficient pressure in the lines, air pressure is maintained into the overhead tank above the water level. The physical arrangement of the pump and the two tanks along with the control components have been shown in Fig. 9.5.

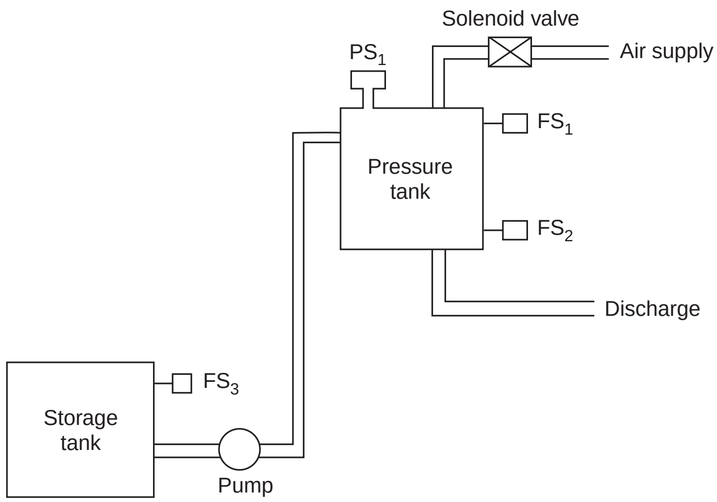


Fig. 9.5 Schematic arrangement of overhead pressure tank

Various requirements for the proper functioning of the control circuit are as follows:

(*i*) The control operation of pump should be possible either on Manual mode or on Auto mode. A three position selector switch may be used for this purpose.

(*ii*) It should be possible to control the pump so as to maintain the water level in the pressure tank between a high and a low limit.

(*iii*) The pump should be prevented from running in case the water level in the storage tank falls below a certain level.

(*iv*) A certain amount of air pressure on the pressure tank be maintained whenever required.

Brief explanation of the functions of various control components has been provided before explaining the control circuit.

Float switch FS_1 will actuate when water of the tank would reach its upper most level H. Under such limiting position the float switch will stop the pump. Float switch FS_2 would sense the lowest level (L) of water in the tank. When this float switch actuates, it would start the pump to raise the water level upto the upper limit. To let pressurised air enter the tank above the water level, a solenoid valve has been provided. When the coil is energised the valve opens and air enters the tank. When sufficient pressure is built up inside the tank, pressure switch PS_1 actuates and supply to solenoid valve is cut off. Float switch FS_3 in the storage tank has been provided to sense a very low level of water. If the water level in the storage tank would reach a very low level the switch would put off the pump, as otherwise, the pump would fail to lift water from such a low level. The control circuit using all these components has been shown in Fig. 9.6.

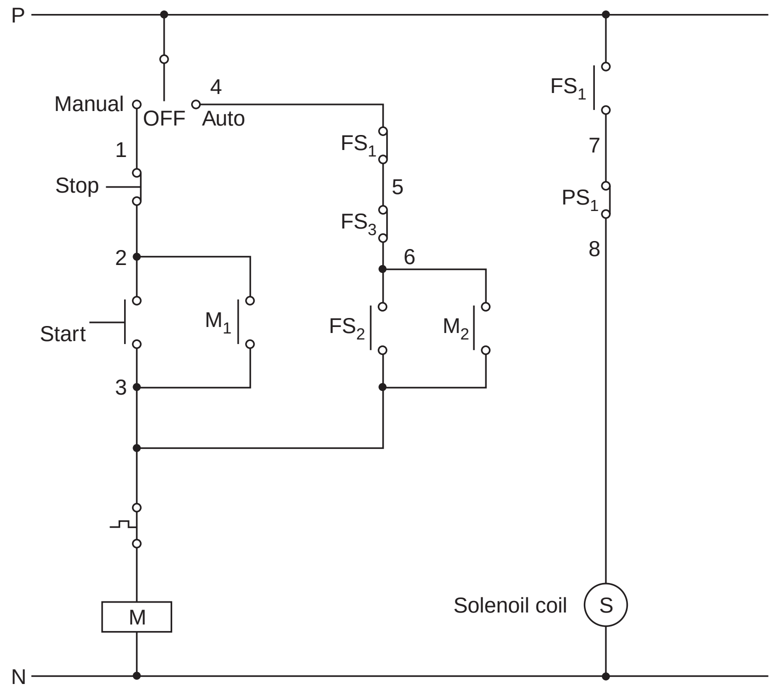


Fig. 9.6 Control circuit for a pressurised overhead tank

In this control circuit, lines have been marked as 1, 2, 3 and so on so as to help explaining the control circuit.

Manual Operation

The pump is run on manual mode when there is some fault in the circuit for automatic operation, otherwise the pump is normally run in auto mode. To run the pump in manual mode, the selector switch is put on manual position '*M*' and line 1 is energised. Contactor *M* of the pump motor gets energised and is held through its own contact M_1 when the START-push button is pressed. The operator has to watch and see that when the tank is nearly full, the pump is stopped by pressing the STOP push button.

Auto Operation

For automatic operation of the pump, the selector switch is put on Auto mode. On Auto mode of the selector switch, control supply reaches line 6 through normally closed contacts of upper level float switch of discharge tank FS_1 and low level float switch FS_3 of the storage tank. Supply reaches line 6, if contact FS_1 and contact FS_3 are not actuated *i.e.,* if water is below the upper most level (*H*) in pressure tank and above the lowest level in storage tank. Contactor *M* gets energised when FS_2 is actuated *i.e.,* water level falls below the lowest level (*L*) in pressure tank. Contactor *M* gets energised through the close contact of FS_2 and is held through its own contact. Float switch FS_2 then loses control and the pump continues to run even when water rises above the lower limit (*L*). When the upper limit float switch FS_1 is actuated and its normally closed *NC* contact opens to disconnect supply at line 5, contactor *M* will get de-energised and the pump would stop. Contactor *M* is also de-energised if FS_3 actuates and opens its normally closed, *NC* contact when water level in the storage tank goes below the lowest level.

From the circuit it is seen that the coil of the solenoid valve is energised when pressure in the tank is below a certain setting and the normally closed contact PS_1 of the pressure switch is closed. Another condition for allowing the air to enter the tank is that water level should be above the upper level limit set by float switch FS_1. When the water level will fall below this level, FS_1 will open and air supply will be cut off. When the pressure of air inside the tank increases above the setting, contact PS_1 opens to de-energise the solenoid S.

9.5 LIFTING MAGNET

Lifting magnets have become an essential material handling equipment where iron and steel are processsed such as in steel mills, foundries, ship operations, scrap yards etc. Lifting magnets are used for handling every form of steel such as scrap, pellets, pig iron and various kinds of finished products such as castings and moulds in foundries, wheels, rails, tie plates, ingots, coiled sheet steel, pipes any type of machine parts.

A lifting magnet is put to use with the help of over-head crane. A crane which has a lifting magnet hanging on the hook of its hoist rope is also called a raw material crane. This crane has got two hoist motors, one is for normal lifting and the other, called auxiliary hoist motor, is for moving the lifting magnet up and down. Figure 9.7 shows a lifting magnet in diagrammatic form.

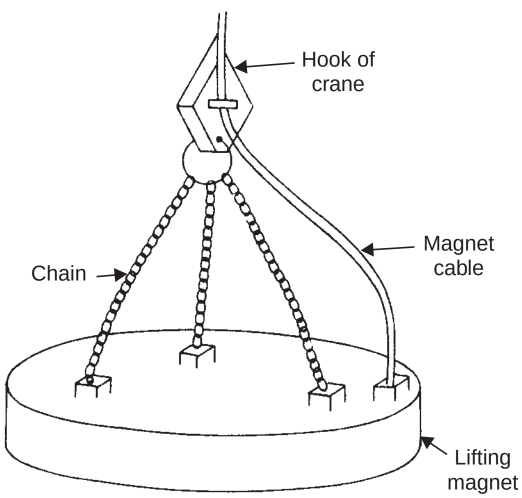


Fig. 9.7 Lifting magnet

For lifting magnets circular construction is the most popular one as it permits the operator to handle most types of material without the necessity of positioning the unit accurately with respect to the load. Rectangular type of magnets on the other hand are particularly used for handling of regular shapes of iron and steel such as bars, billets, plates, pipes etc.

Connections to the exciting coil of the magnet is done through a cable which runs along with the hoist rope. The cable also winds and rewinds over a durm on the crane depending upon whether the hook moves up or down. In the magnet, the exciting coil is placed over the central pole so that mmf producing flux penetrates into the work to be lifted.

The control circuit for energising and de-energising the highly inductive coil circuit of lifting magnet is discussed as follows:

For magnets of smaller sizes, Manual drop magnet controllers are used. These are designed with three position master controller having OFF, LIFT and DROP-points or with three push buttons. The circuit diagram for this type of a controller is shown in Fig. 9.8 (a).

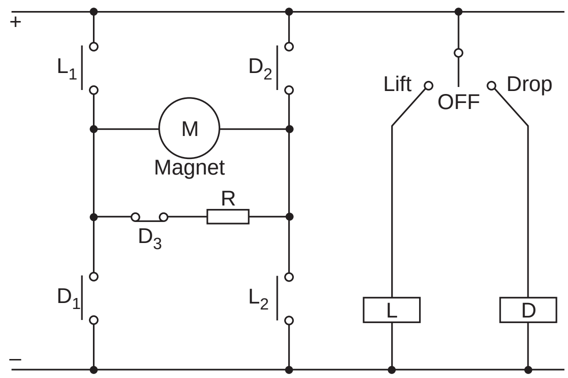


Fig. 9.8 (*a*) Lifting magnet circuit using three position switch

When the master controller is in OFF position, both contactors L and D are de-energised. When the lever is brought to LIFT position, contactor L gets energised and closes its contact L_1 and L_2 to energise the magnet coil. When magnet is to be demagnetised, Master controller lever is brought to DROP-position which energises contactor D and de-energises contactor L. Reverse current flows through the magnet coil through contacts D_1 and D_2 to demagnetise it. When the lever is brought to OFF position, magnet coil discharges through resistance R through normally closed contact, D_3 of contactor D.

Automatic Drop Magnet controllers are generally used with larger magnets. These have two position controllers. In the ON position the magnet is connected to the line and therefore exciting coil is energised. In the OFF position first the magnet discharges fully and then is demagnetised of its residual magnetism by a reverse current. The circuit diagram for this arrangement has been shown in Fig. 9.8 (*b*).

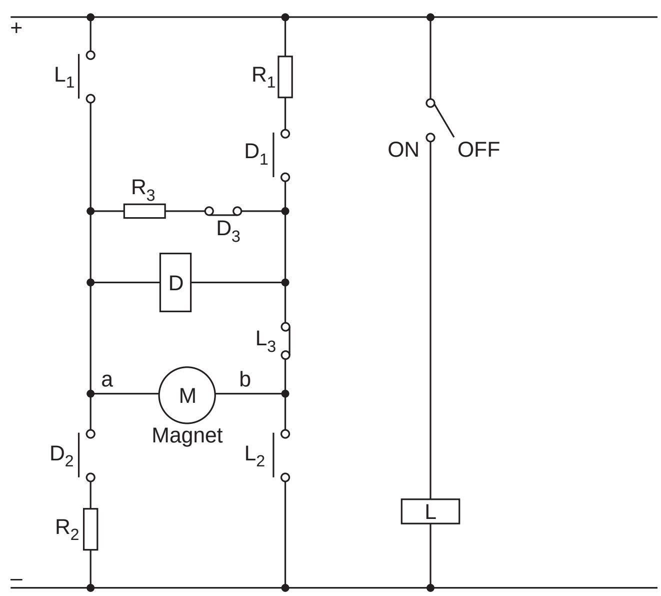


Fig. 9.8 (*b*) Control circuit for lifting magnet with atuo-drop using two position switch

When the master switch is moved to the ON position and contactor L picks up, its two line contacts L_1 and L_2 close and a *NC* contact L_3 opens. Current passes through the coil in the direction from a to b. When the load is to be dropped, master switch is moved to the OFF position, contactor L is de-energised and its contact L_1 and L_2 open. Opening of L_1 and L_2 disconnects power supply to the magnet. As soon as power gets disconnected a large voltage gets induced in the highly inductive circuit that retards current decay. This voltage energises the contactor D placed across it. Contact D_1 and D_2 close while D_3 opens. The exciting coil of the magnet discharges its energy back to the mains and current gradually diminshes. Resistances R_1 and R_2 are provided in the circuit to limit the discharge current since the induced voltage in the coil would be very high. The direction of current through the exciting coil is from a to b. As the induced voltage falls, current will first become zero and then reverse. Current will flow from b to a and will demagnetise the magnet of its residual magnetism. When the induced emf of the coil falls sufficiently, the contactor D drops. Its line contacts D_1 and D_2 open while contact D_3 closes. Now the exciting coil of the magnet will discharge its remaining energy in the resistance R_3.

9.6 CONTROL OF ELECTRICAL OVEN

Electrically heated ovens are used for a wide variety of purpose in industry, *e.g.,* in heat treatment of metals like annealing and hardening, stoving of enamelled wire, drying and baking of cores in foundry, drying and baking of pottery etc. Ovens using wire resistance heating elements can be made to produce temperatures upto 1000°C. Temperatures upto 3000°C can be obtained by using graphite elements. However, such a high temperature is usually obtained by some other convenient methods.

Oven enclosure is constructed by using insulating materials between two metal frames or by lining fire bricks inside a metal enclosure. The heating elements are mounted on the top or at the bottom or on the sides, according to the application. An oven can be of batch type or of continuous type. In a batch type oven, material to be heated is stacked inside the oven and then the doors are closed. The doors are opened when the heating time is complete. In a continuous type oven, material to be heated travels slowly through the oven. Continous loading of material into the oven is made. Material to be heated is placed on trolley which move on rails placed inside the oven. Trolleys containing material are loaded into oven at the entrance door while hot material on trolleys are taken out at the exit door. In ovens if heat transfer from heating elements takes place entirely by radiation then there would be a possibility of considerable temperature difference in various parts of the object being heated. To obtain uniform heating of the material, air inside the ovens is circulated by employing blowers. Blowers pass air over the heating elements and then over the object placed in the oven. In this way a certain degree of uniformity in heating is obtained. However, the side of the material which first comes in contact with air flow gets heated up slightly more than on the other sides. This is because heat is given up by air as it travels pass over the material. More uniform heating can be obtained by periodically reversing the direction of flow of air. It is difficult to make actual calculation of the watts or kilowatts electrical power required to heat an object to a desired temperature in a definite time period. The main problem lies in determining the heat losses.

Various losses in a resistance over are

A = Heat used in raising temperature of oven.

B = Heat used in raising temperature of container or carrier.

C = Conduction of heat through walls.

D = Escape of heat due to opening of the door.

If W is the heat required to raise the object to required temperature, then the efficiency of the oven is given by

$$\text{Efficiency} = \frac{W}{W + A + B + C + D}$$

Efficiency of most ovens lies between 60 to 80%. Resistance ovens are operated on low voltage network of 240 or 415 V supply and they are generally built upto a maximum of 100 kW rating. Temperature control in ovens is obtained by changing current through the heating elements. Current through the heating elements is changed by connecting them in different fashion. Some methods of control of current through the resistance elements are as follows:

(*i*) Using variable number of resitance elements: This method tends to give uneven temperature in the oven if the elements not in use are not evenly distributed over the oven surface. Even distribution of such elements, however, leads to complicated wiring.

(*ii*) Series parallel and star-delta connection of heater elements: This is the simplest and most widely used method of control of current. When this method is used in combination with the method mentioned in (*i*) above, sufficient variations in temperature is obtained for most practical purposes.

In smaller ovens where automatic control of temperature is not required the heater elements are switched ON and switched OFF with the help of drum switches. In ovens of higher ratings requiring automatic temperature control, contactors are used to switch ON or switch OFF the heater elements. Contactors are automatically de-energised by a thermostat switch when required set temperature is reached. The thermostat controls the temperature of the oven within a certain range which is determined by the differential setting of thermostat. For example, if temperature setting and differential setting are 250°C and 20°C respectively then the temperature of the oven will vary from 250°C to 230°C. The heater will be cut off at 250°C and will be energised again when temperature would fall to 230°C. Series-parallel and star-delta type of connections of heaters are discussed as follows:

(*a*) **Series parallel connection of heating elements.** It is sometimes required to reduce the heat in an oven to a low level particularly during the weekend when normal production is stopped.

We already know that heat produced in a resistance heating element is proportional to the square of the voltage applied. Therefore any reduction in applied voltage will greatly reduce the heat. For example, if voltage of heater element is reduced from 240 to 120 V, the heat reduction will be reduced to one fourth.

Half the line voltage can be applied to resistance elements by reconnecting them in series from parallel connection. When two elements are to be in series they should be of equal kilowatt rating so that voltage is divided equally between them. Figure 9.9 shows a single phase circuit for series-parallel connection using a drum switch or a selector switch.

In Fig. 9.9 two heater elements HE_1 and HE_2 are controlled through a drum switch. When the drum switch lever is on right hand side, the heater elements get connected in parallel due to closing of drum switch contacts A, B, and D. Full supply voltage of 240 V appears across each of the heater elements. For having a lower temperature, the drum switch lever is shifted towards the left hand side due to which contacts A and C get closed. The heater elements get connected in series across the supply voltage. The voltage appearing across each heater element is halved if they are of equal wattage rating, and heat produced is reduced to one fourth.

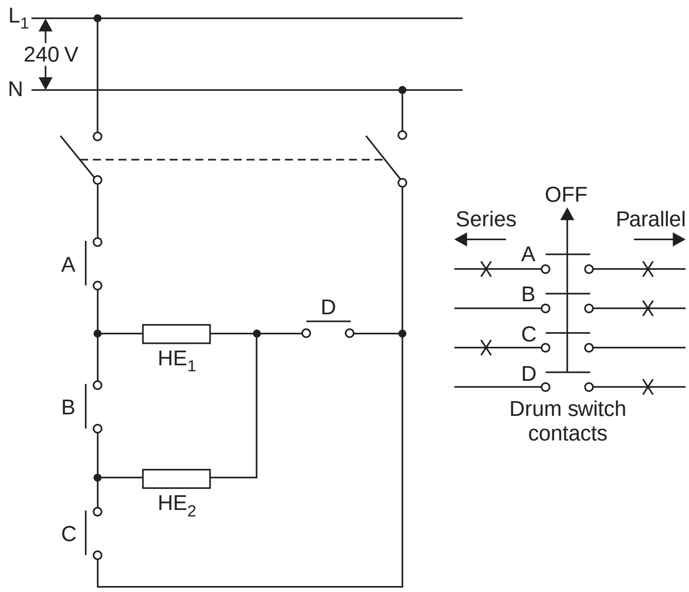


Fig. 9.9 Series parallel connection using drum switch

Series-parallel connection of heaters in 3 phase system has been shown in Fig. 9.10. In a 3 phase system connection of heater elements are controlled by contactors, if automatic control of temperature is desired. Where automatic temperature control is not desired, drum switches can be used.

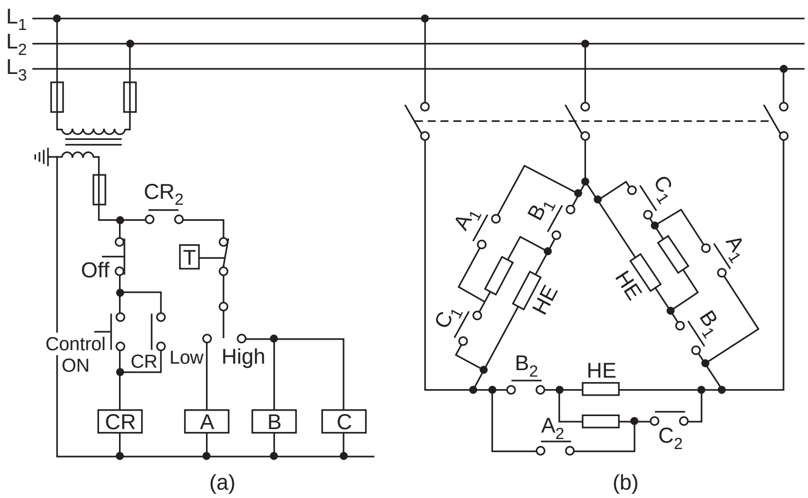


Fig. 9.10 Series parallel connection of heaters in a 3-phase system
(*a*) Control circuit (*b*) Power circuit

As in the control diagram of Fig. 9.10 (*a*), when the control relay *CR* is ON, through a selector switch either contactor *A* or contactors *B* and *C* can be energised. When the selector switch is set for low heat, contactor *A* is energised through closed contact of thermostat (temperature controller). Contactor *A* when energised connects the two heater elements in each phase in series. The line voltage thus gets divided across the two elements. When the selector switch is put on high heat contactor *A* is de-energised and contactors *B* and *C* are energised. Referring to power diagram it can be seen that closing of contactors *B* and *C* results in the two heater elements of each phase getting connected in parallel across full line voltage.

When the selector switch is on high heat, the thermostat setting should also be made at the required higher temperature. Thermostat will control the temperature within a certain range depending upon the differential setting.

(*b*) **Star-delta connection of heating elements.** Figure 9.11 shows a three phase connection where the full line voltage gets applied across each heating element connected in delta when contactor *B* closes. Heater elements can be switched over into star connection if instead of contactor *B,* contactor *A* gets closed. In star connection the voltage across a heater element will be $V/\sqrt{3}$ times the voltage in delta connection, *V* being the line voltage. Thus in star connection the heat will be 33% of that in delta connection.

A selector switch is to be used to energise contactor *A* when low heat is required, and contactor *B* when high heat is required. The thermostat contact connected in series with the selector switch has been used to get automatic switching off of contactors so as to maintain the required temperature.

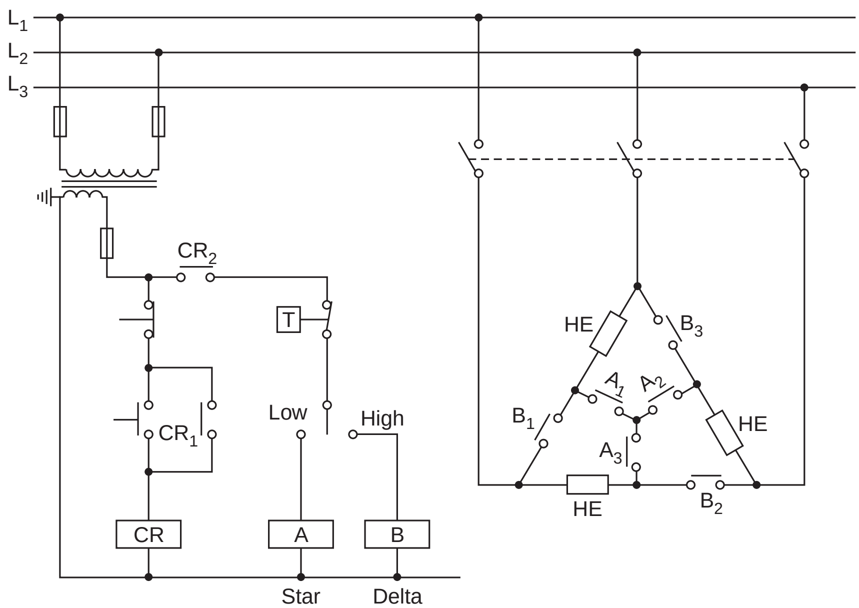


Fig. 9.11 Star-delta connection of heating elements

9.7 OVERHEAD CRANE

Overhead cranes are used for shifting heavy weights within a limited area. The area is decided by the span of 'long travel motion' and 'cross travel motion' of the crane. The wheels of the crane structure move on rails mounted on concrete pillar or steel towers. Weights in the defined area of the crane are picked up and shifted to any desired position with the help of three motions. These motions are hoisting, lowering, long travel *i.e.,* forward/reverse, and cross travel which is perpendicular to long travel.

An over head crane has to handle heavy weights in terms of thousands of kilos requiring high starting torques in all the motions. This necessitates the use of slip ring induction motors for causing all the three motions. Figure 9.12 shows a crane in three views.

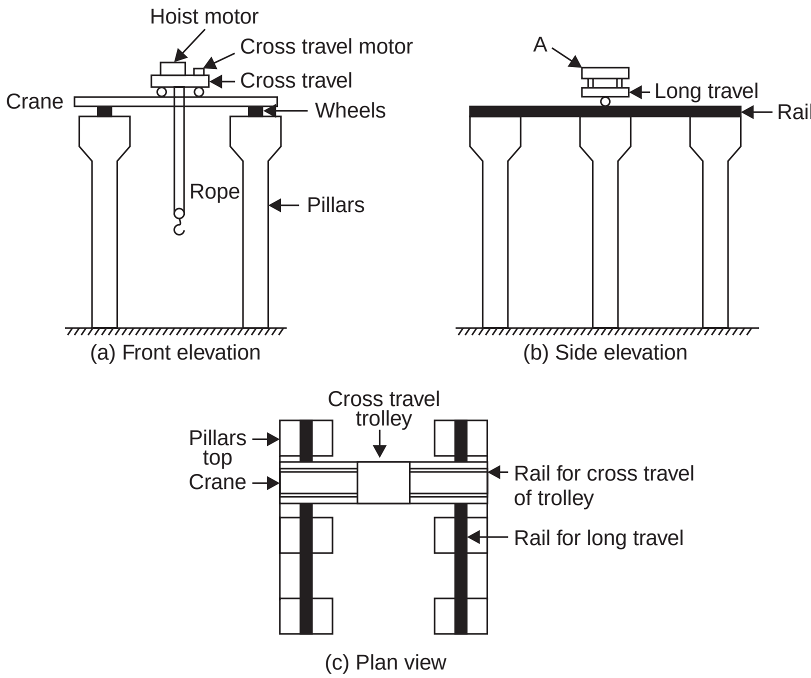


Fig. 9.12 Overhead crane

As shown in Fig. 9.12 (*b*), the whole of the crane structure denoted by letter *A* moves on the rails for long travel, driven by a slip ring induction motor known as long travel or *LT* motor. This motor is installed on the structure itself. The motor rotates the wheel shaft with the help of sprockets and chain arrangement. On the structure itself are mounted rails for cross travel (*CT*) trolley. The *CT* trolley moves on these rails as it is driven by a cross travel motor mounted on the trolley itself. The Hoisting motor is also installed on the trolley. Hoisting is done by a rope wound on the drum attached to the motor shaft. A hook hangs at the bottom of the rope which is engaged with the weight to be lifted. Winding of the rope on a drum results in raising of the weight, whereas rewinding of the rope results in its lowering. The operation of crane is done from a cabin on the crane. Cabin is situated on the lower side of the crane in such a way as to allow clear visibility of the shop floor to the operator. In the cabin are installed three master controllers for hoist, long travel, and cross travel.

An outer view of a master controller has been shown in Fig. 9.13

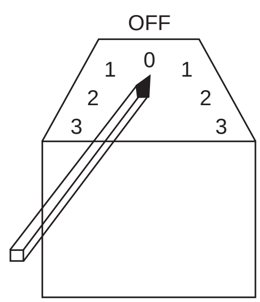


Fig. 9.13 Pictorial view of a master controller

The master controller has three or four steps on each side. At every step of the master controller, a contact actuates which is used in the control circuit. Positions 1, 2, 3 of the master controller in one direction gives three speeds of the motor in one direction. By moving the handle in the other direction the motor can be run in the reverse direction at three different speeds. An important interlocking arrangement made in crane control is that the control can be switched ON only when all the master controllers are in the neutral or OFF position. If this interlocking is not provided accidents can occur due to abrupt starting of the motor. The motion of the crane either in long travel or in cross travel direction is restricted by mechanical stoppers, as well as by control limit switches and power limit switches. Hoist *i.e.,* up down motion is restricted by use of control and power limit switches. In total six control limit swicthes, two for each type of motion are provided.

Supply to the crane is given through overhead bus bars known as down shop leads or DSL. Four bus bars run along the whole length of the long travel below the crane. These bus bars are supported on pillars or steel towers with the help of porcelain insulators. Three bus bars are energised by three phases and the fourth is connected to earth. Current is collected from the bus bars by current collectors which are fitted on a channel on the crane. The arrangement has been shown in Fig. 9.14.

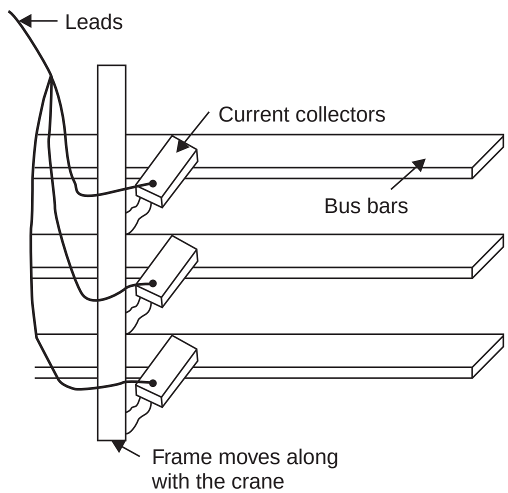


Fig. 9.14 Bus bar arrangement for an over-head travelling crane

The current collectors slide on the bus bars when the crane moves in the long travel direction. Three leads of a cable are connected to three current collectors. Supply through the cable is taken to the control panel on the crane.

Now, we will discuss the power diagram for the crane. Connections for hoist, *LT* and *CT* motors are basically of forward/reverse starter except for the hoist motor in which an extra contactor is used for single phasing of the motor for a few seconds during lowering operation. This is done so as to avoid a sudden jerk on the rope due to the weight when lowering operation has stared. Single phasing of motor during lowering results in development of less torque, and since the brake does not open fully, sudden jerk is avoided. The largest motor on the crane is the hoist motor. For example for a 10 Ton capacity overhead crane the hoist motor is of 30 hp, the *LT* motor is of 10 hp, and *CT* motor is of 5 hp.

For the sake of simplicity power circuit and control circuit for only the hoist motor have been shown in Fig. 9.15 and 9.16 respectively. As shown in Fig. 9.15 contactors 1*M* and 2*M* are respectively for raising and lowering motion while 2*M′* is for single phasing during lowering operation. Resistance in the rotor circuit is cut off in steps by contactors 1*R*, 2*R* and 3*R*.

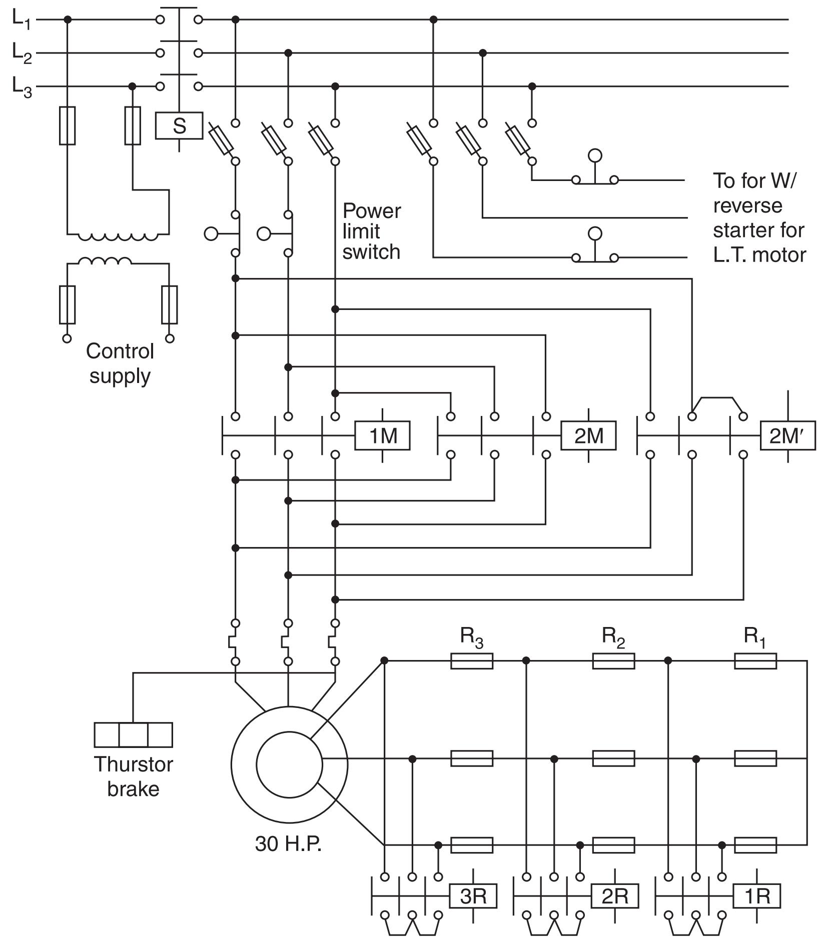


Fig. 9.15 Power circuit diagram for an overhead crane

Before going into the working of the control circuit it is essential to become familiar with the operation of the master controller. Let us refer to the table for master controller given in Fig. 9.16. The master controller has got six contacts numbered 0, 1UP, 1DOWN, 2, 3, and 4. The 0 contact is normally closed (NC) while all other contacts are normally open (NO). Note the mark X placed in front of any contact denotes its operation. For example, contact 0 operates and becomes open for all the lever position from 1 to 4 on either side. Contact 1 *UP* operates and becomes closed for lever operation towards the right at position 1 of the lever and also remains operated for further movement of the lever. Contact 1 DOWN operates on position 1 to 4 on the left side. Contact 2 operates on second position of the lever on both sides and also remains operated for position 3 and 4 on both sides. Contact 3 operates on position 3 of the lever on both sides and also remains operated on position 4. Contact 4 operates when the lever is moved to position 4 on either side.

In the control circuit start relay *S* gets energised and remains held only when the '0' contacts of all the three Master controllers (Hoist, *LT* and *CT*) are in closed position *i.e.*, levers are in neutral or OFF position. Energisation of relay *S* activates the control circuit through contact S_2. Detailed working of control circuit has been explained in steps as follows:

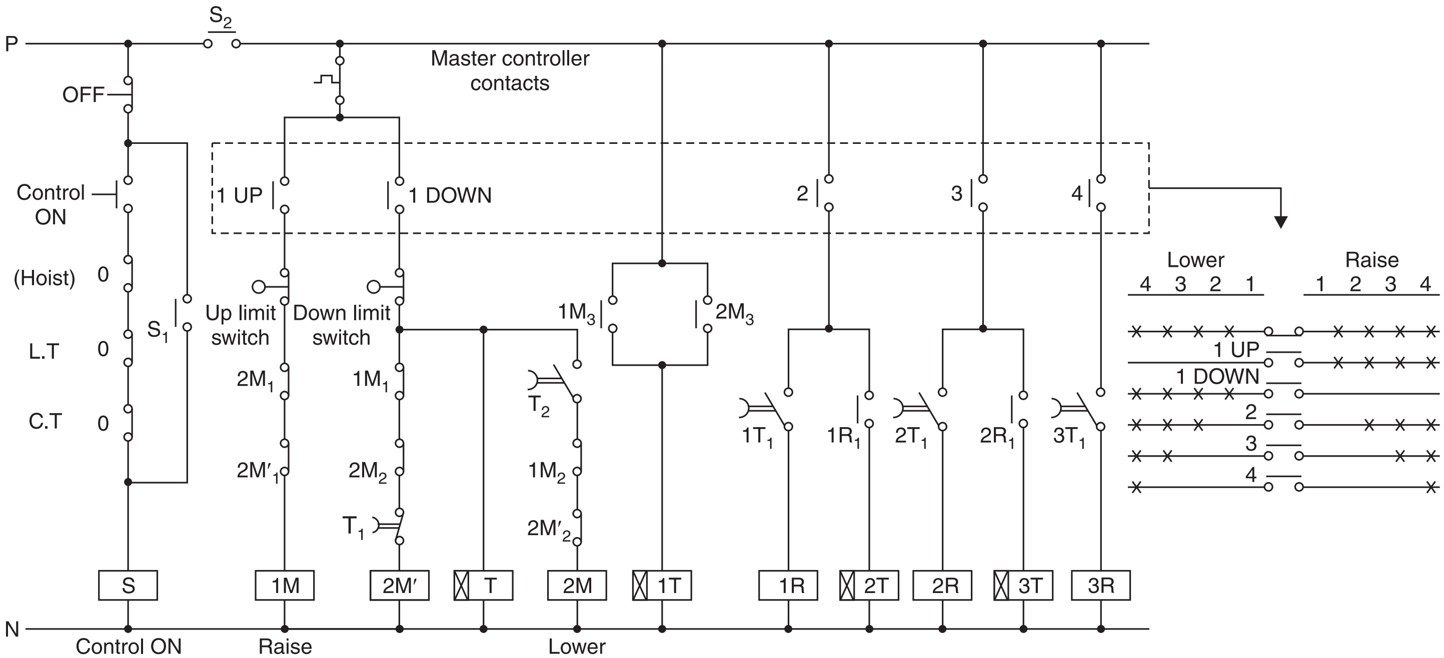


Fig. 9.16 Control circuit for an overhead crane

(1) On moving the controller handle to position 1 on the right for raise operation, contact 1*UP* closes. Closing of this contact energises contactor 1*M* provided the up limit switch contact is closed. When contacor 1*M* closes the motor starts to raise the weight up at slow speed as all the resistances R_1, R_2 and R_3 are connected in the rotor circuit.

(2) When 1*M* is energised, its auxiliary contact $1M_3$ closes and energises timer 1*T*. After the pre-set time, 1*T* operates and its delayed contact $1T_1$ closes in the coil circuit for resistance contactor 1*R*. Contactor 1*R* however gets energised when the controller is brought to position 2, towards right *i.e.,* when the controller contact 2 closes. Energisation of 1*R* cuts off one set of resistance R_1 from the rotor circuit and therefore the motor accelerates to a higher speed.

(3) Auxiliary contact $1M_1$ and $1M_2$ also opens when contactor 1*M* gets energised. They provide interlocking so as to avoid simultaneous operation of lower motion contactors 2*M* and 2*M′*.

(4) Energisation of contactor 1*R*, also leads to energisation of timer, 2*T* through the auxiliary contact $1R_1$.

(5) When timer 2*T* operates, its contact $2T_1$ would close but contactor 2*R* will get energised only when the controller is brought to position 3. Energisation of 2*R* cuts off another set of resistance R_2 from the rotor circuit and therefore the motor accelerates to third higher speed.

(6) Energisation of contactor 2*R* also leads to energisation of timer 3*T* through the auxiliary contact $2R_1$.

(7) When timer 3*T* operates and the lever of the controller is brought to position 4, the resistance contactor 3*R* gets energised which accelerates the motor to the final speed by cutting off the last step or resistance R_3 from the motor circuit.

(8) It may be understood that the timer contacts are used in series with the controller contacts to avoid the possibility of bringing the motor to a higher speed directly. Even if the operator moves the handle directly from OFF-position to fourth position the motor will accelerate to fourth speed in steps because timer 1*T*, 2*T*, and 3*T* will provide delays in energisation of contactor 1*R*, 2*R* and 3*R*.

(9) At the same time it should also be clear that the timers provide only minimum delay required between the energisation of contactors 1*R*, 2*R*, 3*R*. The delay between their energisation can be increased by the operator. He can run the crane on any desired speed by keeping the controller lever on the corresponding position.

(10) To prevent over hoisting of the motor, an UP-limit switch is provided which de-energises contactor 1*M*. The DOWN-limit switch would de-energise contactor 2*M* when the lower limit is reached. Power limit switch contacts are provided only for upper limit. These contacts are connected in two phase leads going to motor terminals. They work as back up protection and operate only if the control limit switch fails to operate.

(11) For downword motion *i.e.,* for lowering, when the lever of the master controller is moved towards the left side position 1, contact 1 DOWN is actuated which energises contactor 2*M′* through normally closed contact of the DOWN-limit switch. This contactor connects only two phase supply to the motor. Thus due to single phasing effect less torque is developed by the motor and the brake also does not release fully. A timer *T* also gets energised in parallel with contactor 2*M′*. When the timer *T* operates after a few seconds its contact T_1 opens and de-energises contactor 2*M′*, whereas

contact T_2 closes to energise contactor $2M$. Energisation of contactor $2M$ supplies three phase power to the motor for lowering operation. This single phasing of motor during starting of lowering operation, as already described, prevents a sudden jerk on the rope due to the weight hanging on the hook.

(12) The auxiliary contact $2M_3$ of contractor $2M$ starts cutting off the resistance in the same sequence as in the case of raising operation, already described.

9.8 BATTERY TROLLEY

A battery trolley is operated by a small dc series traction motor energised from a 24 V battery placed on the trolley itself as shown in Fig. 9.17. The seat of the trolley can be lowered or raised with the help of a hydraulic motor pump and a manually operated hydraulic valve. The forward and reverse operation of trolley is done by two special push buttons which operate a set of five finger contacts. Hydraulic pump motor can be started by pressing an ordinary push button.

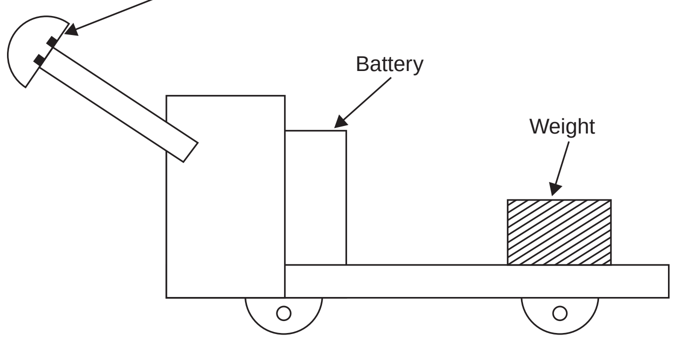


Fig. 9.17 Battery operated trolley

A battery trolley is used in industry to shift any type of weight like finished products, motors, heavy tools etc., from one place to other in the shop floor. This trolley is, however, especially useful for transporting racks because its seat can be lowered or raised by hydraulic pressure. To transport racks the seat of the trolley is to be inserted below the standing rack and then the seat is to be raised by running the hydraulic motor and operating the hydraulic valve. When the seat is fully raised it would lift the rack from ground level. The traction motor can now be run to transport the rack to the desired place. At the destination the seat is lowered, and when the rack comes back to the ground level, the trolley can be taken out from below the rack. Before the control and power circuit for a battery trolley is discussed it is essential to get familiar with the special push buttons used for forward/reverse motion of the trolley. The operation of special push buttons is explained with the help of Fig. 9.18.

The normal positions of the contacts, when neither of the push buttons is pressed have been shown in Fig. 9.18 (*a*). Figure 9.18 (*b*) shows the positions of the contacts when the Forward-push button is pressed. When the Forward-push button is pressed slightly, the strip containing contact 3 bends. As a result contacts 1′ and 3 get broken and contact 3 and 5 get closed. The arrangement is such that on further pressing the push button the strip containing contact 4, 5 and 6 bends in the direction shown by dotted lines and as a result contact 6 touches contact 7. On fully pressing the push button, the strip containing contact 7 also bends and contact 7 and

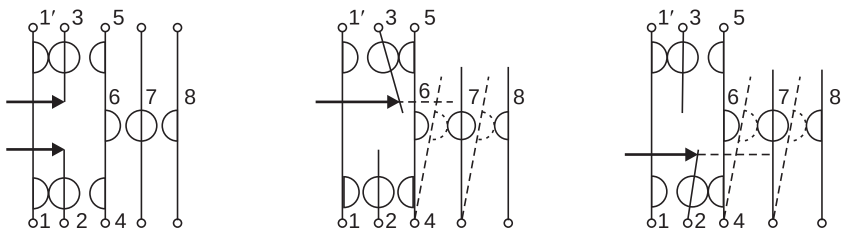


Fig. 9.18 Operation of special push-buttons for battery trolley

8 touch each other. Thus when the push button is fully pressed, connection is made between contacts 3-5, 6-7 and 7-8 resulting in making continuity between contacts 3 and 8. It is to be noted that during pressing of Forward-push button, contacts 1 and 2 continues maintaining contact with each other. Actuation of finger contacts in three steps by gradually increasing pressure on the push button is used for obtaining two speeds of the trolley. Figure 9.18 (*c*) explains the sequence of contact actuation when the reverse-push button is pressed. When the Reverse-push button is pressed contact 2 breaks away from contact 1 and gets connected to contact 4. On further pressing of the push button, contacts 6 and 7 touch each other and when the push button is fully pressed contacts 7 and 8 also touch each other. Thus finally we have continuity between contacts 2 and 8. During the process of pressing the Reverse-push button, contact 1′ and 3 continue to touch each other.

Forward/reverse push button control of the traction motor has been shown in Fig. 9.19 (*a*). Figures 9.19 (*b*) and (*c*) show the direction of current through armature and field windings of the traction motor respectively for forward and reverse motion.

As shown in Fig. 9.19 (*a*) a 24 V battery has been used for traction and control. Contactors A and B have been used for obtaining two speeds of the motor. They are energised from contacts 7 and 8. Resistance R_1 is connected in the armature circuit for obtaining a lower speed. When this resistance is bypassed by contactor B, higher and final speed is obtained. The hydraulic pump motor and also a dc series motor are controlled by contactor C. A toggle switch SW_1 is used for switching supply to the control circuit. The explanation of control circuit is as follows:

When the Forward-push button is pressed, strip containing contact 3 bends and touches contact 5 as shown in Fig. 9.19 (*b*).

Due to the actuation of these contacts, current will flow in the series field and the armature winding as shown by arrows in the figure. Current starts from +ve terminal of the battery and flows in a clockwise direction through the series field winding and the armature winding. This current will, however, start flowing when the push button has sufficient pressure on it and contact 6 and 7 touch other, and contactor A is energised (refer Fig. 9.19). When contactor A closes its contact A_1, the armature gets energised with a resistance R_1 in the circuit. Let the motor run in say forward direction when the Forward-push button is fully pressed. Contacts 7 and 8 will make contact thus establishing continuity from 3 to 8. This will energise contactor B. Its contact B_1, on closing, would short circuit resistance R_1 in the armature circuit. The motor will therefore run on full speed.

When the trolley is to be driven in the reverse direction the reverse push button is pressed. First, contact 2 will touch contact 4. On further pressing when contact 6 touches 7, contactor A is again energised. Now the current through the series field winding will flow in anticlockwise direction while current through armature winding will continue to flow in the same direction as shown in Fig. 9.19 (*c*). The direction of rotation of the motor will thus get reversed. The sequence of operation of contactors *A* and *B* remains the same. When contactor *B* is energised the motor would attain final speed in the reverse direction.

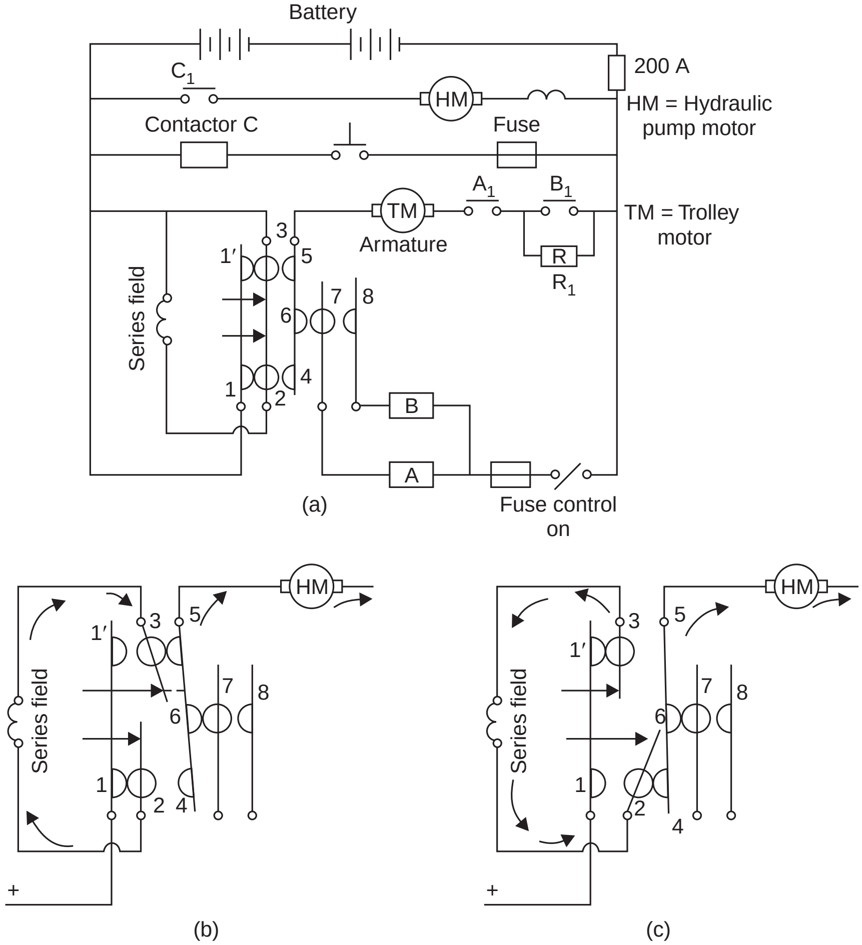


Fig. 9.19 Control of battery trolley

The hydraulic pump motor is controlled by a push button which when pressed energises contactor *C*. The pump would run as long as the push button is held pressed.

The seat of the trolley is lowered or raised manually by operating the lever of a valve. The push button of the pump motor and the lever of the valve have to be pressed simultaneously.

To ensure proper operation of the trolley the battery should be well maintained. With proper care and maintenance the life of the battery can be prolonged and trouble free services ensured. To have continuous working of a trolley for 24 hours, two batteries are sufficient. When one is being used the other should be kept on charging. At the end of each shift of the factory the batteries can be interchanged. A discharged battery should be topped with distilled water and then put on charging. A fully charged battery should give a specific gravity reading of 1.280 and should never be allowed to discharge below a specific gravity level of 1.140.

For details on maintenance of battery the user may refer to the manufacturers handbook on battery maintenance.

9.9 BATTERY OPERATED TRUCK

Battery operated truck is used in industry for shifting heavy weight from one place to another in the shop floor. It is also commonly known as fork lifter as the weight is lifted up on two forks. These forks can move up and down on an assembly of two vertical shafts and this total assembly of forks and vertical shafts can be tilted forward and backward as shown in Fig. 9.20 (*a*).

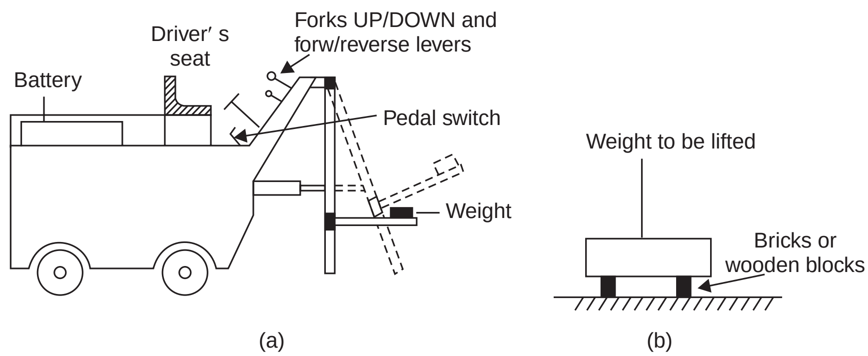


Fig. 9.20 Battery operated truck (*a*) Pictorial view (*b*) Weight placed on wooden blocks or bricks

It may be understood that the forks can be utilised to lift a weight only when the weight has already been placed on some wooden blocks or bricks as shown in Fig. 9.20 (*b*). The forks are first lowered and inserted below the weight and then they are raised to lift the weight. After lifting the weight, the truck can be taken to desired position by running the traction motor. If a weight lying on the ground is to be transported with help of the truck the weight has to be lifted first by an overhead crane or chain pulley block for placing it on the forks.

Two identical batteries of 36 V each are installed on the truck for control of the traction motor and the hydraulic pump motor. The truck is run either in the forward direction or in the reverse direction by a dc compound motor. Forward/reverse direction of rotation is selected through a selector switch provided on the control desk fixed in front of the driver. A control ON selector switch is provided on the control desk fixed in front of the driver. Forward/Reverse selector switch is also provided on this desk.

The motor runs either in forward or in reverse direction when a pedal switch is pressed by the foot of the driver. This pedal switch looks similar to the accelerator pedal in a common four wheel automobiles. Five separate speeds are made possible as the pedal switch is gradually pressed down. The pedal switch has five micro-switches which operate in sequence when the pedal is pressed. The pedal switch is spring returned *i.e.*, it comes back to its original position when the pressure on the pedal is released. Two batteries operate in parallel for the first three speeds and then in series for the fourth and the fifth speed of the traction motor.

Raising/lowering or tilting of forks is done with the help of cylinder piston assemblies which operate on hydraulic oil pressure. Hydraulic oil pressure is generated by a pump driven by a dc series motor. Hydraulic oil from the pump flow to the cylinder piston assembly through a manually operated hydraulic valve. Two valves, one for UP/DOWN operation of the forks and the other for forward/backward movement are provided. The levers for operating these valves are accessible on the control desk in front of the driver. When any of the levers is operated, it first actuates a micro switch which gives signal for running the hydraulic pump motor. The lever also operates the associated valve which allows pressurised oil to flow into the associated cylinder piston. In the control circuit an interlocking is provided which ensures that the hydraulic pump motor can only be run when the batteries are in parallel. This means that the forks cannot be operated when the truck is running on fourth and fifth steps of speed.

The power circuit diagram for the truck and control circuit have been shown in Fig. 9.21 and 9.22 respectively.

An explanation of the truck control circuit has been given in steps as follows:

(1) Pressing the control ON-push button energises control relay *C*. Through its auxiliary contact, control circuit gets energised while its power contact *C* in the power circuit energises the shunt field winding of the traction motor.

(2) Initially when the truck is at standstill and the pedal is not pressed, all the contacts viz S_1 to S_5 are in 0-1 position as shown by dotted lines in the control diagram.

(3) As soon as the control relay *C* is energised contactor 7*C* and 9*C* get energised through the pedal switch contact S_4. The power contacts of 7*C* and 9*C* connect the batteries in parallel.

(4) Forward/Reverse operation of the truck is chosen by selecting For/Rev selector switch connected in series with the pedal switch contact S_1.

(5) When the pedal switch is slightly pressed with foot pressure, its contact S_1 actuates and contact between its terminal 0-2 is made. Depending upon the selection of Forwad/ Reverse switch, either contactor 1*C* or contactor 2*C* gets energised.

(6) Normally closed (*NC*) auxiliary contacts of 1*C* and 2*C* are used in the coil circuit of contactor 3*C* and 4*C*. Thus 1*C*-4*C* or 2*C*-3*C* get energised simultaneously. 1*C* and 4*C* contactors run the motor in the forward direction while contactors 2*C* and 3*C* run the motor in the reverse direction. These two alternate pairs of contactors reverse the current flow through the armature winding of the traction motor while the direction of current through the series field winding Y_1 and Y_2 remains same in both the cases. The motor starts with resistance R_1 and R_2 in the armature circuit.

(7) The purpose of providing contactor 3*C* and 4*C* along with 1*C* and 2*C* is to provide braking torque when the pedal switch is released. When the pedal switch is released both the contactors 1*C* and 2*C* are OFF while the contactors 3*C* and 4*C* are ON. Power contacts of 3*C* and 4*C* shorts the armature of the traction motor through a resistance R_2. As the control circuit is ON, and the motor shunt field winding is energised, the armature of the motor will generate and dissipate energy in the resistance R_2. This generating action would provide a braking torque.

(8) When the pedal switch is further pressed to actuate its contact S_2, contactor 5*C* gets energised. Energisation of 5*C* cuts off resistance R_1, thus the motor accelerates to the second higher speed.

(9) When the pedal switch is further pressed to actuate switch S_3 contactor 6*C* gets energised and shorts resistance R_2 in the armature circuit. The motor therefore attains a higher speed *i.e.,* the third higher speed.

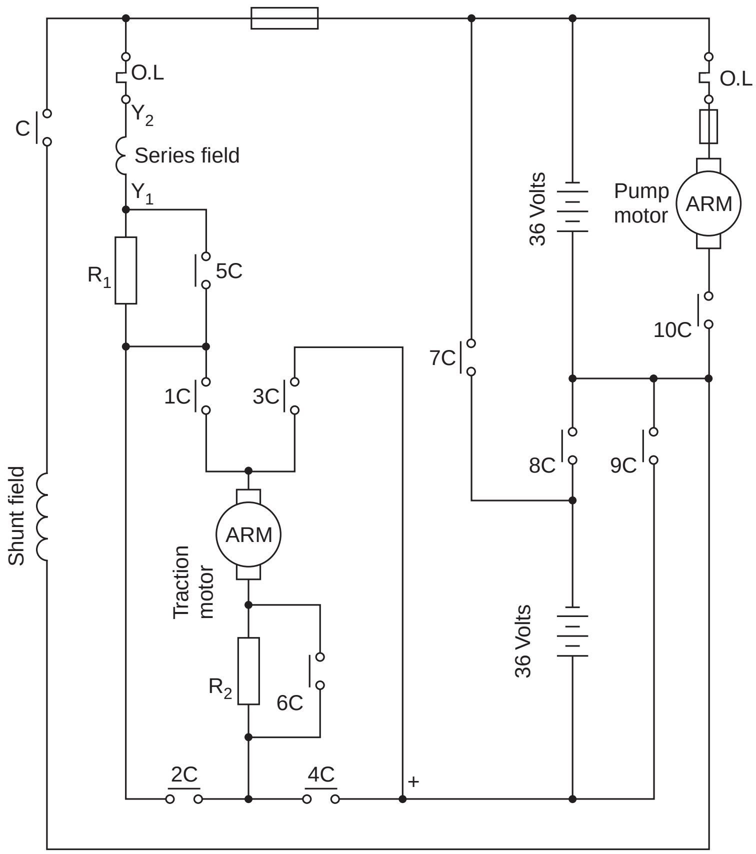


Fig. 9.21 Power circuit for a battery operated truck

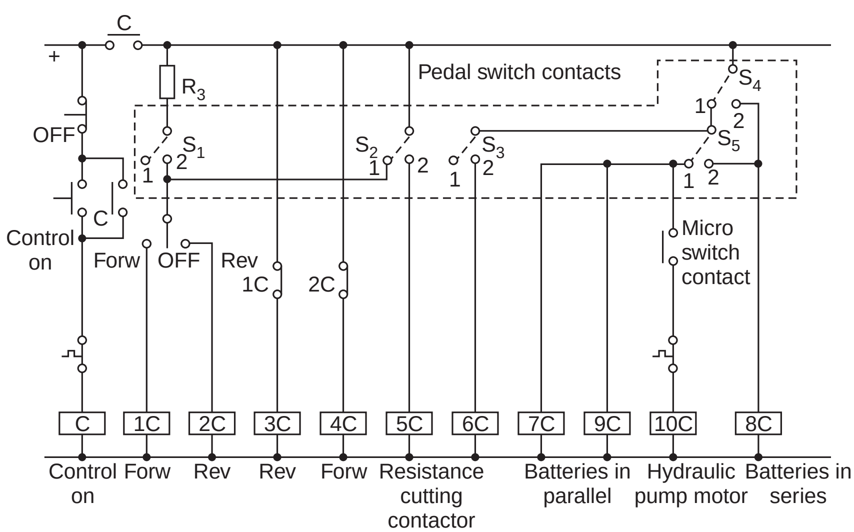


Fig. 9.22 Control circuit for a battery operated truck

(10) When pedal switch contact S_4 is actuated by increasing pressure on the pedal, its contact changes from 0-1 to 0-2. This de-energises contactors 6*C*, 7*C* and 9*C* but at the same time energises contactor 8*C*. De-energisation of contactor 7*C* and 9*C* opens parallel connections of the batteries while energisation of 8C connects them in series. De-energisation of 6*C* inserts resistance R_2 back in the armature circuit. The fourth higher speed is obtained as now a potential of 72 volts is connected across the armature terminals of the traction motor with resistance R_2 in the circuit.

(11) When the pedal switch is fully pressed and contact S_5 gets actuated, it again energises contactor 6*C* through closed contacts of S_4 and S_5. Energisation of 6*C* again cuts off resistance R_2 from the armature circuit and the motor attains its final speed with both the batteries in series.

(12) To avoid direct reversing *i.e.,* to provide antiplugging on higher traction speed, reduced voltage equal to hold on voltage is supplied to contactors 1*C* or 2*C* after the second microswitch operation. Resistance R_3 sends the reduced voltage to 1*C* or 2*C* after the operation of microswitch S_2. If at higher speed the selector switch for FOR/REV operation is changed, contactor 1*C* and 2*C* would fail to pick up due to the availability of a reduced voltage.

(13) The hydraulic pump motor can be started by operating the lever of the valve which actuates a micro-switch. When the micro-switch contact closes contactor 10*C* is energised, which then connects the armature of the motor across the supply. Contactor 10*C* can be kept energised till contact S_4 remains unactuated. This interlocking is provided, as described earlier, to avoid operation of the forks when the truck is running on higher speeds.

(14) Some of the protective devices which are otherwise provided in the control circuit of the truck but have not been shown in Fig. 9.22, are:

(*a*) An under voltage relay will either cut off supply to control circuit or show an indication of low voltage when the battery voltage drops below a ceratin limit.

(*b*) A rectifier provided across shunt field of the traction motor to suppress switching surges.

(*c*) Capacitors provided across the coils of the contactors to suppress switching surges.

9.10 AIR COMPRESSOR

Air compressor is an equipment which one will find in almost all industries. An air compressor is used to build up air pressure in a big reservoir for use in the plant. Air pressure in an industry may be used for various purposes like for cleaning operations, as drive for pressure operated machines, in L.P.G. burning, in circuit breaker operation, etc.

A compressor basically consists of a cylinder piston assembly in which reciprocating motion of the piston is used for building up air pressure. An electrical motor is used as drive for the compressor. Rotary motion of the motor is converted into reciprocating motion of the piston through crank-shaft arrangement. There are two valves provided in the compressor cylinder. They are called suction valve and exhaust valve. When the piston moves away from the suction valve, the valve opens and air from atmosphere is sucked into the cylinder. At this time the exhaust valve remains closed. When the piston moves towards the suction valve, this valve closes while the exhaust valve opens. The air in the cylinder is compressed by the piston movement and is forced into the reservoir. A non return valve and an unloading valve are provided in the pipe line connecting the exhaust valve and the reservoir. The non return valve allows passage of air only in one direction *i.e.,* from the compressor cylinder to the reservoir. It blocks air flow in the reverse direction *i.e.,* from the reservoir back to the cylinder. The unloading valve is used to unload the compressor *i.e.,* to connect the cylinder exhaust to the atmosphere. Most about working of this valve is explained a little later.

Constant movement of the piston inside the cylinder at high speed will generate a lot of heat due to friction. To minimise generation of excessive heat and to facilitate smooth movement of the piston, oil lubrication of the cylinder walls is done. This is accomplished with the help of an oil lubricating pump. This pump is also driven by the main compressor motor. The pump lifts oil from the oil pump and feeds it into the cylinder assembly. Oil lubrication is very essential as, in its absence, the piston will cease due to overheating and thus the compressor will get damaged. A protection is therefore required to ensure that oil lubrication takes place continuously. This is made sure by measuring the oil lubrication pressure. If the oil pressure falls below the set value the compressor motor will trip automatically.

Heat generated due to movement of the piston is removed from the cylinder by surrounding it with a water jacket. Cold water is permanently circulated through this jacket to absorb heat from the cylinder walls. Cold water from a chilling plant is circulated through the water jacket with the help of a water pump. To ensure that proper cooling is being done a temperature switch is provided to measure the temperature of the outgoing cooling water. A flow switch is also provided to ensure that proper flow of cooling water is maintained. If cooling water flow stops or become slow, the flow switch immediately operates to stop the compressor motor. The motor also stops if the temperature of the outgoing cooling water rises above the set value of temperature of the temperature switch. Actuation of the temperature switch would indicate that either the cooling water from chilling plant is not sufficiently cold to produce efficient heat conduction from compressor or there is some defect in the compressor.

In addition to use of an oil lubrication pressure switch, a cooling water flow switch, a temperature switch and a pressure switch can also be provided in the air reservoir for controlling the compressor motor. This pressure switch as described below, can be used in two ways to control the compressor motor :

The Use of Pressure Switch

(*i*) May be used to trip the compressor motor when air pressure in the reservoir reaches a preset high value. When pressure again falls below the set value, the motor does not start automatically but has to be started manually by pressing the ON-push button. This is the disadvantage of using this type of control.

(*ii*) The pressure switch may also be used to control the motor by unloading the compressor when pressure in the reservoir reaches the preset high value. When the compressor is unloaded, the motor runs on almost no-load drawing a low value of current. The compressor can be unloaded by using a solenoid operated valve. When pressure switch actuates and closes its contact the solenoid coil of the unloading valve is energised. Due to energisation of the coil the valve spool shifts and the exhaust line of the compressor gets connected to atmosphere instead of the reservoir. This control, using solenoid operated valve has the advantage that the unloading valve can also be used to unload the compressor during the starting period of the compressor motor. This avoids high inrush of current which the motor will otherwise draw if it is started directly on load *i.e.,* when the compressor exhaust is connected to the reservoir. This starting current will be automatically high when air pressure in the reservoir is high. The control circuit using a solenoid operated unloading valve is shown in Fig. 9.23.

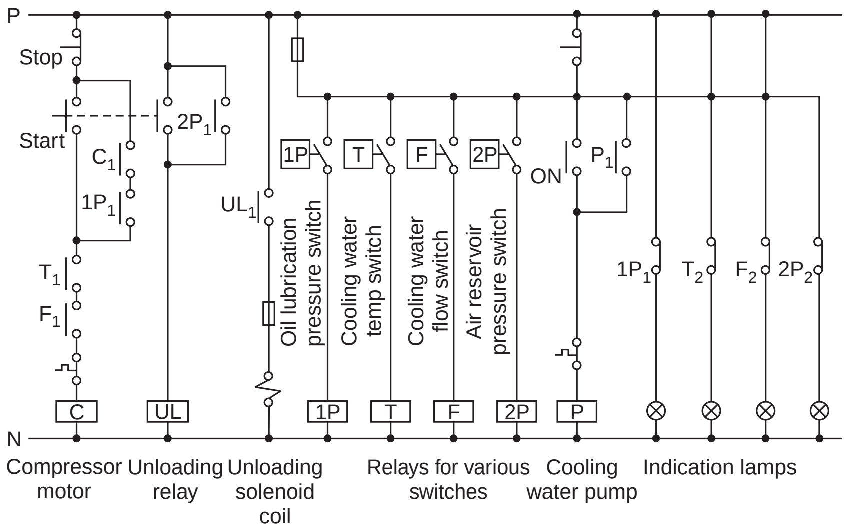


Fig. 9.23 Control circuit for a compressor motor

Unloading and loading of the compressor can also be obtained by using a mechanical valve which operates due to air pressure only. This valve is also called high pressure valve. When air pressure in the reservoir reaches a high preset value this high pressure valve operates to unload the compressor. In this arrangement there is saving of one pressure switch. However, automatic unloading of the compressor during starting of the motor cannot be obtained by this valve. To unload the compressor during starting this valve has to be operated manually by the operator and when the motor reaches its final speed the valve is again operated to load the compressor. If the operator does not unload the compressor and the pressure in the reservoir is high, the compressor motor will start against load and its overload relay will trip due to high inrush current or the fuse may also blow. In addition to the protective devices which stops the compressor motor during any abnormal motion, ON and OFF-push buttons are also provided to manually start and stop the compressor.

In the control circuit diagram of compressor motor in Fig. 9.23, for the sake of simplicity, the motor has been shown to the controlled by a direct on line starter. In actual practice the rating of a plant compressor is generally high, and as such star-delta starters are used.

For better understanding, working of the control circuit has been explained in steps as follows:

(1) When it is desired to start pump, first the water pump is to be switched on. This pump would draw water from the tank of the chilling plant and circulate through the water jacket of the compressor. The flow switch provided to detect the flow of cooling water will operate and close its normally open contact. Closing of this contact will energise relay F due to which its normally open contact F_1 will close in the coil circuit of the contactor C, *i.e.,* the contactor connecting supply to the motor of the compressor.

(2) For maintaining flow of cooling water, normally closed contact of the cooling water temperature switch has been used in the circuit. This contact remains closed as long as the temperature of the outgoing water remains below the high preset temperature. Through this contact a relay T remains energised and hence its contact T_1, which is in the circuit of contactor coil C, remains closed.

(3) Normally open contact of the pressure switch of the reservoir has been used in the circuit of relay 2*P*. When air pressure in the reservoir is less than the preset high value, this contact will remain open and therefore relay 2*P* will be in the de-energised condition. A Normally open contact $2P_1$ of this relay has been used to energise the unloading solenoid coil.

(4) Normally open contact of the coil lubricant pressure switch has been used to energise relay 1*P*. When the compressor motor is at standstill having no oil pressure this contact will remain open. Relay 1*P* will thus be in the de-energised state and its contact $1P_1$ used in the holding circuit of contactor *C* will remain open. As the oil pump is coupled with the main compressor motor, initially the oil pressure is zero. When the motor is started and picks up speed, oil pressure also builds up. When the desired oil pressure as set on the pressure switch gets built up, the contact of the pressure switch closes and energises the relay 1*P*. Its normally open contact $1P_1$ has been used in parallel with the ON-push button.

(5) When ON-push button is pressed, main contactor coil *C* gets energised through closed contacts T_1 and F_1 in series. When the motor picks up speed, oil pump coupled to it will also pick up and oil pressure will build up. When the required pressure gets built up, contact of the oil lubrication pressure switch closes and therefore relay 1*P* gets energised. Its contact $1P_1$ which has been connected in parallel with ON-push button and in series with holding contact C_1 closes and therefore contactor *C* will remain energised through C_1 and $1P_1$. From this it follows that the ON-push button is to be kept pressed till the oil pressure builds up to actuate the pressure switch. If due to some reason oil pressure does not build up or is not sufficiently high enough to actuate the pressure switch, the motor will stop when the ON-push button is released. Oil pressure may fail to build up if there is any leakage or if the oil level in the sump is low.

(6) When ON-push button is pressed another normally open contact used in parallel with the air reservoir pressure switch will also close. Thus relay *UL* will get energised and its contact UL_1 will close to activate the solenoid coil of the unloading valve. Thus, during starting, as long as the ON-push button is kept pressed the solenoid coil will remain energised and will keep the compressor unloaded. When the push button is released, the compressor will get loaded to force air into the reservoir.

(7) If during normal running, the temperature switch of the compressor cooling water operates due to increase in temperature of the outgoing cooling water, the relay *T* will get energised and its contact T_1 will open to de-energise contactor C, thus stopping the motor.

(8) Similarly if cooling water flow stops due to tripping of the water pump, or for any other reason, the flow switch contact will open and contactor *F* will get de-energised. Its contact F_1 will open and the motor will stop due to de-energisation of contactor C.

(9) When air pressure in the reservoir rises to the value set on the reservoir pressure switch, the switch will actuate and contact will close to energise relay *UL*. Energisation of the relay, as explained earlier, will energise the solenoid coil of the unloading valve. This would lead to unloading of the compressor. The compressor motor would run unloaded as long as pressure in the reservoir remains above the set value of the pressure switch. The motor in this condition will draw a low current which could be only a little higher than its no load current. Due to use of air in the plant, when

pressure of air would fall below the preset value, the pressure switch will get deactuated and the solenoid coil will also get de-energised. The spool of the unloading valve will shift again to load the compressor. Air will again be compressed and get forced into the reservoir.

9.11 WALKING BEAM

A walking beam, with the help of hydraulic pressure, is made to move in directions in the following sequence: Upward-Forward-Downward-Reverse so as to return to its original position.

A walking beam is operated in these four directions with the help of four cylinder-piston assemblies. The piston moves due to the pressurised oil fed into the cylinder by a hydraulic pump which lifts oil from an oil tank. Pressurised oil from the pump is fed to the cylinder piston assemblies by a two position single solenoid valve and a spring returned solenoid valve. Four solenoid valves, one for each motion have been provided. A loading solenoid valve is also provided to load the pump when required. The pump motor runs continuously, however the pump gets loaded only when the loading solenoid valve is energised. Normally, this solenoid valve remains off and keeps the pump unloaded by relieving the oil picked up by the pump back to the tank. When any operation is desired, the loading solenoid valve is energised along with solenoid valve for one of the motions and this diverts the pressured oil to the required cylinder through that particular solenoid valve.

Walking beam is used in industry to transfer material on to a moving conveyor. The particular application that we will be discussing, is one where the beam is used to transfer automobile leaf springs to a conveyer. In this particular industry the conveyor takes a number of leaf springs into the annealing furnace. The conveyor belt is made of special metal and therefore does not get damaged due to heat of the furnace. The conveyor moves at a very low speed through the furnace thus annealing the leaf springs placed over it. The leaf springs are dropped into a quenching (cooling) medium on the other side of the conveyor. As the annealed springs are dropped into the quenching medium, new leaf springs are loaded on the front side of the conveyor continously by the walking beam.

The benefit of loading leaf springs on to the conveyor with the help of a walking beam is that the operator remains at a distance from the direct heat of the furnace. Operation of the walking beam has been ilustrated in Fig. 9.24.

In the top view of the walking beam as in Fig. 9.24 (*a*), the beam has been shown in fully down but in reversed position. Leaf springs are placed on the walls on either side of the beam by the operator. On being loaded the beam will move up therby lifting the leaf springs from the walls. When the up limit switch LS_1 is actuated (refer Fig. 9.24 (*c*)) the beam then moves in the forward direction towards right as shown by the arrow. When the forward limit switch LS_2 is actuated the beam will move down, and the limit switch LS_3 will get actuated. While moving down the beam will place the leaf springs on to the conveyor. This is shown in Fig. 9.24 (*b*). A slot is specially cut in the conveyor to enable the beam to place the leaf springs on it. When the beam is fully down and the Down limit switch LS_3 actuates, the beam moves in the reverse direction. It stops when the reverse limit switch LS_4 gets actuated. The beam thus returns to its starting point. In automatic operation, the beam rests at this position for some time to enable the operator to place new leaf springs on the walls. The beam then again moves up to deliver the leaf springs on to the conveyor. Figure 9.24 (*c*) shows the side view of the beam movement and the location of the limit switches.

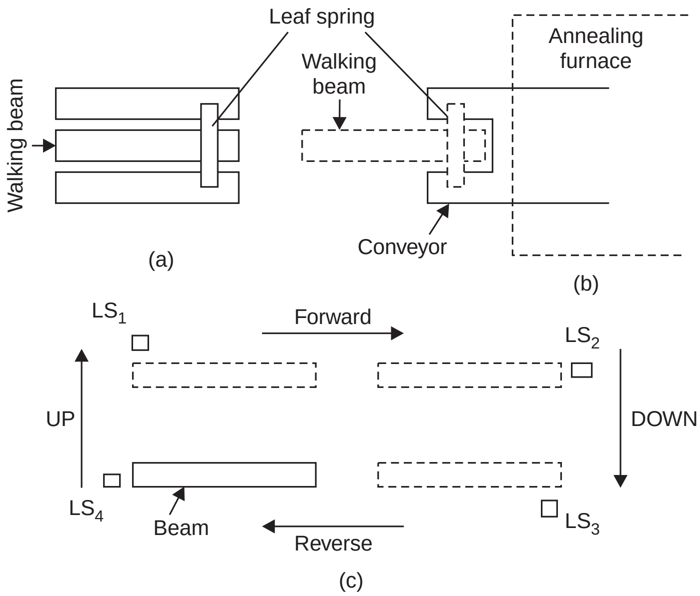


Fig. 9.24 Movement of a walking beam (*a*) and (*b*) Top view (*c*) Side view

The control circuit for the walking beam has been shown in Fig. 9.25. This control circuit diagram has been represented as an actual drawing used in industry. At the top of the control circuit is shown the arrangement of the limit switches, push button legend, and legend of the solenoid valves. These have to be referred to while studying the control circuit drawing. Each vertical line in the control diagram is represented by a number at the top. At the bottom of each contactor, a table shows the line numbers in which the NO and NC contact of the contactor have been used. This information becomes useful in reading control circuit drawing, when a write up (explanation) for the circuit is not available Contactors *U*, *F*, *D* & *R* are respectively meant for the upward, forward, downward and reverse motion of the walking beam. The solenoid valves SV_1, SV_2, SV_3, SV_4 respectively are energised through the normally open contacts U_5, F_5, D_5 and R_5. The loading solenoid valve SV_5 also gets energised when any of the contactors, *U*, *F, D* or *R* is energised. Contactor *A* is for auto selection and contactor *AS* is for auto start. An ON-delay timer *T* has been used for allowing rest time for the beam at LS_4 position in the auto cycle. Starter for the pump motor has not been shown in the diagram for sake of simplicity. The control circuit is energised through the starter contact *M* connected in series with the selection switch. The walking beam has three modes of operation viz Manual, Reset and Auto, selection for any mode is done by the selector switch SW. Selection on any mode energises the respective control bus designated as *L-A* (Auto) *L-M* (Manual) and *L-R* (Reset). The walking beam cycle can be started in auto or manual mode only if the beam is at any extreme end position and actuates a limit switch. To bring the beam from any in-between position to the extreme end positions, reset mode is provided. The operation of the walking beam in three different modes *i.e.* in Manual mode, Reset-mode and Auto-mode are discussed as follows:

(*a*) **Manual mode of operation of the walking beam**

(1) When the selector switch *SW* is turned to manual mode the control bus L-M is energised. If the beam is at its starting point and the limit switch LS_4 is actuated, contactor *B* also gets energised through the close contact of LS_4. Thus when the contactor *B* is closed, its contact B_1 in line 2 gets closed and contact B_2 in line 14 becomes open.

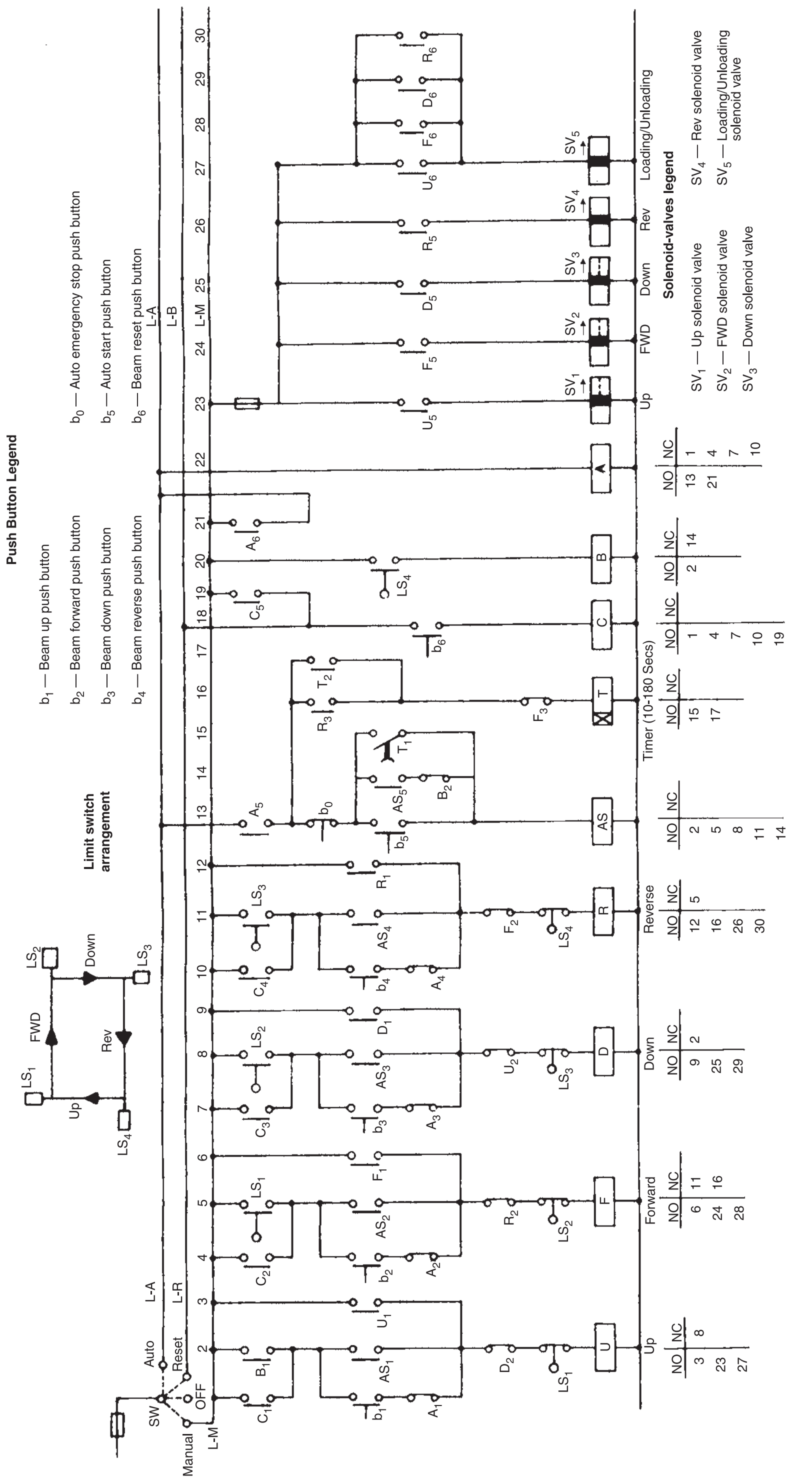


Fig. 9.25 Control circuit for a walking beam

(2) When the beam UP-push button b_1 is pressed, up contactor U is energised through closed contacts B_1, b_1, A_1, D_2 and LS_1. Energisation of contactor U will cause operation of loading solenoid valve SV_5 and also up solenoid valve SV_1 through contacts U_5 and U_6 and therefore the beam will start moving up.

(3) Contactor U gets hold through its contact U_1 before the opening of contact B_1 as a result of de-energisation of contactor B. Contactor B gets de-energised due to opening of contact LS_4 in line 20 when the beam moves in the upward direction.

(4) When the beam reaches its upper limit, limit switch LS_1 is actuated. Its *NC* contact opens and de-energises contactor U. De-energisation of contactor U stops movement of the beam in the upward direction due to de-energisation of solenoid valves.

(5) Acutation of limit switch LS_1 also closes its NO contact in line 5 and thus supply reaches the Forward-push button $b_{2.}$

(6) When Forward-push button b_2 is pressed contactor F gets energised through close contacts LS_1, b_2, A_2, R_2, and LS_2 in line No.5. Energisation of contactor F also helps energistaion of the respective solenoids through its contacts F_5 and F_6. The beam moves in the forward direction till limit swtich LS_2 is actuated.

(7) On actuation of LS_2 forward contactor F is de-energised and the beam movement in forward direction stops while supply reaches Down-push button b_3 through the closed contact of LS_2 in line-8.

(8) The beam can be run in down motion by pressing push button b_3. When the limit switch LS_3 is actuated, the beam can be run in reverse direction by pressing its push button b_4. Limit switch LS_4, when actuated stops the reverse motion of the beam.

This way one cycle of beam movemnt is completed. In practice, the beam is not run in this fashion. It is run mostly in auto operation. The manual push button b_1 to b_4 are mostly utilized only to reset the beam if it stops inbetween due to power failure.

(*b*) **Reset mode of operation of walking beam.** Reset mode is required to reset the beam since neither the manual nor the auto cycle can be started if the beam positon is such that no limit switch gets actuated. The beam will stop in any intermediate position during its travel cycle if there is power failure. On restoration of power the beam cannot be made to run in manual or auto mode from such intermediate position. For example let us examine the case when the beam has stopped while moving in forward direction due to power failure. In such a case, both the limit switches LS_1 and LS_2 are in deactuated condition. The beam cannot be run in forward direction as contact of LS_1 in line 5 is open and hence supply does not reach upto push button b_2. To make the push button effective the beam should be reversed to actuate LS_1 or alternately the beam should be taken to fully forward condition to actuate LS_2 so that operating cylcle can be started for downward motion. The beam is reset to actuate LS_1 or LS_2 with the help of reset-push button b_6.

When the beam is to be reset, first the selector switch *SW* is put on reset mode, This will energise the reset control bus *L-R*. Now b_6 is pressed which energises contactor C. Its contact C_5 closes and energises the manual control bus *L-M*. Also the control contacts C_1,C_2,C_3 and C_4 close to bypass the contact B_1 and normally open contacts of LS_1, LS_2 and LS_3.Thus supply reaches at all the push buttons from b_1 to b_4. The required push button can now be pressed along with b_6 to complete the beam movement in a particular direction. Push button b_6 is released when the beam reaches the required limit and the concerned limit switch has actuated. Then the selector switch is returned back to Manual or Auto mode as per requirements.

(*c*) **Auto mode of operation of the walking beam**

(1) When selector switch is placed in Auto made, control bus L-A is energised and contactor A picks up. Its normally open contact A_6 closes and energises the manual line L-M. Its NO contact A_5 also closes to make the Auto start push button b_5 effective. Its NC contacts A_1 to A_4 open to make the push button b_1 to b_4 ineffective during auto operation.

(2) Let us start the walking beam in auto from the starting point *i.e.,* when beam is down in fully reversed position. In this position limit switch LS_4 will be actuated and its contact in line No. 20 will close to energise contactor B.

(3) When auto start push button b_5 is pressed, auto start contactor AS gets energised and closes its contact AS_1. Contactor U gets energised through closed contacts B_1, AS_1, D_2 and closed contact of LS_1. Contactor U is held through its own contact U_1.

(4) In auto cycle, during starting, the push button b_5 in line 13 has to be kept pressed till LS_4 is de-actuated due to the movement of the beam in the upward direction. This is so desired because auto start contactor AS will hold only when contactor B is de-energised due to de-actuation of limit switch LS_4. When B is de-energised contactor AS is held through contacts AS_5 and B_2.

(5) When the beam reaches up and LS_1 is actuated its *NC* contact opens and de-energises contactor U. At the same time its NO contact closes in line 5 to energise forward contactor F. Contactor F gets energised through closed contactor LS_1, AS_2 and *NC* contact of LS_2.

(6) When the beam is fully forward, LS_2 gets actuated, it de-energises contactor F and energises contactor D for downward motion in a simillar fashion.

(7) When Down-limit switch LS_3 gets actuated, it de-energises contactor D and energises contactor R for reverse motion of the beam. At the same time a timer T is also energised through the contact R_3. Timer T is held through the instantaneous contacts T_2. The timer is of 3 minutes duration.

(8) When the beam is fully reversed, limit switch LS_4 gets actuated. Its NO contact closes in line 20 to energise contactor B. Contact B_2 thus opens and de-energises auto start contactor AS.

(9) The beam now does not start in upward direction due to opening of contact AS_1, as AS is de-energised.

(10) When timer T operates after the pre-set time delay, its delayed contact T_1 closes and energises contactor AS. Timer T decides the time for which the beam should rest at the location of LS_4 required for loading of leaf springs on the beam.

(11) Energisation of AS through timer contact will again start the beam in upward direction as contactor U will get energised through closed contacts B_1, AS_1, D_2 and LS_1.

(12) As the beam moves up, LS_4 is de-actuated and contactor B gets de-energised. The holding circuit for AS also gets completed through contacts AS_5 and B_2 in addition to the timer contact circuit.

(13) Timer T resets when the beam starts moving in forward direction due to opening of contact F_3. Its contact T_1 will open but the contactor AS will continue to remain energised through its own holding circuit.

9.12 CONVEYOR SYSTEM

In large plants, materials are shifted from the place of storage to near the machines for processing, through belt conveyors. Finished products from the machines are also carried away through conveyors. Infact, any heavy material can be transported by conveyors. For example in airports, luggage of passengers is transferred through belt conveyors. The drive for such belt conveyors is an electric motor. A conveyor consists of a rubber belt about 3/4 to 1 metre wide tightly fitted over two pulleys as shown in Fig. 9.26.

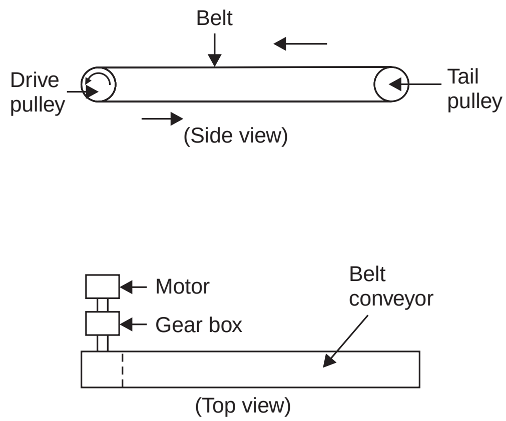


Fig. 9.26 Top and side view of a conveyor

One pulley is coupled to the motor through a gear box as the belt is required to move at a slower speed as compared to the motor speed. The pulley which is coupled with the motor is shown as drive pulley while the other pulley is called the tail pulley. As the belt is fitted tightly over the two pulleys, rotation of the drive pulley will cause movement of the belt over the two pulleys. A number of such conveyors may be used to shift material from one place to the other at different heights. The number of conveyors in a system can be very large depending upon the requirement. One example of a small conveyor system with 5 conveyors has been shown in Fig. 9.27. In this system the final product from plant is first stored in silos (large containers) with the help of conveyors.

As shown in Fig. 9.27, conveyors 1 and 2 feed material into silos, 1 and 2. Diverters are provided on conveyor 2. When diverter 1 is down, material will fall in silos 1 and when diverter 1 is up and diverter 2 is down material will fall in silos 2. When both the silos are filled, proximity switches provided in silos will actuate and stop conveyors 1 and 2. Finished product from silos can be taken out through gates on to conveyor 2 and taken to packaging machine through conveyors 3, 4 and 5.

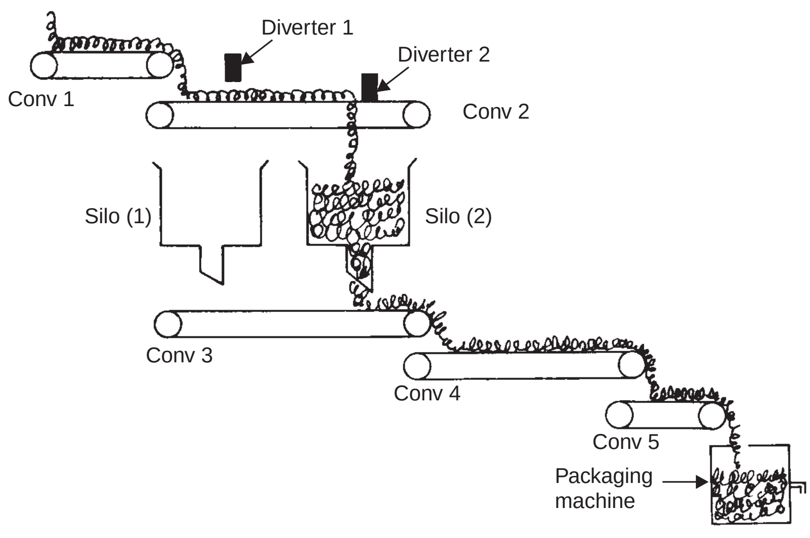


Fig. 9.27 Schematic arrangement of a conveyor system

Conveyor motors are started in sequence one after the other. One major reason for sequence starting of conveyors is to avoid high inrush current during simultaneous starting of motors. If all the motors in a conveyor system are started simultaneously the current drawn from supply will be the sum of inrush current of all the individual motors. This current obviously will be very high as it is known that inrush current of an induction motor is 6 to 7 times its rated current. Another reason for sequence starting could be the process requirements. In some applications stopping of conveyors may also be required to take place in a particular sequence. For example in the conveyor system just discussed, it is desirable that conveyors 3, 4 and 5 should stop in sequence and further, conveyor 4 and 5 should stop after a successive gap of 30 seconds each. This is required to enable material lying on belts get emptied into the packaging machine before the conveyors stop.

Conveyor motors can be started in sequence by using auxiliary contact interlocking, if no time gap is required between starting of two conveyors. However, if time gap is required between successive starting of motors then timers have to be used. Control circuit using auxiliary contact interlocking and timers for sequence starting of motors has been shown in Fig. 9.28.

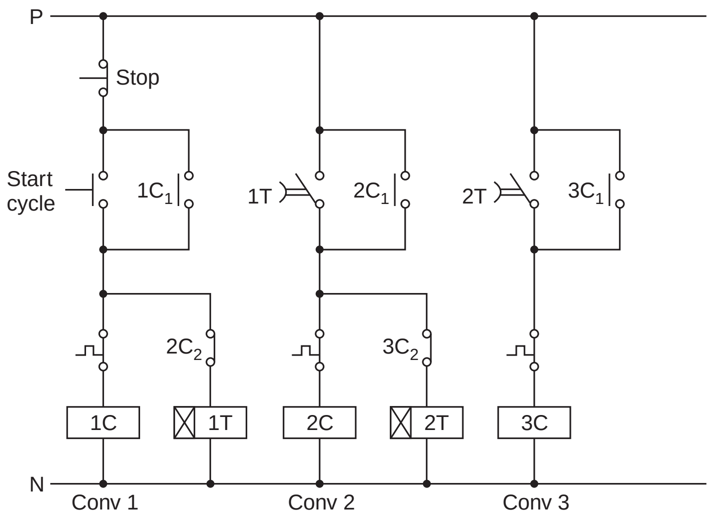


Fig. 9.28 Control circuit for sequence starting using timers

In this control circuit, it is seen that to start three motors in sequence with a time gap, two timers are needed, thus if the number of motors to be started are more, say 10, then we will require nine timers. Such circuit will obviously be very costly. In practice there are many appliactions where the conveyor system consists of a large number of conveyors. To economise on expenditure for such control systems a special timer, known as *cam timer*, is used to start conveyors in sequence. Cam timers have already been discussed in chapter 2. In a cam timer, there is a small synchronous motor which rotates a shaft. On the shaft are mounted plastic cams which actuate there respective contacts at particular instant of time during the rotation of the shaft. A conveyor system which uses cam timers is discussed as follows:

Sequence starting of three conveyors in manual and auto mode is explained. Only three conveyors have been taken for sake of simplicity although in practice the number may go upto fifteen or so. In this conveyor system there is provision to start the conveyor in auto cycle through cam timer or through manual operations. In manual operation there is a provision to start individual motors in sequence either from the control panel or with the help of push buttons provided by the side of the respective motors. It may be understood that control panels for conveyor systems are located at a suitable enclosed place preferably in a room away from the conveyor system where dust and dirt of plant can not enter the panel. This centralised control panel of a number of conveyor motors is also known as Motor Control Centre or MCC.

A general safety precaution employed in all conveyor systems is that before starting of conveyors a hooter is sounded for about 60 secs or so to alarm the workers that the conveyor system is going to be started. This alarm is meant to inform that if any body is near the conveyor or working on them he should get aside. If somebody is working on the conveyor and conveyor is not in working condition or disassembled, the site emergency push button can be pressed which will not allow the conveyors to start. Control circuit having all the functions discussed above is shown in Fig. 9.29. An Auto/Manual selector switch is used to select conveyor system operation either in auto mode or in manual mode.

(*a*) **Manual mode of operation**

(1) When the selector switch is placed on manual mode, relay M will get energised. Its contact M_1 will close and energise the manual bus. Normally closed contacts of contactor M *i.e.,* M_2 M_3 and M_4 will open and thus will isolate the cam-timer contacts from the circuit during manual operation.

(2) In manual mode, conveyor 1 can be started by pressing panel ON-push button or site ON-push button which is provided near the motor. These push buttons are connected in parallel. When any of these ON-push buttons is pressed, contactor 1C will get energised and will remain energised through its auxiliary contact $1C_1$. Now supply to the coil of contactor $1C$ reaches through the contact of the OFF-push button of the panel, auxiliary contact A_4, auxiliary contact $1C_1$, and the site OFF-push button on conveyor 1.

(3) When contactor 1C is energised its auxiliary contact $1C_2$ in the coil circuit of contactor $2C$ also closes thus providing an interlocking, where conveyor 2 can only be started if conveyor 1 is running.

(4) Now, conveyor 2 can also be similarly started by pressing its ON-push button. After starting of conveyor 2, conveyor 3 can also be started by pressing its ON-push button.

(5) Any conveyor can be stopped by pressing its panel or site OFF-push button. The following conveyor will also stop due to interlocking. Over-load tripping of any conveyor will also result in stoppage of the conveyors following it.

(*b*) **Auto mode of operation.** Before the working of the circuit in auto mode is discussed it is essential to get familiar with the operation of cam timer used for this circuit. The cam timer used has four contacts as shown in Fig. 9.30.

As shown in Fig. 9.30, normally open (NO) contacts of contact block CT_1, CT_2 and CT_3 have been used while normally closed (*NC*) contact of CT_4 has been used. The starting position of the cam timer will always be the same as shown in Fig. 9.30. Observe the protruding portions of the cams. In the starting position shown, it is clear that contact block CT_4 is in actuated position as its knob is pressed by the protruding portion of cam 4. Thus it is clear that during starting, position of cam timer contact CT_4, will be open as this contact block is actuated. This contact will remain open as long as the protruding portion of cam 4 pushes the knob of the contact block. For any other position of cam 4 *i.e.,* throughout 360° of cam rotation, contact block CT_4 will remain deactuated and thus its contact CT_4 will remain closed. This point has to be kept in mind while studying the control circuit for auto operation. The other contacts CT_1,

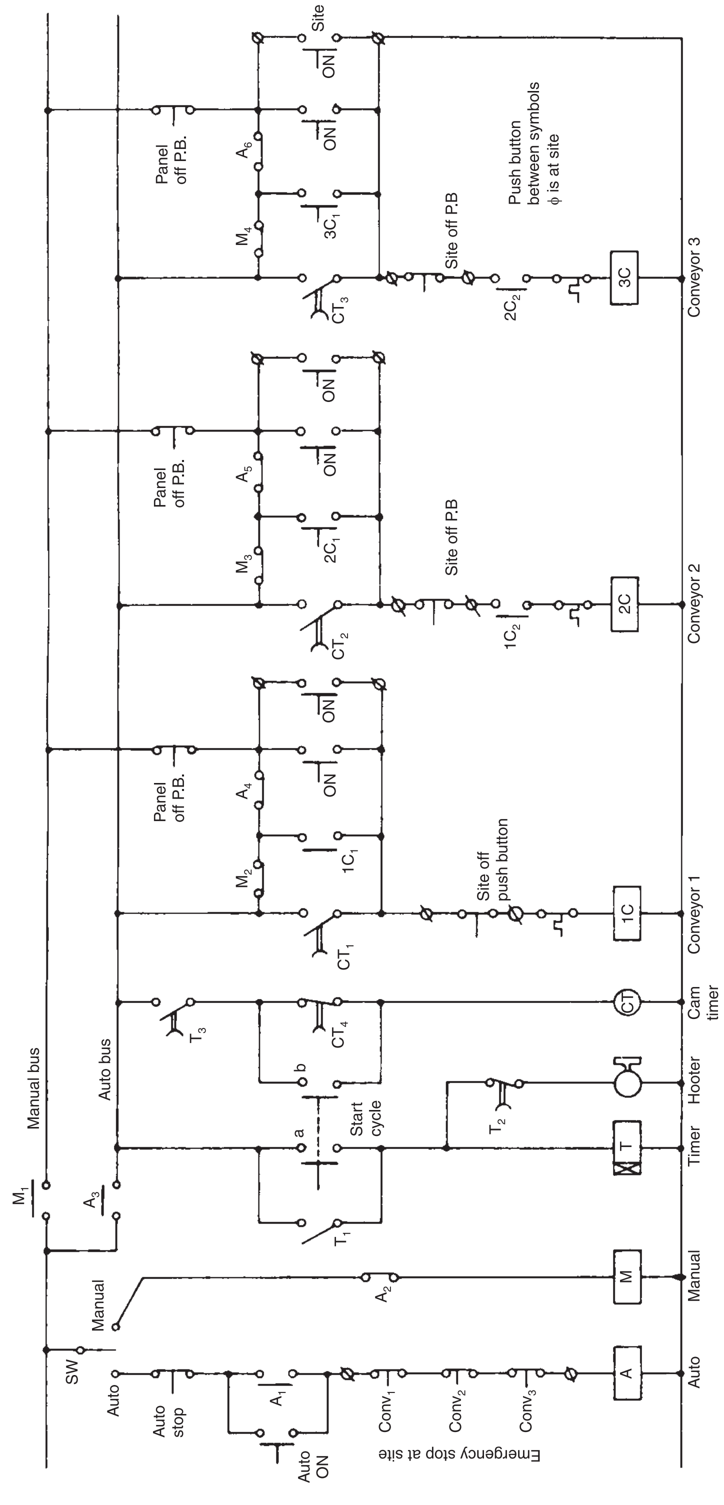


Fig. 9.29 Control circuit for a conveyor system

CT_2, CT_3, will close when their contact blocks are actuated by protruding portions of their respective cams 1, 2 and 3 during rotation of the timer shaft in anticlockwise direction as shown in the figure.

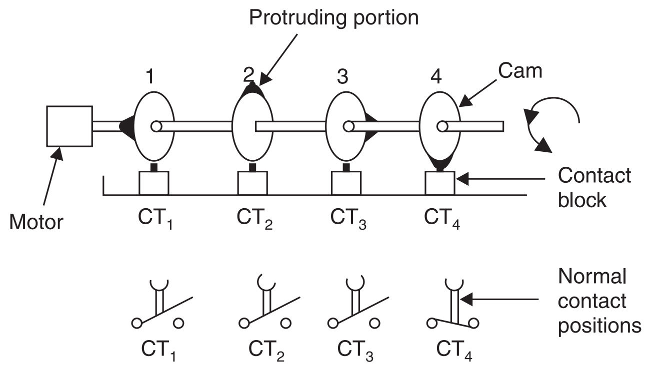


Fig. 9.30 A cam timer with four contacts

The working of the control circuit is explained below in steps:

(1) When selector switch is in Auto mode, Auto relay *A* will get energised on pressing the Auto ON-push button. Due to energisation of relay *A*, Auto bus is also energised through closing of contact A_3. Normally closed (NC) contacts A_4, A_5, A_6 will open to isolate manual ON and OFF push buttons from the circuit.

(2) When the START cycle push button is pressed, its both contacts *a* and *b* will close. Closing of contact '*a*' will energise timer *T* and also hooter *H* through delayed NC contact T_2 of the timer. Timer *T* gets hold through its instantaneous contact T_1. The setting of the timer is kept at about 60 secs to warn the workers that conveyors are going to be started. When timer operates after preset time, its contact T_2 opens to de-energise the hooter while its contact T_3 will close.

(3) When contact T_3 of timer closes, cam timer motor *CT* will get energised if contact '*b*' of the START cycle push button is still closed. This means that START cycle push button has to be kept pressed during starting for more than the time setting of the timer, so that energisation of cam timer motor is possible. As the motor starts rotating in the direction shown, immediately the contact block CT_4 will deactuate and its contact CT_4 will close *i.e.,* it will come back to its normal position. As soon as this happens, START cycle push button can be released. Now cam timer motor *CT* will remain energised through its own contact CT_4 till cam 4 rotates through 360° to again actuate contact CT_4.

(4) When cam timer shaft rotates by 90° from its initial position, contact block CT_1 will be actuated by cam 1 and contact CT_1 will close. Contactor 1*C* for conveyor 1 will get energised through this contact and will get hold through its own contact $1C_1$. As the protruding portion of cam 1 moves past contact block CT_1, contact CT_1 open but contactor 1*C* will remain energised by getting supply through its contact $1C_1$.

(5) When timer shaft rotates by 180°, protruding portion of cam 2 will actuate contact block CT_2. Its contact will close and energise contactor 2*C*. When protruding portion of cam 2 moves past the contact, contractor 2*C* will remain enrgised rotation its own contact $2C_1$.

(6) Similarly contactor 3*C* for conveyor 3 will get energised when after 270° rotation, cam 3 actuates contact block CT_3.

(7) When the shaft has rotated by full 360° i.e., when it comes back to its starting point, contact block CT_4 will get actuated to open its normally closed (NC) contact CT_4. This will de-energise cam timer motor CT and hence the cam timer will stop at this point. Cam timer motor CT will remain de-energised till it is again energised by pressing the START cycle push button.

(8) If auto STOP-push button or Emergency STOP-push button of any conveyor is pressed, all the conveyors will stop immediately due to de-energisation of relay A. De-energisation of A will switch off the auto bus due to opening of relay contact A_3.

(9) When any site OFF-push button of a conveyor is pressed, then that particular conveyor and the conveyors following it will stop while the conveyor preceding it will continue to run. For example, if site OFF-push button of conveyor 2 is pressed, conveyor 2 and conveyor 3 will stop while conveyor 1 will continue to run. Similarly, tripping of over load relay of any of the conveyors will also trip the conveyors following it.

9.13 ELEVATOR

Elevators or lifts are used in multistoried buildings for carrying passengers from one floor level to another at a fast speed. The cage in which passengers travel (also known as car) travels vertically, guided by four rails in the hoist-way. There are doors at each floor through which passangers can enter into or come out of the car. These doors are also referred to as hall gates. There is a gate in the car which should open only when the car is stationary in front of any of the hall gates. All these gates are of collapsable type. The gates may be hand operated or servo motor operated. A lift can not be operated if any of the hall gates or the car gate is open.

The car is suspended in the hoist way by one end of a wire rope which is wound on a drum at the top of the hoist way. On the other end of the rope a counter weight, whose weight is generally 60% more than the weight of the empty car, is suspended. The wire wound drum is coupled to a motor through gears for achieving the required speed. Rotation of drum in one direction will lift the car up while the counter weight will go down. When the drum rotates in the reverse direction, the opposite will follow. Motor drum and control panel for the lift are situated at the top of the hoist way *i.e.,* on the top most ceiling of the building.

Motors, nowdays being used for lifts are 3 phase induction motors instead of dc motors used earlier.

Lifts can be of a single speed type or double speed type. Double speed lifts are faster than single speed ones. Double speed lifts run at lower speeds near starting and stopping and at faster speeds during free running.

In both the types of lifts, a set of electromechanical brakes are provided to stop the car exactly at the floor level. Normally, the brake remains engaged but opens when the motor gets the start command. The details of a single speed lift are discussed as follows:

Control of a lift is obtained through a set of push buttons and limit switches. A set of push buttons (equal to the numbers of floor levels in the building) enable the operator to take the car to the required floor level. One push button is also provided near each hall gate for calling the lift to that particular floor. If the lift is idle at some floor level and its door is closed the lift can be brought to the required floor level by pressing the Hall gate-push button. When the lift gate is open, pressing of any one of the Hall-push buttons will sound a bell and also light an indicating lamp to inform the operator about the floor level at which the lift is required by the passenger.

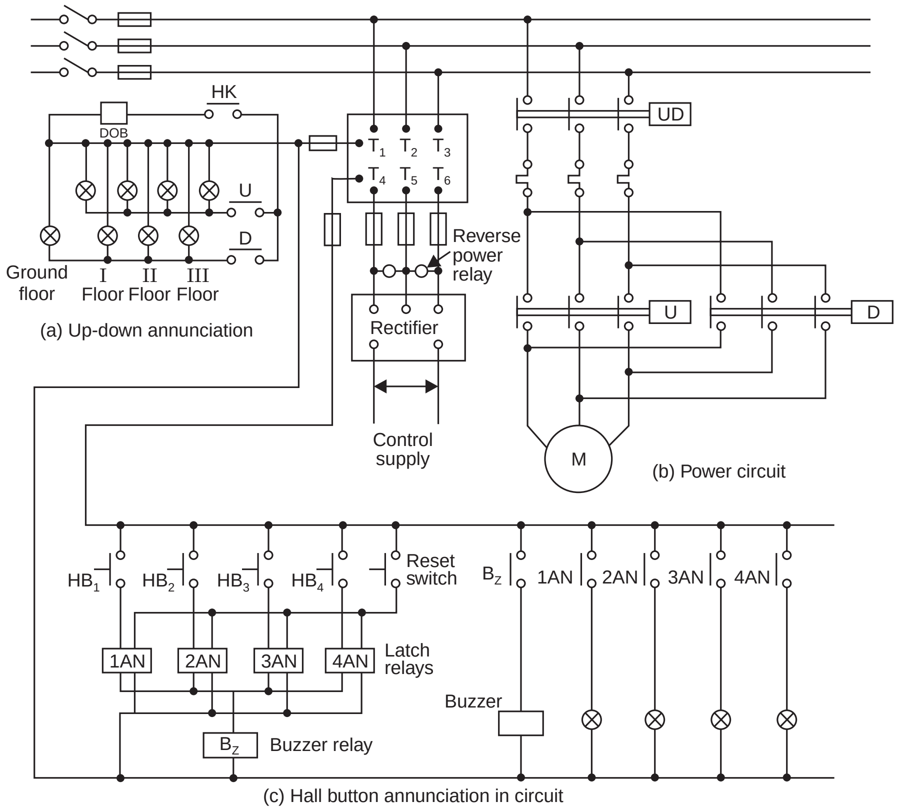


Fig. 9.31 Power and annunciation circuit for a lift

The bell is called 'door open bell' indicating that the door should be closed so that the lift can be brought to the required floor by the waiting passenger. The Hall-push buttons become inoperative when the lift is moving up or down. However, indication can be given to the operator about the floor level at which the lift is required.

Main annunciation circuits (light indicators, buzzers, bells etc.,) provided in the lift are as follows:

(1) A light indicator is provided at each floor level to show 'up' or 'down' movement of the car.

(2) A target annuciation comprises indication showing the floor towards which the car is approaching. This is provided at each floor level and also in the car panel.

(3) Hall-push button annuciation which comprises indication of floor level at which the lift is required by the passenger along with a buzzer in the car to attract operators attention.

(4) A bell provided in the car which rings when the car door is open and the lift is wanted at some other floor by a passenger.

In the case of failure of power supply during the travel period, the car will immediately stop. In such eventuality either an alternative supply arrangement from standby generator is to be made for bringing the car to the nearest floor opening, or a manual handle is to be used through which a drum is rotated to bring the car to the nearest opening so that the entrapped passengers may come out. In case of rope failure, there is a provision of safety shoes with the car which will jam with the guide rails when the car would fall down at 150% of its rated speed. In case of phase reversal of supply the lift becomes inoperative due to energisation of a reverse phase relay, provided in the circuit.

The control circuit which is being discussed here is based on the control circuit for a lift manufactured by a leading concern. The control circuit shown in Fig. 9.32 has been simplified to some extent from the original drawing for easy understanding. Lighting, fan, and alarm circuits have been omitted and the annunciation circuit has been simplified. Before explaining the working of the control circuit, some important devices, relays and selector switches used in the lift control are discussed as follows:

(*a*) A retiring cam device is provided at the top of the car which mechanically locks the car at a particular floor so as to enable passengers to come in or go out without physically shifting the car. Retiring cam device consists of a coil and a plunger. When coil *CM* is energised it attracts the plunger against a spring pressure. Normally, when the lift is working, this coil remains energised. It has 1600 μF capacitor across it. When the lift remains 30 cms away from desired floor level, the level limit switch actuates and coil *CM* is de-energised. The condenser across *CM* discharges through the coil and makes the plunger drop softly into the hole provided in the hoist way at the top of the hall gate. If a condenser is not provided across the coil, the plunger would drop abruptly and make a lot of noise. A blocking diode is used in the circuit which does not allow the condenser discharge current to flow back into the rest of the circuit.

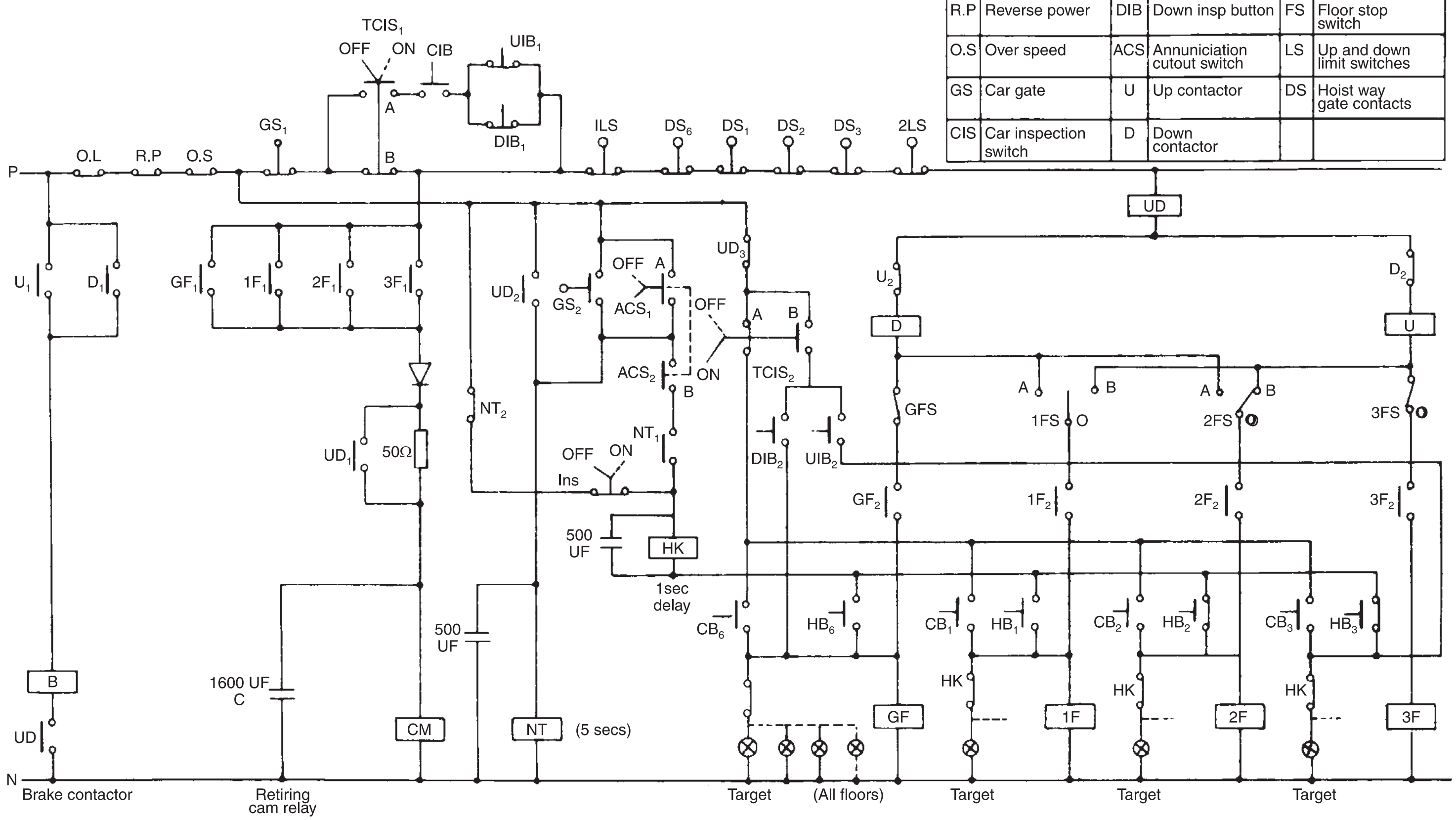
(*b*) Another important relay used is the Hall time switch relay, NT. Function of this relay is to make the hall push button in-operative when the lift is in motion and also for 5 seconds after its stoppage. This delay in operation of hall buttons after stoppage is desired so as to allow the operator to open the car gate. Once the car gate opens, lift cannot be operated from hall gate. Thus if this delay is not there, the lift will not stop at the floor level where the operator desires, but will move to another floor level where a waiting passenger has pressed the hall button.

(*c*) An annuciation cut out switch '*ACS*' is used in the control circuit to cut-off the hall buttons permanently.

(*d*) An inspection switch 1*NS* is provided in the car panel which also makes the Hall-push button in-operative enabling the lift to be operated only through the Car-push buttons.

(*e*) At the top of the car, inspection switch *TES* is provided which allows inspection of the car carriage way. This switch makes both the car and Hall-push buttons in operative. The car can be operated by the person who is inspecting the carriage-way using Up and Down push buttons provided on the top of car.

(*f*) Level sensing limit switches used to stop the lift at different floors are also of special construction. Their contact operation has to be thoroughly understood before reading the control circuit. The lowest level and the highest level limit switches *i.e., GFS* and 3FS are of ordinary type. There is only one contact which opens when the limit switch is actuated. However, the limit switches provided in the intermediate floors are of special construction. The contacts are of changeover type with three terminals. This type of a limit switch contact has been shown in Fig. 9.33 in three different positions.



O.L	Over load	UIB	Up insp button	UD	Main contactor
R.P	Reverse power	DIB	Down insp button	FS	Floor stop switch
O.S	Over speed	ACS	Annuniciation cutout switch	LS	Up and down limit switches
GS	Car gate	U	Up contactor	DS	Hoist way gate contacts
CIS	Car inspection switch	D	Down contactor		

Fig. 9.32 Control circuit for a lift

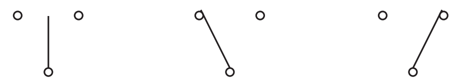


Fig. 9.33 Limit switch contact position (*a*) when lift actuates it at a particular floor (*b*) when lift moves to a higher floor level (*c*) when lift moves to lower floor level

When this particular limit switch is actuated, the contact position will be as shown in Fig. 9.33 (*a*). When the lift moves to a higher floor the contact position will be as shown in Fig. 9.33 (*b*). If, however, the lift moves to a lower floor from its position the contact position will be as shown in Fig. 9.33 (*c*). The contact positions described here are with reference to the limit switch usage in the control circuit. In the particular example we are studying, the level sensing limit switches for floor 1 and 2 will be of the special construction described above while ground floor and top floor limit switches are of ordinary type. Also, the final Up and Down limit switches are of ordinary type.

In Fig. 9.31 have been shown the power circuit and the annunciation circuit of the lift. In the power circuit it is seen that the motor is controlled by three contactors *UD* (main contactor), *U* (upward motion contactor) and *D* (downward motion contactor). The main contactor has been provided for the sake of saftey. In case one of the contactors *U* or *D* gets stuck or their contacts weld-during operation, accident is avoided due to opening of the main contactor, *UD*. Use of three contactors is justified here as public safety is directly involved. DC control supply is obtained through a rectifier and a control transformer as shown. The value of control supply is kept low *i.e.,* 110 V for sake of saftey of the operator.

A reverse phase relay is connected between the output terminals of the 3 phase control transformer *T*. There are two secondary windings of the control transformer. Three phase windings T_4, T_5, T_6 have been used for main control. These three phases are connected to the rectifier. Single phase ac output between T_7, T_8 has been used for the annunciation circuits.

Now let us refer to the control circuit in Fig. 9.32. Working of this circuit from the car push button is described as follows :

Operation of the lift through Car-push buttons

(1) The lift can be operated in Up or Down motion by pressing car push button if control supply reaches the upper coil terminal of contactor *U* and *D*. Supply reaches upto these points if the contacts of all components such as over load relay (*OL*), reverse power relay (*RP*) over speed switch (*OS*), car gate switch (*GS*), contact *B* of car inspection switch *TCIS*-1, upper and lower final limit switches *ILS* and 2*LS*, hall gate limit switches DS_6 and DS_1 to DS_3 are closed. If the contact of any of the above mentioned components opens the lift will not operate.

(2) The level sensing limit switch contact position shown in the control circuit of Fig. 9.32 indicates that the lift is on the first floor, as first floor limit switch 1*FS* has been shown actuated. Now let us examine how the control works when lift is to be taken to second floor. Car push button CB_2 is to be pressed. Control, supply would reach coil of relay 2*F* through closed contact UD_3, contact *A* of switch $TCIS_2$ and push button CB_2. Relay 2*F* will get energised and its contact $2F_2$ will close. This will lead to energisation of contactor *U* and *UD*. The circuit will complete through coil of contactor *UD*, contact D_2, coil of contactor *U*, contact *OB* of second floor limit switch 2*FS*, contact $2F_2$ and coil of relay 2*F*. Thus the lift will move in upward direction. When it would reach second floor, limit switch 2*FS* will get actuated.

(3) When the lift leaves the first floor for the second floor, contact position of limit switch 1*FS* will change. Its contact *OA* will be made.

(4) From the control circuit it may be observed that, when contactor *UD* gets energised, supply to car buttons is cut off due to opening of contact UD_3.This means that the car buttons become inoperative, once the lift starts moving. A command given while the car is stationary can not be overruled by pressing car buttons when the lift is moving.

(5) If now the lift is moved to the third floor by pressing car button CB_3, contactor *U* and *UD* get energised through closed contact of floor limit switch 3*FS* and coil of relay 3*F* and its contact $3F_2$. The lift stops when 3*FS* is actuated.

(6) When the lift moves from second floor to third floor, second floor limit switch contact will change position. It moves from neutral to *OA* position. When the lift is at third floor *i.e,...* , at the top most floor (in this case). The contact position of the limit switches at all the floor levels will be as shown in Fig. 9.34.

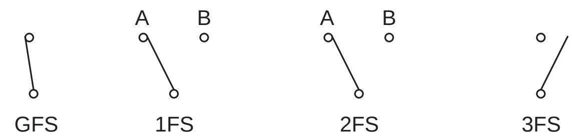


Fig. 9.34 Various limit switch contact positions when lift car is at the third floor

(7) Now let us see the downward motion of the lift from the third floor. To bring the lift to the second floor, car button CB_2 will be pressed. This will energise relay 2*F* and hence its contact $2F_2$ will close. Down contactor *D* will get energised as the contact of 2*FS* is closed in *OA* position. Remember, this contact has changed over in (refer Fig. 9.34) this position during the movement of the lift from the second floor to the third floor. When the lift reaches second floor, 2*FS* is again actuated and both contacts *OA* and *OB* will be open.

(8) When the lift is moved further down to first floor, contact position of limit switch 2*FS* will change and now contact would be made between *O* and *B*.

(9) When the lift reaches the ground floor contact position of various limit switches will be as shown in Fig. 9.35.

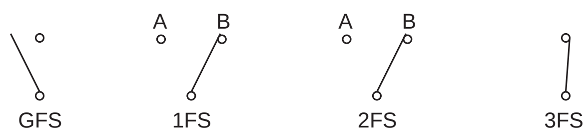


Fig. 9.35 Various limit switch contact positions when the lift is at ground floor

(10) The lift can be moved from ground floor to the top floor or any other floor directly without stopping at intermediate floors. For example, if the car button of third floor is pressed, the lift will move from ground floor to third floor directly without stopping in between at first and second floor. This can be verified by tracing control operation in the control circuit diagram.

Operation of the lift through Hall-push-buttons

(1) When the car gate is closed *i.e.,* contact GS_1 of car gate switch *GS* is closed and GS_2 is open and the lift is stationary, lift movement can be controlled by Hall-push but-

tons also. When the lift is stationary, *UD* is de-energised and therefore its contact UD_2 is open and thus *NT* is in de-energised condition. Supply to Hall-gate-buttons will reach through contact NT_2. Pressing of any of the hall buttons will energise the respective floor relay and the lift will move to the desired floor level through energisation of contactor *U* or *D* and *UD*.

(2) When the lift is moving in Up or Down motion, contactor *UD* is energised and therefore its contact UD_2 is closed. This will energise relay *NT* which has a 500 μ*F* capacitor across it. When *NT* is energised its contact NT_2 will open and supply at Hall-buttons is cut off. Thus the Hall-button contacts shown in Fig. 9.32 become inoperative. However, the other set of contacts of the hall buttons which have been used for the annunciation circuit remain operative. These contacts have been shown, in Fig. 9.31 (*c*).

Referring to this circuit it may be seen that when any one of the Hall-buttons is pressed, a latch relay and buzzer relay B_Z are energised. Closing of latch relay will energise an indicator through its contact and a buzzer will get energised through buzzer relay contact B_Z. It may be recalled that the latch relay has got two coils. The relay will remain closed even when supply to its latch coil is disconnected. It will drop only when its other coil called unlatch coil is energised (refer chapter 2). For example, let us assume that button HB_2 is pressed, then relay 2*AN* will get energised and get latched. Its contact 2*AN* will close and energise the indicator on car control panel and a buzzer will also sound to draw operators attention. This indication will go off only when the operator presses the Reset-push button to drop 2*AN* by energising its unlatch coil. This means that as long as the operator does not accept the information sent by the waiting passengers, the buzzer will continue to sound along with the floor indication signal of the floor at which the lift is required.

(3) When the lift comes to a stop at any floor level, contactor *UD* will get de-energised and it will also cut off supply to relay *NT* due to opening of contact UD_2. Relay *NT*, however, remains energised for about 5 seconds due to discharge current of condenser *C* fitted across it. This delay is to keep the Hall-buttons inoperative for 5 seconds after stoppage of a lift so as to allow the operator to open the car gate. As described earlier, if this delay is not there, then the lift will not stop at the required floor but will move over to that floor where the Hall button has been kept pressed by the waiting passanger.

(4) Once the lift car gate opens, relay *NT* is again energised through closed contact GS_2 of the gate limit switch. Now supply reaches hall buttons through closed contact GS_2, contact *B* of *ACS* switch, contact NT_1 and through relay *HK*. When any of the Hall-buttons is pressed having the car gate open, the respective floor relay (*GF*, 1*F*, etc) is energised. However the lift does not operate as supply does not reach the upper coil terminal of contactor *UD* due to open gate contact GS_1. Energisation of relay *HK*, in this case, will energise a bell called *DOB i.e.* Door open bell through its contact HK_1 (refer annunciation circuit in Fig. 9.31 *b*). This bell rings to attract operators attention and demands that the door should be closed so that the waiting passenger can bring the lift to the desired floor level.

Functions of Various Switches

(1) **Inspection Switch (INS):** When the switch INS is put in ON position, supply at the upper terminal of relay HK and thus also to the Hall-push buttons is cut off. The lift can not therefore be operated when the switch INS is put on 'ON' position.

(2) **Top of Car Inspection Switch (TCIS) :** Two contact block of this switch have been used, designated as $TCIS_1$ and $TCIS_2$. In the OFF position of the switch, contact *B* of $TCIS_1$ is closed while contact *A* of $TCIS_2$ is closed. When inspection of the car carriage-way is to be done, this switch is put ON. The contacts will change over their position. Now contact *A* of $TCIS_1$ and contact *B* of $TCIS_2$ are closed. Due to closing of contact $TCIS_1$ ON-push buttons *CIB* and OFF-push buttons UIB_1 and DIB_1 come into circuit. On the other hand closing of $TCIS_2$ will bring 'UP' and 'DOWN' push buttons UIB_2 and DIB_2 in the circuit. All these push buttons *CIB*, UIB_1, DIB_2, UIB_2 are on the top` of the car. When a person, who is on the top of the car for inspection of car carriage-way, pushes button *CIB* and DIB_2, relay *GF* is energised and the lift moves towards the ground floor irrespective of where it is situated.

(3) **Annunciation Cutout Switch (ACS) :** When this swtich is placed in ON position, its contact *A* will close and contact *B* will open. Closing of contact *A* will permanently energise relay *NT*. Energisation of *NT* will cut off the supply to relay *HK* and Hall-buttons and thus the door open bell annunciation circuit will be cut off.

(4) **Target Annunciation :** This is provided in the car panel and at all floor levels towards which the car is approaching. As seen from the control circuit diagram these indication lamps glow along with the energisation of relay *GF*. 1*F*, 2*F* etc. For example, when the car button CB_2 has been pressed, relay 2*F* will get energised, and in parallel with this relay, five indicating lamps provided one each at all the floor levels and one in the car panel will get enrgised.

(5) **Up and Down Indication :** These are provided at all floor levels to indicate up and down movement of the lift. The indication lamp for up or down movement of the car at all floors gets lighted up through contacts of contactors *U* or *D* as shown in Fig. 9.31 (*a*).

REVIEW QUESTIONS

1. In a planer machine, what will happen if the right hand side limit switch does not actuate? What back-up protection should be there to cover up such malfunctioning?
2. What is the purpose of pressurised air in an overhead tank?
3. In lifting magnets the material will drop when power supply fails. What precaution should be taken to avoid accidents due to such power failure?
4. What is the necessity of providing power limit switches in overhead cranes?
5. Why single phasing of hoist motor in overhead crane is done at the start of lowering motion?
6. Draw the control circuit for a Battery trolley by using a simple selector switch and push buttons.
7. How will you modify the control circuit of a battery truck so that it does not operate when the battery voltage is low.
8. What will happen if the unloading relay does not energise in an air compressor ?
9. What will happen if air reservoir pressure switch in an air compressor fails to actuate?

10. In the control circuit of a walking beam, it may happen that sometimes beam may not stop at LS_4 position but will stop at LS_1 position. What could be the possible reason?

11. Design control circuit for following specification:

(*a*) One push button should start conveyor motors in sequene;

(*b*) An over load on any conveyor should stop all conveyors;

(*c*) One stop button should stop all conveyor in sequence;

(*d*) There should be 30 seconds delay between the stopping of each conveyor working in sequence.

12. Design and draw the control circuit for a lift to be used in a four storied building with the desired features. Also explain in brief its working.

10

Troubleshooting in Control Circuits

10.1 INTRODUCTION

Troubleshooting or fault finding in control circuits can take a few minutes, hours or days depending upon the complexity of the problem and the expertise of the troubleshooter. If the troubleshooter does not understand the control functions and is not familiar with control components and troubleshooting procedures, then, even a small fault in the electrical control circuit can baffle him. This may lead to unnecessary production loss in the plant. A technician engineer who may be skilled in wiring a control circuit from the given diagram may not necessarily be able to troubleshoot control circuits efficiently. For troubleshooting of control circuits the main asset is the possession of analytical mind trained in all aspects of control functions, knowledge of components and circuits. The secret to efficient and accurate troubleshooting lies in determining the section of the control circuit that contains the trouble component and then selecting the proper component to be checked. This can however be accomplished by efficient and accurate circuit analysis and not by trial and error or by checking of components at random.

Troubleshooting starts with the analysis of the problem. To analyse any problem it is helpful to first identify the type of problem. This limits the area in which troubleshooting is to be done. In identifying the type of fault the following areas might be considered:

- Electrical
- Mechanical
- Hydraulic power system
- Pneumatic system

If the exact area of fault is not identified successfully then the troubleshooter will unnecessarily waste time. Sometimes what appears to be an electrical problem at first instance turns out be a mechanical one. Sometimes when electrical maintenance and mechanical maintenance of a plant are looked after by different persons this discrepancy in deciding the type of problem cause undue wastage of time. An employer therefore always prefer that his technician engineer should be responsible for both mechanical and electrical maintenance. In small industries almost always the same man is responsible for troubleshooting electrical and mechanical faults. In big industries an electrical engineer however will look after electrical maintenance while mechanical engineer will look after mechanical maintenance.

In a plant, problem sometimes arises in the machines due to operators misunderstanding, lack of cooperation among the operators, or lack of knowledge of the machine. Whatever may be the reason of the problem it should be handled carefully so that the machine can be returned quickly to its trouble-free operation.

Before discussing the general troubleshooting procedure, it will be helpful to go through the possible trouble spots described in the following section.

10.2 TROUBLE SPOTS

As it is impractical, if not impossible to list all the trouble spots, only those trouble spots have been discussed in which the troubles are quite frequent. The possible trouble spots are as follows.

10.2.1 Fuses

It should be the first spot to be checked but very often this is overlooked.

One of the trouble at this spot could be looseness of fuse carrier or its falling out due to looseness. Fuse carrier can become loose and come out due to vibrations of the machine. In such case the permanent solution is to insulate the control panel from vibration. Temporary solution is to adjust the male contacts of the fuse carrier so as to fit tightly into female contacts of fuse base. Alternatively the fuse carrier can be replaced with a new one.

Another trouble at this spot could be the blowing of the fuse. As it is known, the fuse will blow only when there is some short circuit or grounding in the control circuits. One can try once or twice by replacing the fuse, as some times the fault is of transitory nature and may get cleared by itself. If replaced, the fuse should be exactly of the same voltage and current rating. If the fuse continues to blow out then further checking should be done to detect the fault. If the control circuit is very large then it is better to have sub control fuses for different sections of the control circuit.

This way the faulty position of the control circuit is very easily segregated from the rest of control circuit. For example, a control circuit having relays and solenoid valves, can have separate fuses for relay circuit and solenoid valve coils.

10.2.2 Loose Connections

The control circuit as we normally see on a drawing does not give a true picture of its complexity. In practice the control circuit is wired between three locations viz.:

(1) Control panel,

(2) Operators panel, and

(3) The machine.

Control relays are located in the control panel, pilot devices like push buttons and indication lamps are provided on operators panel while limit switches, pressure switches, float switches etc. are provided on the machine. Control wires from control panel get distributed to the operators panel and the machine through terminal blocks. In modern machines there are hundred of connections involved in wiring the control circuit. These connections are at relay contacts, coils, terminal blocks, pilot devices and sensing devices. All these connections are the possible trouble spots for loose connection. Advancement in the design of terminal block and the use of stranded conductors in place of solid round conductors have greatly reduced this problem. To avoid problems due to loose connections, the best course of action will be to follow a good programme of preventive maintenance in which connections are periodically checked and tightened.

The problem of loose connection becomes serious in case of power circuits as the current handled is of higher magnitude. A loose connection in a power circuit generates local heat which spreads to other parts of the same component and also to adjoining components. Loose power connection finally damages the component due to insulation failure. Loose connection in thermally sensitive components may result in malfunctioning.

For example, a thermal sensitive overload relay may trip due to conduction of heat to it. A regular check for loose connection is the best remedy for avoiding such troubles. Flexible control wires are preferred for wiring a control circuit. These wires are not connected directly in the terminal block or at the relay terminals but are connected after crimping a terminal end on the wire end. Different type of terminal ends are shown in Fig. 10.1.

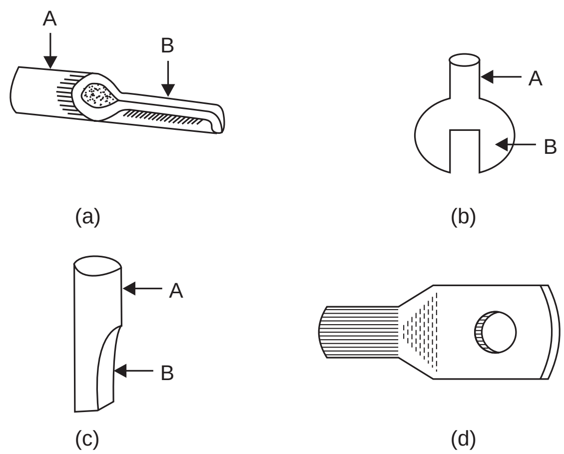


Fig. 10.1 Different types of terminal ends (*a*) Pin type (*b*) Ring type (*c*) Reducer type (*d*) Tubular type

In Fig. 10.1 (*a*) is shown a control terminal end or a pin type terminal end. In the portion '*A*' flexible control wire is inserted after applying a crimping paste on it, and then, this portion is crimped *i.e.* pressed and squeezed by a crimping plier. Terminal end is inserted in the terminal block, keeping portion '*B*' on upper side and tightened with the help of terminal block screw. The terminal end shown in Fig. 10.1 (*b*) is for connecting wires at relay/contactor terminals. Flexible wires are inserted in portion '*A*' and crimped after applying crimping paste. The other end '*B*' of the lug is tightened at the relay contact terminals. Crimping paste is an inhibitor compound used so as to avoid oxidation.

Power connection at the main switch, contactors, terminal blocks etc. are also done through reducer terminal ends and Tubular terminal ends, shown in Fig. 10.1 (*c*) and (*d*). Stranded cable conductors are used. Crimping of terminal ends is done by a hydraulic crimping machine. A pressure gauge is fitted on the crimping machine. Terminal ends are crimped upto a pressure as prescribed by the manufacturer. Terminal ends are available in different sizes and corresponding matching terminal blocks are available for connections. For proper crimping exact pressure should be applied during crimping. If a solid conductor is to be connected through a terminal end then the terminal end is to be soldered to the conductor. A soldering rod is melted and put in the portion *A* to hold the conductor.

10.2.3 Faulty Contacts

This trouble occurs in such components as motor starters, contactors, relays, push buttons, and various types of switches.

The most common problem appears with normally closed contacts. Although visible observation shows that such contacts are closed but in actual practice they may not be conducting current. Contacts may not be conducting due to dirt or formation of copper oxide films which is an insulator. Another reason could be improper spring pressure. Oxide film from the contact can be cleaned by drawing a piece of rough paper between the contacts. Care should however be taken to use only a fine abrasive to clean contacts. Contacts should never be filed. Most of the contacts being used today have silver coating, the silver coating will get destroyed if filing is done. If the contacts are badly worn out and heavily pitted these should be replaced. Problem with silver coated contacts is that the silver oxide film formed becomes conducting. If this film is not cleaned at regular intervals, it may short circuit the adjacent contact terminals. It is therefore recommended that silver coated contacts should be cleaned with carbon tetrachloride at regular intervals to remove silver oxide film.

Another problem with contacts is that they may get welded together during an overload or a short circuit fault. If the contacts get badly damaged they should be replaced. Sometimes the spring pressure on contacts is not sufficient, this should be adjusted, or springs should be replaced with new ones.

In a newly wired control circuit, problem may be due to use of wrong contacts. Error is often made in wiring a control circuit, particularly when only one of the two available contacts of a component is used. The error consists of wiring the wrong contact, that is using a NO contact instead of a NC contact or vice-versa.

This error is too frequent, it can be due to carelessness or lack of familiarity with the component being wired. To avoid such problems the person who is wiring should be completely familiar with components and he should double check his work.

10.2.4 Incorrect Wire Marking

This problem will usually appear at the initial stage of control panel wiring or at the stage of assembly and erection of the machine in the plant. The error can also creep in during preventive maintenance or during any alteration done in the control circuit. This error becomes difficult to locate as control cables running from a control panel to the machine may have as large as 20 conductors. One common problem is the transposition of numbers. Another problem that may occur with numbering ferrules is during connecting conductors into a terminal block. With a long block and many conductors, it is a common error to connect a conductor either one block above or one block below the proper position.

10.2.5 Combination Problems

As described earlier some of the problems in machines cannot be referred to as faults exclusively due to defective electrical or mechanical or hydraulic or pneumatic system. Mere observation does not give any positive clue to the area of trouble spot. The problem may be in one area or it may be simultaneously in two areas. Whenever such a discrepancy arises, it is better to first check the electrical circuit as it is faster to check an electrical circuit than a mechanical system.

To quote an example, one very common combination problem is overload tripping of a motor. The motor may be tripping due to actual mechanical overload or due to malfunction of overload relay or due to defect in the motor itself. It is also possible that two abnormalities may be existing at the same time. An overload may malfunction due to heat generated by a loose power connection. A motor may take more current due to damaged bearing. If discrepancy arises in such cases the motor should be decoupled from mechanical load and thorough checking from electrical point of view should be done first.

Another example of combination problem is burning of solenoid valve coils. Probably, over 90% of all troubles on valves develop from a faulty mechanical or pressure condition, which prevents the solenoid plunger from seating properly leading to drawing of excessive current by the coil. As a result either the fuse blows or the solenoid coil burns out.

Electrical cum pressure could also be another combination problem. A particular operation of a machine may not happen due to fault in the control circuit or due to improper fluid or pneumatic pressure.

An electrical cum temperature combination problem can occur in ovens and furnaces. Required temperature may not be obtained and the possible reason could be low voltage, damaged heaters, blown fuses or leakage of heat due to use of improper heat insulating material.

A methodical approach should be made to analyse such problems instead of attempting a trial and error method.

10.2.6 Low Voltage

If the system voltage becomes low, relays, contactors, timers etc. start dropping (getting de-energised) and as a result control circuit starts malfunctioning. Motors would trip at low voltage as they would draw more current from the supply. The system voltage may become low because of heavy loading or inadequate conductor size. A common source of such problem is the addition of new machines without properly checking the capacities of power supply line and the transformer.

Low voltage will result in generation of inadequate heat in ovens. For example, if the voltage is dropped to one half the heating element's rated voltage, the heat output will be reduced to one fourth.

10.2.7 Grounding

We can have two types of control supply, one is with neutral grounded and the other without grounding. Each has its own merits. In the first case one terminal of control supply from control transformer is grounded. The other terminal of control power supply is protected by a fuse or a miniature circuit breaker. The advantage of this method is that it is easy to check supply at any point, as it is to be done with reference to ground. In this method when a ground fault occurs, the control fuse blows and the machine remains inoperative until the fault is located and removed.

The second type of control supply with ungrounded neutral is preferred for large production shops. In this type of control supply the circuit continues to work even if a ground fault occurs. Control fuse will blow and the machine will stop only when a second ground fault occurs. The method thus has an advantage because production can continue with one ground fault leaving some time to locate the fault and remove it. In this type of control supply, some type of indication has to be provided which should convey that a ground fault has occurred. Two indication lamps are used to denote which one of the control lines has got grounded. This scheme is shown in the control circuit of Fig. 10.2.

In this control circuit, ground detection indication lights are *A* and *B*. Wire no.10 between *A* and *B* is solidly grounded. When none of the line 1 and 0 are grounded, both the indication lights *A* and *B* will glow at half brilliance as two 220V bulbs are connected in series. If a ground fault occurs in the system, one of the lamps will go off, while the other one will glow at full brilliance. A bulb getting switched off in a particular side will indicate that control supply of that side has become grounded.

If a ground fault occurs at wire no. 3 and also simultaneously at wire no. 8, control fuses will blow due to short circuiting of the secondary terminals of the control transformer.

The advantage with ungrounded control supply is that even if any point of the control circuit gets grounded, it would not cause immediate trouble. Production can go on without interruption and ground can be detected and removed on the maintenance day.

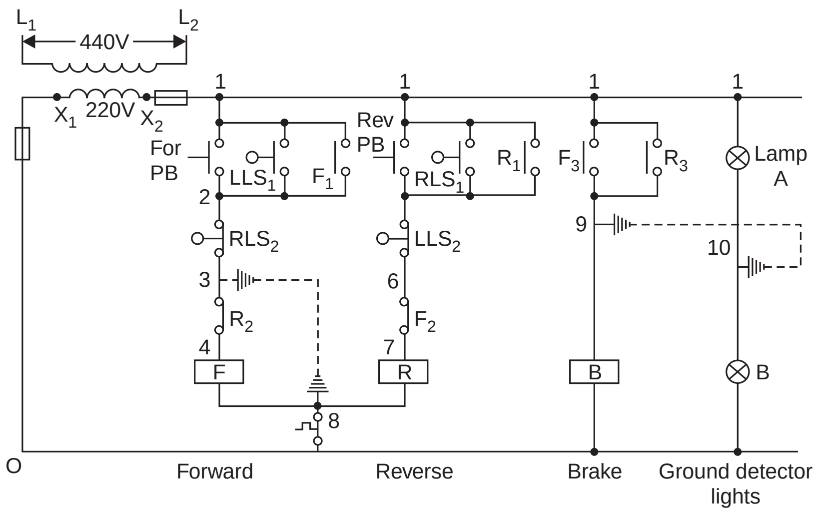


Fig. 10.2 Control circuit having ground detector lights

There are many locations on a machine where a ground can occur. However, there are a few spots in which grounds occur more often. These spots are discussed below:

(1) Often ground fault occur in limit switches, pressure switches, temperature switches, float switches etc. Most of the time this is due to the compact design of many components allowing very small space for making connections. Due to lack of space, bare conductors at terminals of a component may come in contact with the case of the component. Many times the cables/wires going to a component may get pulled and cause breakage or grounding of the wires. Control wires in control panel can also get grounded in the panel itself or with an adjacent ground wire.

(2) A ground may occur due to damaging of insulation while pulling control wires through a conduit, if proper care is not taken. Insulation damage may also occur when there are several bends in the conductors.

(3) A ground fault may also occur due to improper use of a stranded conductor. Care must be taken while placing a stranded conductor into a connector. All strands must be used. One or two strands which have not been used may touch the case or a normally grounded conductor. Even if this does not happen, current carrying capacity of the conductor gets reduced due to less number of strands in use.

10.2.8 Momentary Faults

Sometimes faults occur but do not persist for a long time. It becomes really difficult to locate the origin of such momentary faults.

The operator of the machine needs to keep a close observation to find out at which part of the cycle of control circuit operation the fault occurs. When the part of the cycle at which the fault occurs is identified, the control circuit pertaining to that portion needs to be checked thoroughly. If the fault occurs at random during the cycle then those components which are common for the whole cycle operation should be checked.

Loose connection or a broken conductor inside the insulation can also be the cause of momentary fault. Sometimes a control component may be malfunctioning. In case of doubt a component can be replaced by a new one. If the machine is new, fault may already exist in the control circuit due to improper connection.

10.2.9 Poor Maintenance

If regular maintenance of a machine is not done the frequency of occurrence of faults will increase. Regular maintenance also includes proper cleaning of machine and control panel. The control panel door should be properly sealed so as not to allow dust and dirt to enter the panel. Though manufacturers of components have improved their product design so as to prevent dust, dirt, and fluids entering inside the components, proper care should also be taken by the users. In large motor starters moving mechanical parts should be checked for loose pins and the bolts. Dust, dirt and grease should be removed from electrical parts, otherwise short circuit may develop. It is recommended that a regular maintenance schedule should be followed. History sheet of each individual machine should be maintained. In this history sheet details of all break-downs occurring on machines and also details of preventive maintenance done should be noted. History sheet can be very useful to a supervisor in detecting fault in the machine.

10.3 GENERAL PROCEDURE FOR TROUBLESHOOTING

Firstly, we will consider a control circuit which has just been wired but is not working as per the design. The procedure for detecting fault in such a circuit is as follows:

(1) The first step should be to analyse the control circuit and ascertain that it has been properly designed as per the control function requirements;

(2) The next step is to run the machine and follow the operation through the expected sequence until one finds the section of control circuit which is not operating;

(3) After locating the faulty section, wiring should be checked. If wiring is as per drawing then control components of this section should be checked thoroughly;

(4) When trouble in the faulty section is located and removed, the machine should be started again to run successfully throughout the complete cycle. In case of fault existing in any other section of the control circuit, one should now try to locate the fault of that section.

Secondly, we will study the troubleshooting procedure for an already existing circuit which was working properly before the occurrence of a fault. The possibility of improper connection therefore is eliminated. The procedure for troubleshooting in such a circuit is as follows:

(1) The first step is to understand the operation and control circuit of the machine. If the control circuit is very large and complex, help of the operator should be taken to find out how much of the circuit is operating. In this way one can directly start with the section of the circuit that does not function.

(2) When the faulty circuit section has been identified, first a careful check of the circuit and components involved in that section should be done. A careful visual inspection may help to detect a faulty component or an open wiring. If nothing is found out in the visual inspection then the procedure may be as follows.

(3) Find out which operation is not taking place and identify the contactor/solenoid valve coil which is responsible for this operation. Operate the machine and check whether there is voltage across the coil of relay or the contactor/solenoid valve coil. If proper voltage is available across the coil then trouble, most likely, is in the winding of the coil itself. Now, to check the continuity of coil, power is switched off and continuity of the coil is checked with an ohm meter. If the coil is alright, a low resistance is indicated. Working of the contactor or solenoid valve should be checked before replacing the burnt coil. If it is suspected that contactor closing mechanism or solenoid valve is defective, a new contactor or a new solenoid valve should be installed.

(4) Suppose that in the step discussed above voltage is found to be not reaching the contactor coil. This indicates that some contact is not closing when it should, thus disconnecting supply to the coil. In such a case control circuit drawing should be referred, to find out components whose contacts should close to energise the coil. These contacts may be of different relays, limit switches, pressure switches, temperature and float switches etc. Now the task will be to determine which of the components connected in series is not making contact.

(5) To find out contact of which particular component is not making, supply should be checked at various points leading to the contactor coil. Here, note that difficulties may be faced in checking if limit switches, pressure switches etc. which are on the machine are wired directly in the control circuit. If, however, relays are energised through limit switches etc., and then contacts of these relays are used in control circuit, checking will become easier. This point has already been explained in Chapter 2 while discussing relays. Once the defective component is detected then the cause of malfunctioning can be found out. If the contact is not making due to a copper oxide film or dirt, cleaning should be done and if contact is not closing properly, adjustment can be done. If, contact is badly pitted it should be replaced. The other possibility during this checking can be detection of open circuit due to a broken or burnt wire.

(6) Having eliminated the fault, the machine should be started again and if the machine does not operate successfully throughout the complete cycle of operation, the above procedure should again be applied to the next section of the control circuit which is faulty.

(7) Quite frequently, grounding of a wire going from control panel to the machine may be the cause of trouble. A check should be made for detection of ground fault, by putting off the power supply. Resistance to ground of the wires should be checked with an ohm meter, or alternatively, a test lamp can be used to detect ground, where 230 V supply with neutral earth is available.

To check ground, one side of test lamp is connected to phase wire while the other end is connected to the wire which is to be tested for ground. If the wire is grounded the lamp will glow, otherwise it will remain off. This is shown in Fig. 10.3.

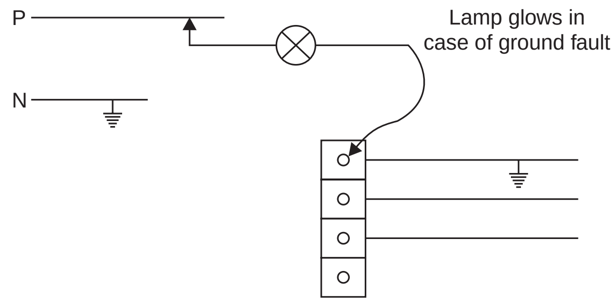


Fig. 10.3 Detection of ground fault using a test lamp

The above procedure of fault detection is based on the fact that control circuits are made up basically of only two things viz., contacts which make and break the circuit, and relay coils which operate these contacts. If the contacts open and close as they should, then proper voltage gets applied to the coils or the coils get de-energised, as desired. The fault can thus lie with the contacts, relay/contactor coils, or the associated wires which carry current through the contacts to the coil.

One improtant rule to be observed while troubleshooting is to attend to only one thing at a time. If you suspect that a contact is malfunctioning, first correct this contact and then check machine operation. If fault persists then proceed to check other suspected possible trouble spots. It is very seldom that several parts of a machine would wear out at the same instant even though their condition may be poor. Tempering with more than one component at a time may introduce more trouble than original trouble. In order that the procedure outlined above for troubleshooting becomes clear, we will determine probable causes of some troubles which we will assume to have occurred in the circuit. The circuit is a simple control of an air compressor motor shown in Fig. 10.4.

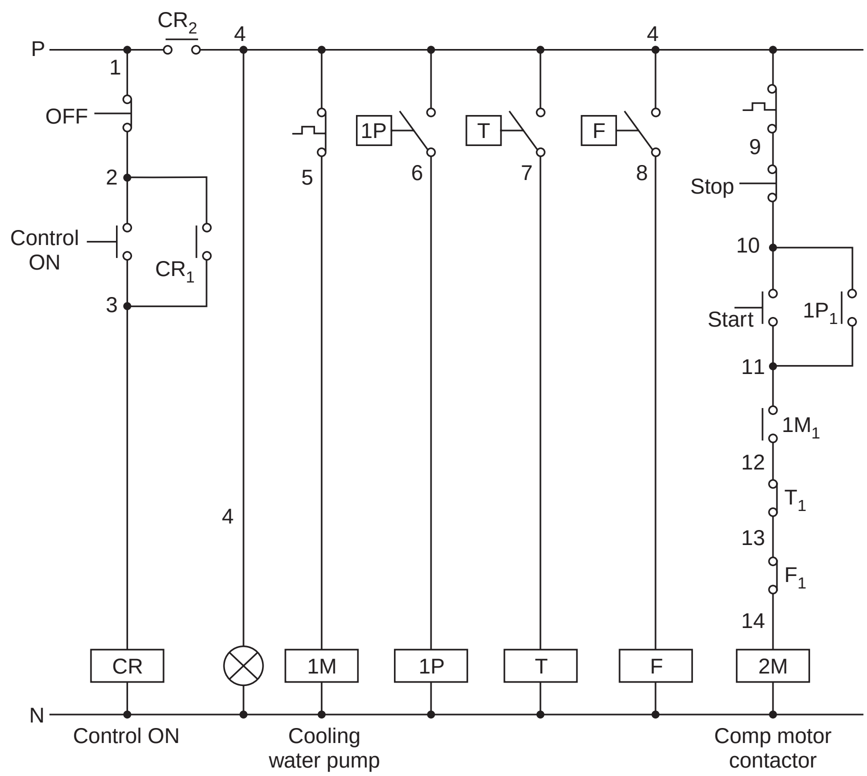


Fig. 10.4 Control diagram for an air compressor motor

In this circuit *CR* is control relay, 1*M* is cooling water pump motor contactor, 2*M* is compressor motor starter contactor. Oil lubrication pressure switches, cooling water temperature switch, and cooling water flow switch energise relays 1*P*, *T*, and *F*. Contacts of these relay are used in the starting circuit of the compressor motor contactor 2*M*. Brief description about working of circuit is that when control relay *CR* is energised by pressing control ON-push button, relay *CR* closes and is held through its contact CR_1. Its contact CR_2 also closes and energies terminal 4. Cooling water pump starts due to energisation of contactor 1*M* (Remember cooling water pump circulates cold water for cooling the compressor). Compressor motor contactor 2*M* can be energised by pressing START-push button. Contactor 2*M* gets energised if contact $1M_1$, T_1 and F_1 are in closed condition. When 2*M* is energised, compressor motor starts and lubrication oil pressure also starts building up as the oil pump is coupled with the main compressor motor. If sufficient pressure builds up, oil lubrication pressure switch 1*P* closes and energises relay 1*P*. Contact $1P_1$ of this relay closes across the START-push button and contactor 2*M* is held through contact $1P_1$. START-push button has to be kept pressed till contact 1*P*1 closes. Having understood the working of the circuit, we will now discuss detection of some troubles assumed to have occurred in the circuit:

(1) Suppose that the trouble reported by operator is that the control circuit is not functioning. This will also be indicated by non-glowing of 'control ON' indication lamp. First of all, by visual inspection check if the control relay *CR* is closed. If found closed, then check supply at terminal 4. If there is no supply then contact CR_2 is not making contact. Take action to rectify defects in the contact. If on visual inspection, relay *CR* is found to be de-energised, then press control ON-push button and check supply across the coil. If full voltage is available then fault lies in the coil. Disconnect the coil and check its continuity. If the coil is found burnt replace it after checking the relay.

In the previous check, with the ON-push button pressed, if no voltage is found available across the coil *i.e.*, at terminal 3 with respect to neutral 0, then proceed to check voltage at terminal 2. If voltage is available at terminal 2, it would mean that control ON-push button is not making contact on being pressed. Replace the contact block to rectify the fault. If, however, supply is not available at terminal 2, fault may be there in the OFF-push button, its *NC* contact may not be making contact. If during this checking no supply is detected upto terminal 1, then it would mean that the control fuse is blown. Check the control fuse. The control fuse may get blown due to fault in any part of the whole control circuit. Fuse can blow due to any coil getting shorted as a result of burning or due to grounding of any wire. If control fuse is blown, proceed as follows to detect the fault.

To detect the trouble spot for fuse blowing, first one has to find out the section in which fault exists. If the fuse is getting blown before the compressor motor has started, the possibility of fault lying beyond terminal 11 is ruled out. Now remove all the wires marked number four (4) from the contactor strip and check with the help of an ohm meter or test lamp each individual wire for a ground. Suppose wire no. 4 going to cooling water temperature switch is showing ground then check for any physical damage to the wire going from panel to the switch. Also check the switch as wire may be getting ground by touching the case of the switch.

(2) Another problem with control relay may be that it does not remain energised when the ON-push button is released. For this, check if any wire is open at contact CR_1 of the relay. If wires are found connected properly then the problem, most probably, is with the contact CR_1. This contact may not be making due to oxide film or dust and dirt etc. It may also need adjustment or replacement.

(3) Another problem could be that the compressor motor fails to start when the START-push button is pressed. First step should be to check visually in the control panel the condition of relays *T*, *F* and 1*M*. 1*M* should be closed while *T* and *F* should be open. Suppose the relay *T* is found closed, it would mean that the cooling water temperature switch is actuated. It should be found out whether the temperature switch is malfunctioning or whether the temperature of the cooling water has actually increased. If the temperature switch is defective it should be replaced. If cooling water temperature had increased find out the cause and remove it. Fault may be in the compressor itself, or perhaps the inlet water temperature is already high.

If during visual inspection, the condition of the relay is found as desired, then proceed to check voltage at various points, starting from the coil terminal 14 with the START-push button pressed. If voltage exists at terminal 14, then disconnect coil of contactor 2*M* and check its continuity. If no voltage exists at terminal 14 then proceed backward to check voltage at terminal 13, 12, 11, 10, 9 till the terminal where supply is available is reached. Suppose supply voltage is found at terminal 9 and not at terminal 10, it would be clear that OFF-push button is not making contact. Remove dust from this push button contact element, or if required replace the contact block. Suppose the supply was detected at terminal 12 while there was no supply at terminal 13 then fault lies in the contact T_1 of relay *T*. Proper contact may not be making, or the wire may be open at the terminal of the relay.

(4) Suppose the problem reported is that the compressor motor starts but does no hold *i.e.*, trips as soon as START-push button is released. Since oil lubrication pressure switch contact $1P_1$ is used to hold the contactor 2*M*, immediately check is to be made whether oil pressure is being developed so as to actuate the pressure switch and relay 1*P*. The problem may be in the contact $1P_1$ or pressure switch itself or oil level in the sump may have fallen down due to leakage and thus oil pressure is not building up.

REVIEW QUESTIONS

1. What are the two main assets of a troubleshooter which help him in early detection of a fault ?

2. What are the possible troubles in the fusebase and carriers ?

3. What problems are caused by loose connections in control and power connection ? Draw different types of terminal ends used in solving the problem of loose connections ?

4. What type of contacts may cause trouble and yet they appear to be in good condition ?

5. Why should you never file a contact ?

6. What is a combination problem as applied to machine control ?

7. What conditions lead to a low-voltage problem in plants ?

8. Discuss the merits and demerits of using a control supply with grounded and ungrounded neutral.

9. Explain with the control diagram how indication lamps are used to denote which of the control line has got grounded in an ungrounded control supply scheme.

10. List a few spots where ground fault occur more often.

11. Explain the general procedure for troubleshooting.

12. Draw a sketch explaining detection of ground fault using a test lamp.

11

Static Control of Machines

11.1 INTRODUCTION

An industrial control system, whether it is magnetic control or static control can be divided into three distinct sections viz.:

(*i*) Information gathering section or *input section*

(*ii*) Decision making section or *logic section*

(*iii*) Actuating device section or *output section*

Relationship between the three sections is shown in Fig. 11.1.

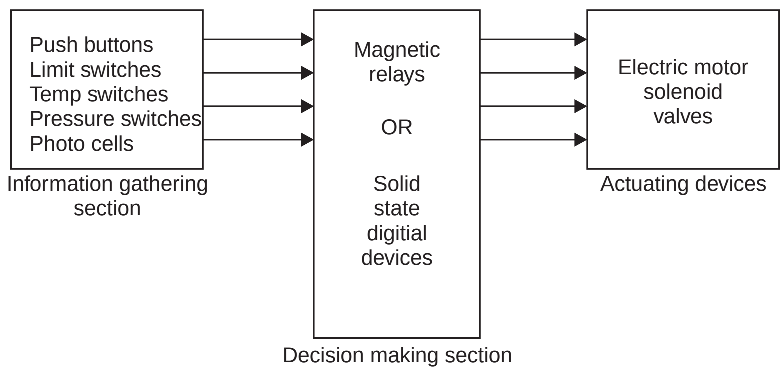


Fig. 11.1 Relationship between the three sections of an industrial control system

It is clear from Fig. 11.1 that information gathering section components like push buttons, limit switches, pressure switches etc. and actuating devices like motors and solenoid valves are common in both types of control *i.e.*, static or magnetic. The components in the decision-making section are, however, different. In magnetic control circuits, magnetic relay constitute the decision making elements. In static control, decision-making section consists of solid state/ digital devices. These devices have no moving parts and no contacts. Digital devices used in decision-making are:

AND Gate	Memory
OR Gate	Delay Elements or Timers
NOT Gate	Registers
NAND Gate	Counters
NOR Gate	

It is known that in electromagnetic control, relay contacts have only two possibilities *i.e.*, they can either be closed or open. Similarly in digital or static control there are two conditions or states. These two states are the two voltage levels, high or low. The two voltage levels are represented by binary digits 0 and 1. When 0 represents a low voltage and 1 represents a high voltage, it is known as positive logic. When 0 represents a high voltage and 1 represents a low voltage, it is known as negative logic. We will confine only to positive logic in the rest of the chapter. The above mentioned form of reasoning is derived from Boolean algebra which was developed by an Englishman named George Boole in the last century. It was used at that time as a way of expressing statements that could be either true or false. It thus follows from the above that the two states, high voltage and low voltage represented by digits 1 and 0 in solid state logic circuits correspond to closed and open condition of relay contacts.

Digital devices were originally made using discrete combinations of diodes, transistors and resistors on a board. Now these are available as integrated circuits in a single chip of semi-conductor material. Digital devices were first fabricated using resistor transistor logic (RTL) followed by diode transitor logic (DTL). These logic elements are not much in use now. Now a days logic gates and devices are made using transistor logic, known as TTL logic. TTL logic elements operate on 5 volts. A voltage level of + 5 volts is considered as a high level voltage and that of 0 volts as a low level voltage. Another type of logic frequently used in industry is high transit logic (HTL). This is used because it ignores the voltage spikes and drops caused by starting and switching of induction devices. *HTL* generally operates on 15 volts.

Another type of logic which has become very popular is *CMOS* which stands for complementary-symmetry metal oxide semi-conductor. The advantage of this logic is that it has a very high input impedance and it requires very less power to operate. This logic also has certain disadvantages. One major disadvantage is that it is very sensitive to voltage, sometimes even the static charge of a person's body touching the *IC* can destroy it. People who work with *CMOS* logic often use a ground strap which straps around the wrist like a bracelet. This strap prevents static charge from building up on the body. Another limitation of this logic is that unused inputs can not be left open. Unused inputs must be connected to either a high state or a low state.

A control engineer need not go into the internal structure of an *IC* but should be thoroughly familiar with their functions and use as components in control functions. The objective of this chapter is to enable the students to design control circuits using digital devices. To give an idea about the internal structure of digital devices only two devices, AND gate and OR gate will be discussed. Before various digital gates and their applications in building up control circuits are discussed, it will be worthwhile to compare the advantages and disadvantages of static control with respect to magnetic control.

11.2 ADVANTAGES OF STATIC CONTROL OVER MAGNETIC RELAY CONTROL

(*i*) The first and very important advantage is the more reliable and maintenance free operation. Although nowdays with high quality materials available, relays can be designed for a longer trouble free operation yet their life expectancy is shorter as compared to static switches. This is because relays have moving mechanical link-ages and contacts which are subject to wear. Relay coils draw fairly high inrush currents to produce the necessary force to move the linkages. This puts stress on the coil wire and insulation. This limits the life expectancy of relay to a few million operations. Relay parts are exposed to atmosphere and therefore dirt particles inter-fere with proper movement of relay parts. Also, the chemicals in atmosphere can damage coil insulation and contacts.

Solid state gates on the other hand are completely independent of number of operations performed and thus have unlimited life expectancy. They have no moving parts and no appreciable inrush current. They are impervious to atmosphere dusts or dirts as they come in sealed packages. Thus, if these devices are protected against thermal shocks and over currents, they will last almost forever and will require no maintenance.

(*ii*) Static switches provide much higher speed of operation which is often desirable in modern machines and processes. Relays operate in milli seconds whereas, most solid state devices operate in micro seconds or nano seconds. Thus a solid state gate is at least 1000 times as fast as a relay.

(*iii*) Static switching provides comparatively simpler circuit design than relays for complicated processes, which must sense and evaluate many factors and conditions. This is due to the basic difference between a static switch and a magnetic relay. Static switch is a multiple input and single output device whereas a relay is a single input multiple output device. The above will become clear on studying various static switches.

(*iv*) Static switches can be used in explosive environment as they switch ON and OFF without sparking. If relays have to be used in explosive environments they have to be housed in expensive airtight enclosures.

(*v*) A solid state logic element is much more compact than a relay. Thus for extensive control circuits, which require hundreds of relays, use of solid state logic will require much less space as compared to relay logic circuit.

(*vi*) Solid state logic is cheaper than an equivalent relay circuit for an extensive control circuit. A solid state logic circuit requires extra dc power supply, signal converter and output amplifier. However, the low 'per gate cost' over-rides the expenses due to the above mentioned equipments for extensive control circuits that contain hundreds of decision-making elements.

(*viii*) Solid state logic gates consume very less power as compared to relays. Therefore, for extensive circuits there can be an appreciable saving of energy.

11.3 DISADVANTAGES OF STATIC CONTROL OVER MAGNETIC RELAY CONTROL

(*i*) Static circuits can malfunction due to noise signals. Separate circuits are to be provided to safeguard against these. Relays on the other hand are not prone to noise pick up.

(*ii*) A static circuit is not suitable for a small control circuit as it requires separate dc power supply, signal converters for interfacing information, sensing devices, and amplifiers for interfacing output devices. This increases the cost of the circuit. Relay circuits are cheaper and simpler for small control circuits.

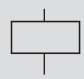
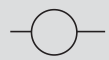
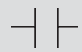
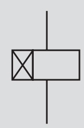
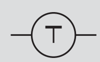
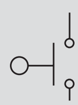
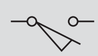
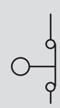
(*iii*) Solid state logic gates do not work well at high temperature. In an industrial environment, where temperature is generally high, some type of cooling, like fan cooling or air-conditioning, of the panel is required. This negates the advantage of energy conservation and reliability. In comparison to this, relays work well at high ambient temperatures.

(*iv*) Alteration or modification in an existing static circuit is dificult to accomplish as compared to magnetic relay circuit.

(*v*) Trouble shooting is difficult in static control circuits as compared to relay circuits.

Two sets of symbols are used to represent logic gates. They are USASI symbols and NEMA symbols. USASI symbols, which are more common, will be used in this chapter. Control diagrams using logic gates have been drawn in the ladder form of diagram. In these, control supply is represented by two vertical lines spaced apart. Control circuit is built between these two lines in form of horizontal rungs. These rungs resemble the rungs of a ladder and therefore these diagrams are known as ladder type diagrams. This is the universal procedure for making diagram using logic gates. For the sake of symmetry, in this chapter, relay circuits have also been drawn in ladder form. (Although in previous chapters the relay circuits have been drawn in the other form). In earlier chapters the control supply was represented by two horizontal lines and the circuit was built up in rungs from left to right. Some of the magnetic control symbols used in this chapter are different from that used in previous chapters as they are more suitable in ladder form of diagram. Another purpose of using different symbols is to familiarise the student with these symbols as these symbols are also widely used in Indian Industries. Various magnetic components which have been shown different in this chapter are tabulated in Table 11.1. Static switch symbols will be discussed as we proceed to study various switches.

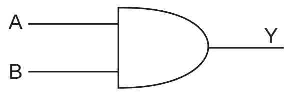
Table 11.1 USASI symbols for some common control components

S.No.	*Component*	*Conventional Symbol*	*USASI Symbol*
1.	Relay/Contactor coil		
2.	Normally Open (NO) Relay/Contactor contact		
3.	Normally Closed (NC) Relay/Contactor contact		
4.	Time Delay relay coil		
5.	Limit Switch (NO) contact		
6.	Limit Switch (NC) contact		

11.4 EXPLANATION OF DIFFERENT GATES

11.4.1 AND Gate

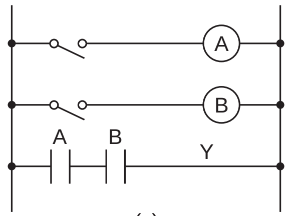
The symbol for AND Gate is shown in Fig. 11.2 (*a*), it has two or more inputs but only one output. In an AND Gate output signal is obtained when all the input signals are present. Thus, output *Y* will be high *i.e.*, 1 when both input *A* and *B* are high *i.e.*,1, if any of the input is low *i.e.*,0, output will also be low *i.e.*, 0. This relationship between inputs and output for a two input gate is tabulated in truth table shown in Fig. 11.2 (*b*).



(a)

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

(b)



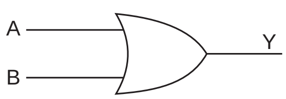
(c)

Fig.11.2 (*a*) Symbol (b) Truth table (*c*) Equivalent relay circuit for an AND gate

The equivalent relay circuit for AND Gate as shown in Fig. 11.2 (*c*), consists of two normally open contacts of relay *A* and *B* connected in series. In this circuit when both the relays *A* and *B* are de-energised there will be no supply at point *Y*. If any of the relays *A* or *B* is energised, even then, there will be no supply at point *Y*. When both the relays are energised only then there will be supply at point *Y*, as both relay contacts in series are closed. These conditions are analogous to the conditions shown in truth table of AND Gate, if it is assumed that an energised relay corresponds to high input *i.e.*, 1 and a de-energised relay corresponds to low input *i.e.*, 0.

11.4.2 OR Gate

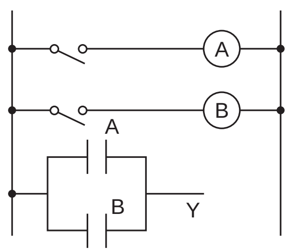
OR gate symbol for two inputs is shown in Fig. 11.3 (*a*) In OR gate output is obtained if there is signal at any one of the inputs. This means, output *Y* is high if any of the input *A* and *B* is high. This relationship between inputs and outputs are tabulated in truth table of Fig. 11.3 (*b*). The equivalent relay circuit for OR gate shown in Fig. 11.3 (*c*) consists of two normally open contacts of relay *A* and *B* connected in parallel. When both the relays are de-energised output *Y* will be zero. When any one of the relays is energised there will be output *Y* due to closing of either contact *A* or *B*. When both the relays are energised, again there will be supply at *Y*. Assuming that energised relay corresponds to high input i.e., 1, de-energised relay corresponds to low input *i.e.*, 0, these conditions of relays and output *Y* are found analogous to conditions in the truth table.



(a)

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

(b)



(c)

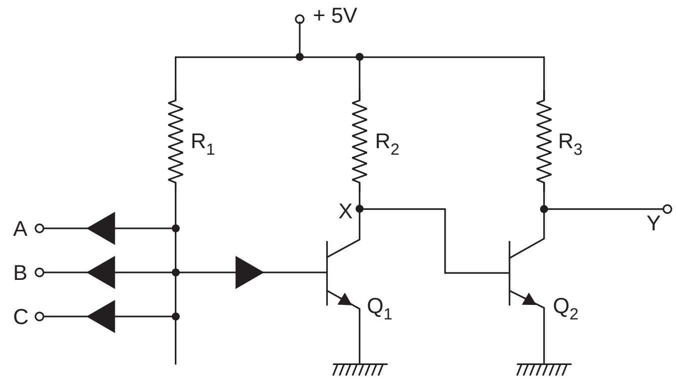
Fig.11.3 (*a*) Symbol (*b*) Truth table (*c*) Equivalent relay circuit for an OR Gate

Some students may be interested to know the internal circuitry of these gates. To give an idea how transistors are used to build gates, only AND and OR gates will be discussed. Internal circuitry for these gates have been shown in Figs. 11.4 (*a*) and (*b*).

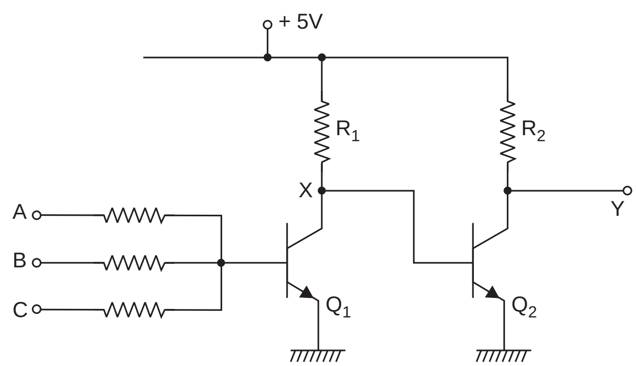
In Fig.11.4, dc supply is used for operating these circuits. High voltage here refers to + 5 V while low voltage is 0 volts.

In the AND gate circuitry when any of inputs A, B or C is low the voltage at the base of transistor Q_1 is low (0) as most of the + 5 volts drops across resistance R_1. Transistor Q_1 is therefore in cut off state. Thus voltage at collector of transistor Q_1 *i.e.*, at point X is high and this voltage is coupled to the base of transistor Q_2. Thus base of transistor Q_2 is at higher voltage with respect to its emitter. Transistor Q_2 therefore conducts and is in saturation state. Voltage at point Y on the collector side of transistor Q_2 is therefore low. When all the inputs A, B and C are + 5 V high *i.e.*, + 5 volts, the voltage at the base of transistor Q_1 is also high and therefore transistor Q_1 conducts, and the voltage at point X or at the base of transistor Q_2 is low, thus it does not conduct. If Q_2 is cut off then voltage at point Y is high (+ 5 V). Thus it is clear that output Y will be high (+ 5 V) only when all the inputs are also high.

Now, referring to the OR gate circuitry, when any of the input is high, the base of transistor Q_1 is also high with respect to its emitter, as a result the transistor conducts. This leads to low voltage at point X and thus transistor Q_2 remains cut off. As Q_2 is cut off, the voltage level at point Y is high. If all the inputs are low then Q_1 will be cut off and Q_2 will conduct. This gives low voltage at Y. Thus we see that this circuit fulfills the conditions described for an OR gate.



(a)



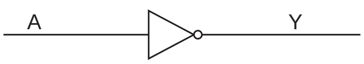
(b)

Fig.11.4 (*a*) AND gate circuitry (*b*) OR gate circuitry

In practice the high and low values for static devices are not rigidly fixed at + 5 V or 0 volts. For example with 7400 series TTL devices any input voltage between 0 and 0.8 V is considered low and any input voltage between 2 and 5 V is considered a high input. This is so, because voltage within these ranges can force the output to change states. Similarly low output from a 7400 series device may be from 0 to 0.4 V and in the high output value may be from 2.4 to 5 V. In other words, output voltage, as small as 2.5 V, is considered high as this voltage can drive the other TTL circuits.

11.4.3 NOT Gate or Inverter

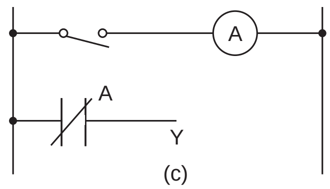
This is the simplest of all gates. It has one input and one output. The output is inverted or becomes opposite of the input. If input is high (1) then output is low (0) and if input is low (0) then output is high (1). The symbols, truth table, and equivalent relay circuits are shown in Fig. 11.5.



(a)

A	Y
0	1
1	0

(b)



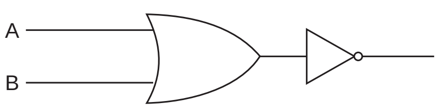
(c)

Fig.11.5 (*a*) Symbol (*b*) Truth table (*c*) Equivalent relay circuit for a NOT Gate

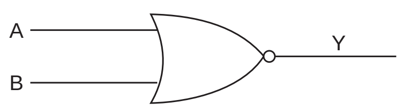
Equivalent relay circuit is a single normally closed (NC) contact of relay *A*. When relay *A* is in de-energised state there will be output at *Y*, whereas when it is energised, there is no output at *Y*. If we compare these conditions with the truth table it will be found that the conditions are analogous.

11.4.4 NOR Gate

NOR gate is equivalent to connecting a NOT gate to the output of an OR Gate. This is depicted in Fig. 11.6 (*a*). The symbol for NOR gate is obtained by connecting a bubble to the OR gate symbol as shown in Fig. 11.6 (*b*). Comparing the truth table of a NOR gate with the truth table of an OR gate it will be observed that for the same inputs, the output of NOR gate is the inverse of the output of OR gate. The equivalent relay circuit for NOR gate consists of two normally closed (NC) contacts of relay *A* and *B* connected in series as shown in Fig.11.6 (*d*). When both relays *A* and *B* are de-energised, there is an output at *Y*. If any or both the relays are energised, there is no output at *Y*. These conditions are analogous to the conditions shown in truth table. If an energised relay corresponds to a high input, a de-energised relay corresponds to a low input.



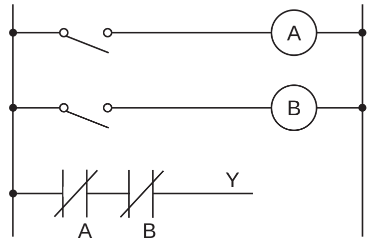
(a)



(b)

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

(c)

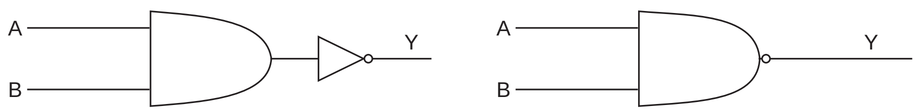


(d)

Fig. 11.6 (*a*) and (*b*) Symbols (*c*) Truth table (*d*) Equivalent relay circuit for NOR gate

11.4.5 NAND Gate

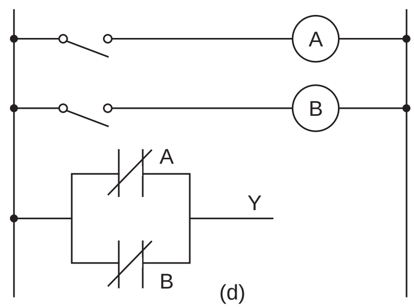
NAND gate is equivalent to an AND gate followed by a NOT gate. This is depicted in Fig. 11.7 (*a*). The symbol for NAND gate is obtained by connecting a bubble to the AND gate symbol as shown in Fig.11.7 (*b*). On comparing the truth table of NAND gate shown in Fig.11.7 (*c*) and the truth table of AND gate, it is found that for same input conditions the output for NAND gate is inverse of the output of AND gate. The equivalent relay circuit for NAND gate consists of two normally closed contacts (NC) of relays *A* and *B* connected in parallel as shown in Fig. 11.7 (*d*). When both relays *A* and *B* are de-energised or any one of them is de-energised there will be output at terminal *Y*. When both the relays are energised there will be no output at terminal *Y*. These conditions are analogous to the truth table conditions where an energised relay corresponds to high input and a de-energised relay corresponds to a low input.



(a) (b)

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

(c)

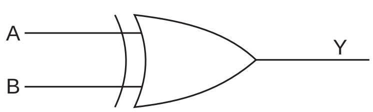


(d)

Fig. 11.7 (*a*) and (*b*) Symbols (*c*) Truth table (*d*) Equivalent relay circuit for NAND gate

11.4.6 Exclusive OR gate

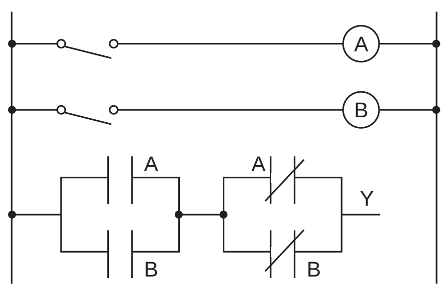
This gate gives an output only when either of its input is high (not when all the inputs are high). Symbol, truth table, and equivalent relay circuit for this gate are shown in Fig. 11.8.



(a)

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

(b)



(c)

Fig. 11.8 Symbol, truth table, and equivalent relay circuit for an Exclusive OR gate

On comparing truth table of an Exclusive OR gate with an OR gate it is found that first three conditions are same while the fourth is different. Equivalent relay circuit consists of two normally open (NC) contacts of relay *A* and *B* connected in parallel followed by normally closed (NC) contacts of same relays connected in parallel. On comparing the conditions of relay circuits with truth table of logic gate it is found that they are analogous.

11.5 SOLID STATE TIMER

Solid state timers are built using transistors and resistor-capacitor charging circuit. A standard solid state timer symbol shown in Fig. 11.9 (*a*) is analogous to an ON delay type timer with a normally open delayed contact. The standard timer can be modified as shown in Fig. 11.9 (*b*), (*c*) and (*d*) to give functions which are analogous to the function of ON and OFF delay timer relays. Input output waveforms, shown besides each timer, describe the operation of a timer. While comparing action of a solid state timer with an analogous relay contact it is to be kept in mind that a high output corresponds to closed condition of relay contact, while a low output corresponds to an open contact condition.

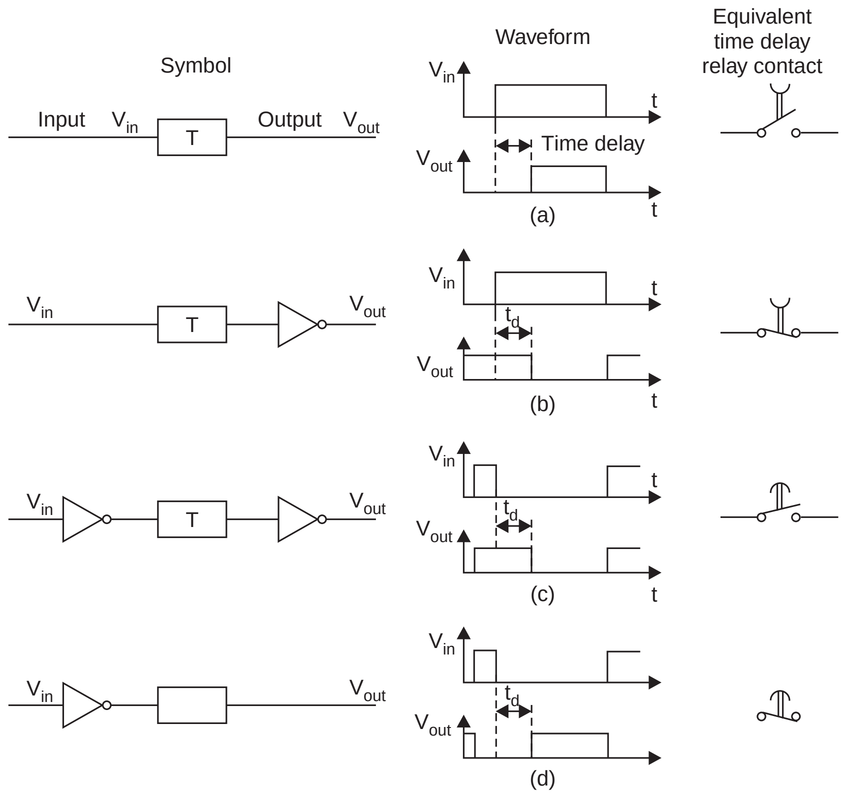


Fig.11.9 Solid state timer and their input-output waveforms along with analogous time delay relay contacts

In the waveform for the standard timer shown in Fig.11.9 (*a*) the output voltage V_{out} becomes high after a pre-set delay t_d from the instant the input voltage V_{in} becomes high. V_{out} becomes low immediately as V_{in} becomes low. Equivalent relay contact for this timer is the normally open (NO) delayed contact of ON delay type time delay relay. In Fig. 11.9 (*b*) timer duplicates the action of normally closed (NC) delayed contact of an ON delay type time delay relay. This is done by adding a NOT gate in the output of the standard timer circuit. The action of timer is also represented in the waveform. In Fig. 11.9 (*b*) when V_{in} is low, V_{out} is high because of NOT gate. When V_{in} becomes high, timer output will become high after a pre-set delay of time t_d , while V_{out} will become low. When V_{in} returns to low value, V_{out} will return to high value. This action of timer is analogous to normally closed (NC) delayed contact of ON-delay type time delay relay.

Modified timer shown in Fig. 11.9 (*c*) is analogous to a normally open (NO) delayed contact of an OFF-delay type time delay relay. Recollect that in off-delay timer when timer coil is initially energised, its normally open contact closes immediately. The contact opens after a pre-set delay from the instant when timer coil is de-energised. It is to be observed that the waveform depicting the action of solid state timer in Fig. 11.9 (*c*) is analogous to the above mentioned action of normally open contact of an OFF-delay timer. When V_{in} is high, timer input is low, therefore timer output is also low thus giving a high V_{out}. When V_{in} goes low due to input NOT gate, the timer input goes high. V_{out} remains high as timer output is still low. After a pre-set delay of time t_d, when timer output goes high the V_{out} goes low due to the NOT gate. This is analogous to the action of normally open contact of an OFF delay timer. Similarly, the modified timer circuit and its associated waveforms can be shown analogous to normally closed (NC) delayed of an OFF-delay time relay.

11.6 MEMORY ELEMENTS (OFF-RETURN TYPE)

The well known flip-flop circuits can be used as memory elements in the control circuits. Flip flop memory is an off-return memory *i.e.* memory is washed away when control supply fails. Its equivalent relay circuit is the widely used holding circuit or sealing three wire control circuit. The simplest off-return memory element used is the *RS* flip flop.

Circuit for an *RS* flip is shown in Fig.11.10. In this circuit when control input *S* is made high, transistor T_1 is saturated, while T_2 is cut off. Thus output at terminal *Q* is high while at $\overline{Q}$ is low.

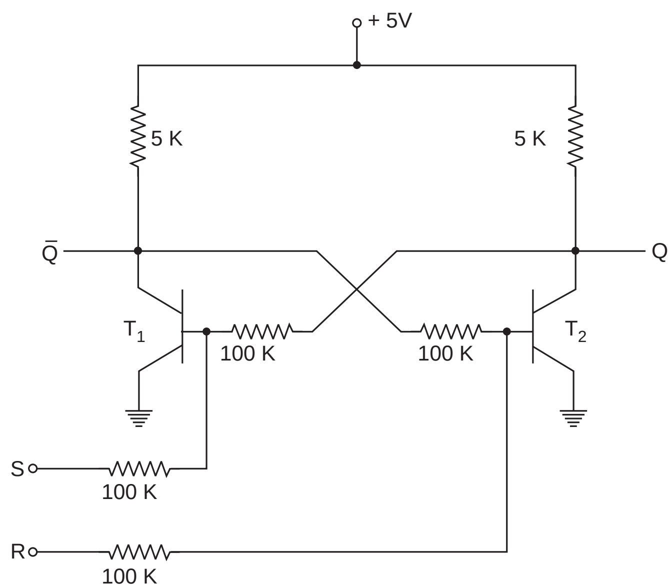
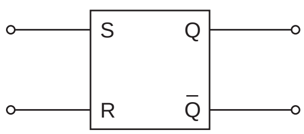


Fig. 11.10 Circuit for *RS* Flip-flop using discrete components

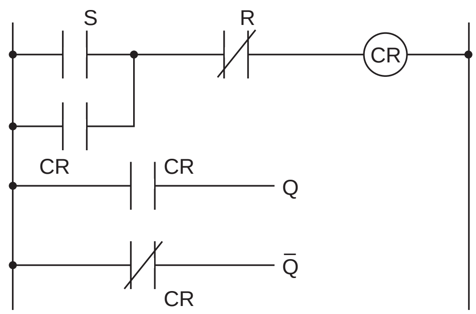
Output at *Q* and $\overline{Q}$ remains the same even when *S* goes low. When control input *R* is made high, it will saturate transistor T_2 while T_1 will be cut off. The output will thus change states. The output becomes low at *Q* and high at $\overline{Q}$. This output condition is retained even when *R* goes to low. Applying a high input to *S* is called the setting mode, and applying a high input to *R* is called the *resetting mode*. When both *S* and *R* are low, there is no change in the output, as transistors remain in their previous states. This condition is called inactive mode because there is no change. when both S and R are high, the output is unpredictable and this condition is called a *race condition*. This input condition is forbidden. The general symbol, truth table and equivalent relay circuit for an RS flip-flop are shown in Fig. 11.11. The asterisk mark in the truth table denotes the race condition or forbidden input.



(a)

R	S	Q	Comments
0	0	NC	No change
0	1	1	Set
1	0	0	Reset
1	1	*	Race (Forbidden)

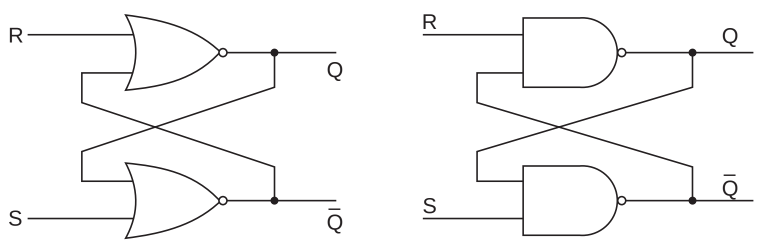
(b)



(c)

Fig. 11.11 (*a*) Symbol (*b*) Truth table (*c*) Equivalent relay circuit for a *RS* flip flop

RS flips are no longer manufactured using discrete components as shown in Fig. 11.10. Instead, they are manufactured using NOR or NAND gates as shown in Fig. 11.12.



R	S	Q	Comment
0	0	NC	No change
0	1	1	Set
1	0	0	Reset
1	1	*	Race (Forbidden)

R	S	Q	Comments
0	0	*	Race (Forbidden)
0	1	1	Set
1	0	0	Reset
1	1	NC	No change

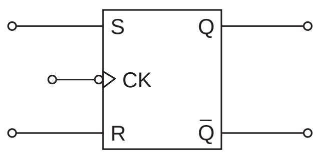
Fig. 11.12 *RS* flip-flops using NOR gates and NAND gates

On comparing the truth tables of both types of flip flops it is found that inactive and race conditions for the two types are exactly opposite. Therefore to avoid using the forbidden inputs, it is essential to know the type of flip flop being used.

11.6.1 Clocked RS Flip Flop

Clocked *RS* flip flop has an extra terminal called clock terminal. This provision helps to pervent the flip flop from changing state until the right time is determined by the clock pulse. Whenever it is required to change the state of flip flop according to the state of inputs (*S, R*) a square wave is sent to the clock terminal. Flip flop responds to its *S* and *R* inputs only when clock pulse switches a transition from high to low or vice-versa.

A positive edge triggered flip flop responds to its static inputs (*S, R*) when the clock line makes a transition from low to high *i.e.*, during the rising edge of a square pulse. A negative edge triggered flop flop responds to its static inputs *S* and *R* when its clock line makes a transition from high to low *i.e.*, during the falling edge of a square wave. Edge triggering is used to prevent oscillations in the flip flop. In this chapter all flip flops are assumend to be negative edge triggered. The symbol and truth table for this flip flop is shown in Fig. 11.13.



(a)

CK	S	R	Q	Comment
0	×	×	Last state	No change
1	×	×	Last state	No change
↓	1	0	1	Set
↓	0	1	0	Reset
↓	1	1	* Race	Forbidden

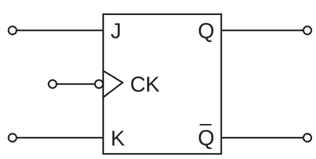
(b)

Fig. 11.13 Schematic symbol for a negative edge triggered clocked *RS* Flip flop

The small circle outside the box in front of clock terminal *CK* is the general digital symbol used for distinguishing a negative edge triggered clocked device from a positive edge triggered clocked device. In the truth table, a downward pointing arrow ↓ denotes a negative going transition from high to low, (×) denotes any state, high or low.

11.6.2 JK Flip Flop

The most widely used flip flop is the *JK* flip flop. It has two inputs just like the *RS* flip flop, but the inputs are referred to as *J* and *K*. The action of *JK* flip flop is quite similar to *RS* flip flop, the only difference being that *JK* flip flop has what is called a toggling mode.



(a)

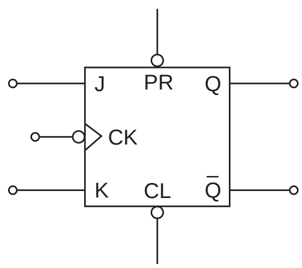
CK	J	K	Q	Comment
0	×	×	Last state	No change
1	×	×	Last state	No change
↓	1	0	1	Set
↓	0	1	0	Reset
↓	1	1	Changed states	Toggle

(b)

Fig. 11.14 Schematic symbol and truth table for a negative edge triggered JK flip flop

Toggles means switching opposite state. The schematic symbol and truth table for a negative edge triggered *JK* flip flop is shown in Fig. 11.14.

The inactive, set mode and reset mode are similar to *RS* flip flop except that input terminals are designated as *J* and *K*. Flip flop is in toggling mode when *J* and *K* are both high and it is possible to set or reset the flip flop depending on the current state of the output. If *Q* is high, the lower gate passes a reset trigger on the next negative clock edge. On the other hand when *Q* is low, the upper gate passes a set trigger on the next negative clock edge. Either way, *Q* changes to the compliment of the last state. Therefore, $J = 1$ and $K = 1$ means that flip flop will toggle on the next clock edge. Many *JK* flip flops have *preset* (*PR*) and *clear* (*CL*) static inputs which override the clocked inputs *J* and *K i.e.*, they have the first priority. Preset and clear have active low states. This means that the signal at preset and clear terminals are normally high, and taken low temporarily to preset or clear the circuit. When preset goes low the *Q* output goes high and stays there, no matter what the *J* and *K* and clock (*CLK*) inputs are doing. The output will remain high as long as preset is low. Therefore, the normal procedure in presetting is to take the preset low temporarily, then return it to high. Similarly for clear function, clear signal is made low to reset the flip flop, then taken back to high to allow the circuit to operate. The schematic symbol and truth table for *JK* flip flop with preset and clear function are shown in Fig. 11.15.



(a)

Preset	Clear	CK	J	K	Q	Comment
0	0	×	×	×	* Race	Forbidden
0	1	×	×	×	1	Set
1	0	×	×	×	0	Reset
1	1	0	×	×	Last state	No change
1	1	1	×	×	Last state	No change
1	1	↓	1	0	1	Set
1	1	↓	0	1	0	Reset

(b)

Fig. 11.15 Schematic symbol and truth table for a *JK* flip flop with preset and clear function

There are other types of flip flops also, like *D* flip flop, *T* flip flop, etc. In this chapter only the *RS* and *JK* flip flops have been used for developing the control circuit.

11.7 RETENTIVE MEMORY ELEMENT

Retentive memory element retains the conditions of output corresponding to the input last provided, irrespective of whether control power is maintained or not. These memory elements are built using tiny toroidal magnetic core.

Nowadays, Charge Coupled Devices (CCD) and Magentic Bubble Memory (MBM) techniques are also used for building retentive memory elements. Retentive memory is also known as non-volatile memory. The schematic symbol and equivalent relay circuit for retentive memory element is shown in Fig. 11.16.

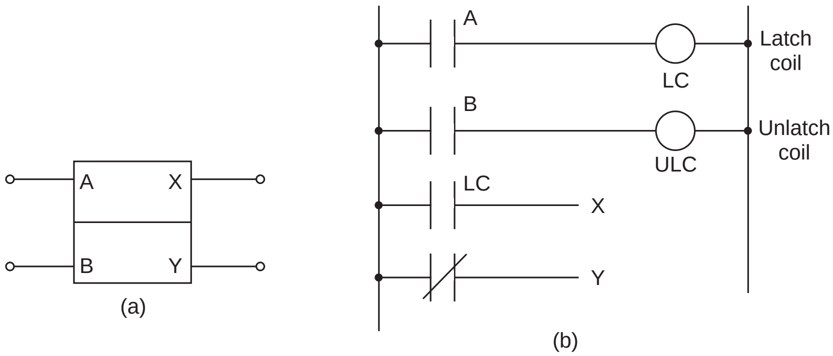


Fig. 11.16 Symbol and Equivalent relay circuit for a retentive memory element

Relay equivalent for retentive memory is the mechanically held or permanent magnet latch type relay. In the memory element when input $A = 1$ (high) and $B = 0$ (Low), the output X is high (1) and Y is low (0). This output state is maintained even when control supply is restored after a failure. When input states change *i.e.*, $A = 0$ and $B = 1$, then output X becomes low (0) and Y becomes high (1). Considering the relay circuit for analogous operation it is observed that closing of contact A (equivalent to $A = 1$) will energise latch coil (*LC*), giving output at X through closing of its normally open (*NO*) contact. Once the latch coil is energised, it remains latched even when control supply fails. Supply at X can be cut off by dropping the relay. Relay drops when its mechanical latch is disengaged or the core is demagnetised by energising another coil *i.e.*, *ULC*. It is clear from Fig. 11.16 that coil *ULC* is energised when contact B closes.

This is equivalent to $A = 0$ and $B = 1$ for the static element. Both A and B cannot be high as it is the forbidden input and leads to unpredictable output (Race condition).

11.8 DEVELOPMENT OF LOGIC CIRCUITS

Digital logic elements and their circuitry can be understood better by comparing them with their equivalent relay circuits. However, once the fundamentals of logic design are understood, one should try to design the circuit directly using digital elements, instead of first developing the circuit with relays and then converting it into digital circuitry. Developing circuit directly in digital logic will avoid wastage of time and labour. No universal theory can be given on how to approach the circuit design as circuit details vary considerably from job to job. Inspection and common sense are the most important tools for designing the control circuits. However, a few suggestions are given here on how to approach the design of logic circuit for a specific application. Design work is greatly simplified if the following steps are followed:

(1) Study the various machine operations and write them in their proper sequence.

(2) Identify the control devices used for controling each operation. Write down the relation between control devices and resulting operation in simple English logic statements.

(3) Draw logic diagram of each statement by translating the word picture of statement into logic element block diagram.

(4) Combine the individual logic sequence to form a complete control circuit.

(5) Inspect the diagram, minimise circuits and save devices by simplifying circuits.

To start with the three wire holding sealing control circuit which has so frequently been used in the study of magnetic controls is taken. This circuit is shown in Fig. 11.17 (*a*). Equivalent digital logic circuit for holding/sealing function are shown in Figs. 11.17 (*b*), (*c*) and (*d*). The same function is designed in three different ways by using different logic elements like OR gate, AND gate, and MEMORY element. At this stage there is no need of explaining the first circuit as the reader is already familiar with relay circuits.

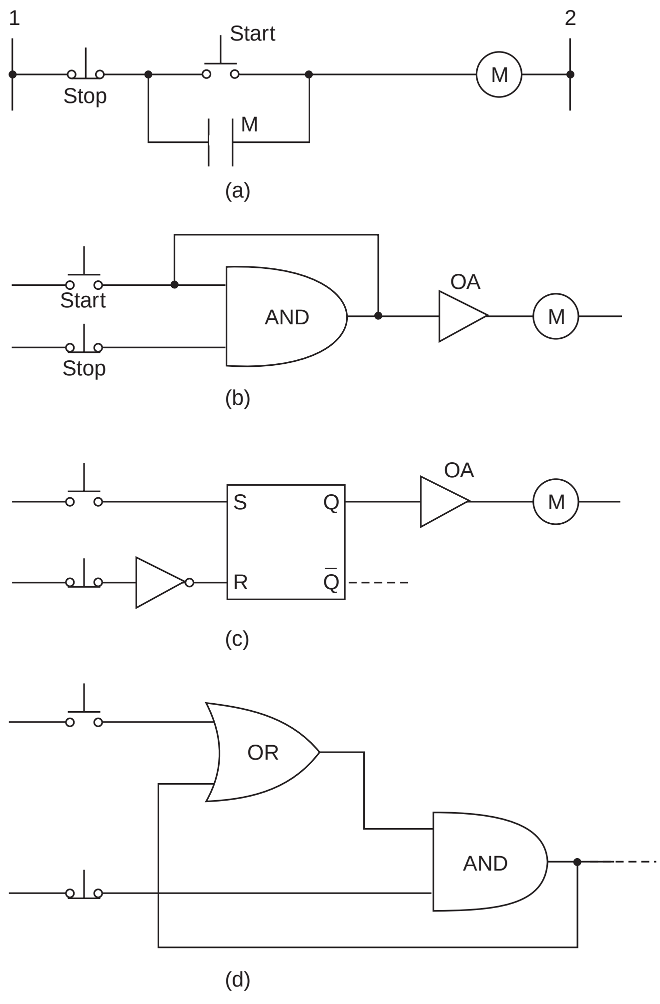


Fig. 11.17 Development of a simple logic circuit for holding funtion

Now refer to the logic diagram in Fig.11.17 (*b*), one input is always provided to the AND gate through STOP-button. When START-button is pressed, the second and final input to AND element is provided and output is obtained. Once an output is obtained, the internal feed back loop maintains the input even though the START-button is released. This is equivalent to holding or sealing function of Fig.11.17 (*a*). When the STOP-button is pressed, AND gate loses one input and so, the output goes to the low (O) value and the contactor *M* is de-energised. Observe that an amplifier (*OA*) is used in between output of the AND gate and contactor *M*.

This amplifier has been used because output of AND gate is a low voltage dc and can not directly energise the output devices like contactor, solenoid, etc.

In Fig. 11.17 (*c*) an *RS* flip flop has been used for obtaining a holding circuit. As STOP-button is always closed, there is always a low input at terminal *R* of flip flop due to a NOT gate in series with the STOP-button. When START-button is pressed, input at terminal *S* becomes high and flip flop is set. A high output appears at terminal *Q* which energises contactor *M*. Output *Q* remains high even when input *S* goes to low value due to release of START-button. When contactor *M* is to be de-energised or sealing of the circuit is to be broken, the STOP-button is pressed. This applies a high input at terminal *R* of the flip flop and it gets reset. Output *Q* becomes low and contact *M* gets de-energised. Another holding circuit can be built using *OR* gate and AND gate as shown in Fig. 11.7 (*d*).

An important difference between a relay circuit shown in Fig.11.17 (*a*) and a digital logic circuit shown in Figs. 11.17 (*b*), (*c*) and (*d*) is that in a relay circuit, current flow can be traced from line 1, through the control devices, contactor coil and back to line 2 and is easy to understand. On the other hand, a digital logic circuit is only a block diagram of the control functions of the circuit. In the logic circuit actual wiring is omitted and only symbolic representation is done. The logic diagram, therefore, does not represent the actual circuit. The common bus to which all input and output voltages are referred to is also omitted so as to avoid unnecessary cluttering of circuit. Also, it adds nothing to the information given by the logic diagram.

In the above discussed circuits, pilot devices like push buttons have been shown connected directly to the logic elements. However, in practice they are connected to the digital elements through signal converters as shown in Fig. 11.18.

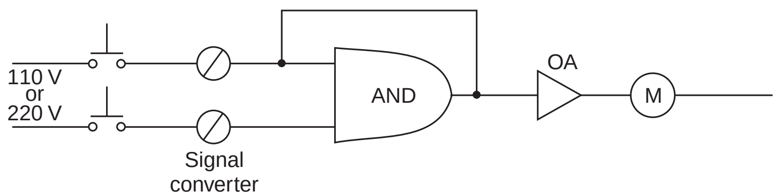


Fig.11.18 Logic circuit with signal converters

Logic elements are low voltage low power devices. They operate at say + 5 V dc (*TTL*). The control components may be even 500 metres away from the circuit. If the push buttons or limit switches in control ciruits are directly connected through logic elements, there will be appreciable voltage loss. Therefore, the practice is to feed high voltage *i.e.*, 110 V and 220 V ac to the sensing device and then convert back to low dc voltage by signal converters for feeding to digital logic elements. On the output side, output devices also work on high voltage. Therefore, the output from logic elements is amplified and then fed to these devices.

Before control circuits are discussed, it will be worthwhile to stydy an example on how the specifications for a control operation are first written in logic statments in English, and then converted into graphical logic diagrams.

The specifications for a control circuit are as follows:

A contactor coil *M* is to be energised whenever a normally open push button PB_1 is pressed or whenever both limit switch LS_1 and temperature switch T_1 are closed and extreme limit switch LS_2 and extreme temeperature switch T_2 are open.

The first step in developing a logic circuit is to convert the above specifications into logic statements. The first statement is:

Contactor M will be energised when PB_1 or LS_1 and T_1 are closed. The above statement is translated into graphical picture as shown in Fig. 11.19 (*a*). The inputs from LS_1 and T_1 are ANDed and then ORed with inputs from PB_1 in the diagram.

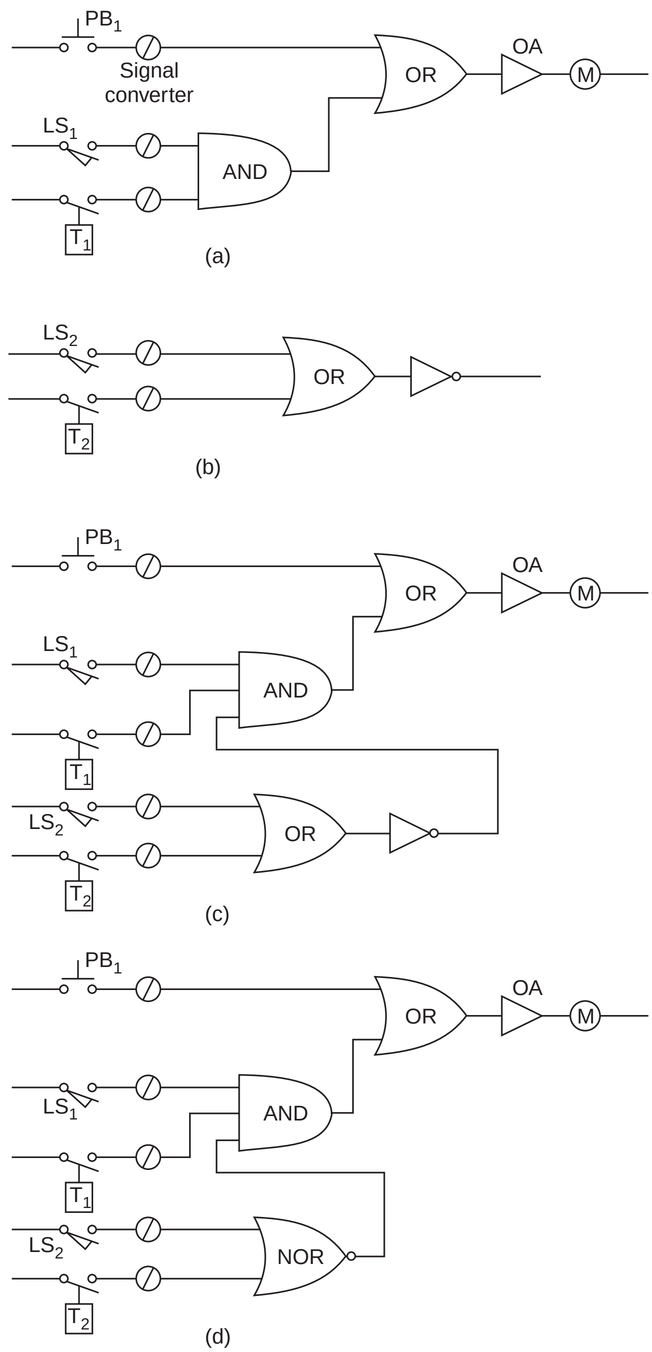


Fig. 11.19 Development of logic circuit

The second statement is: Statement 1 will be true only if LS_2 and T_2 are open. The graphical picture for second statement is obtained by ORing inputs from LS_2 and T_2 followed by a NOT element as shown in Fig. 11.19 (*b*).

The next step is to combine the circuits for the above two statements. This is done as shown in Fig. 11.19 (*c*). Further, next step is to simplify the circuit, if possible. In this case it is done by using a NOR gate instead of an OR gate followed by a NOT gate. The last step is to analyse the circuit whether it works according to the specifications. According to Fig.11.19 (*d*), when PB_1 is pressed, it sends a signal to OR gate through its signal converter. There is an output from OR gate, which is fed through an amplifier for energisation of contactor *M*.

If LS_1 and T_1 are both closed, there are two inputs at the AND gate. The third input is provided by the inputs from LS_2 and T_2. If these two are open, there is no input to the NOR element, and therefore it will have an output which is the third input to the AND gate. When all the three inputs are present at the AND element it will have an output. The output of AND gate provides an input to the OR element and thus there is an output for energising contactor *M*.

11.9 INPUT DEVICES FOR SOLID STATE LOGIC

In addition to signal converters mentioned in last section, another input device used in series with pilot and sensing device is the bounceless switch. It is necessary to use this because mechanical switches never make a clean contact closing in a single action. Most of the contacts of pilot and sensing devices are snap action type *i.e.*, they are spring loaded. When the movable contacts meet the stationary contact, there is often a fast bouncing action. This means, the movable contact may make and break the contact three or four times in succession before the switch finally closes. The action of contact bounce is shown in Fig. 11.20.

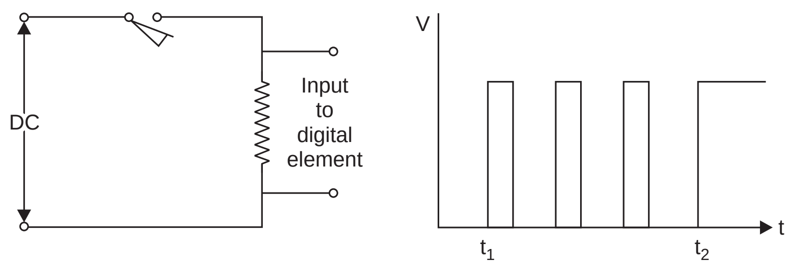


Fig. 11.20 Illustrates the contact bounce problem

As a result a series of pulses are generated till the final closure of contact takes place. Each of the pulse generated due to bounce can act as a command. As the digital elements are very fast acting, they will respond to these commands and control circuit will malfunction. An intermediate circuit is thus required which should not allow the bouncing action to affect the control circuit. Bouncing of contacts, however, does not pose any problem in relay circuits as relays are relatively slow acting devices as compared to digital logic elements. In digital circuits the bouncing action of contacts can be prevented from effecting the control circuit by using capacitive switch filters or Bounce eliminators.

11.9.1 Capacitive Switch Filters

A capacitive switch filter is shown connected in between a limit switch contact and a logic gate in Fig. 11.21.

When the limit switch first closes, capacitor C starts getting charged through the venin resistance of R_1 and R_2. As the limit switch contact stays closed only for a very short time during the bouncing action, the capacitor does not get charged to such an appreciable value as to trigger the logic gates. When permanent closure occurs the capacitor will get charged to the full voltage required to turn on the digital element. This filter circuit also helps in arresting high speed noise pulses on the load coming from the switch. The final value of voltage appearing across the capacitor is less than the supply voltage due to the divider action of resistance R_1 and R_2. This, however, does not cause any problem, as digital elements can operate reliably with an input voltage less than the full supply voltage. For example, for a TTL gate although the high voltage signal is 5 V, it can operate with as low a voltage as 2.4 V.

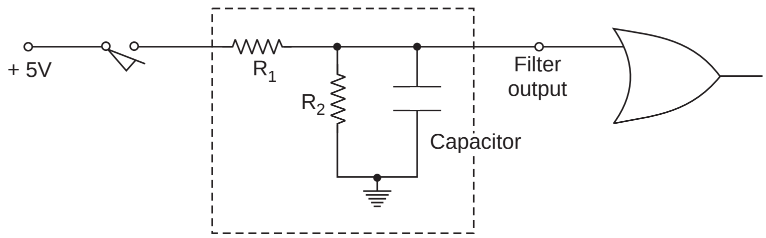


Fig. 11.21 Capacitive switch filter to eliminate effects of contact bounce

11.9.2 BOUNCE ELIMINATORS

Bounce eliminators are manufactured using gates as shown in Fig. 11.22. In bounce eliminators, the output appears at its terminal on the first contact bounce, instead of waiting for the final closure of limit switch contact as in capacitive filter circuits. The disadvantages of this circuit is that it requires a double throw switch instead of a single NO contact.

When the limit switch contact is open as shown in Fig.11.22 (*a*), high input is applied to R_2 and also to input 2 of NOR_2. The output of NOR_2 is thus low causing input 2 of NOR_1 to be low. Input 1 of NOR_1 is also low because contact of the limit switch is open. Output of NOR_1 is thus high, as both its inputs are low. The output of NOR_1 is then inverted to make the final output low.

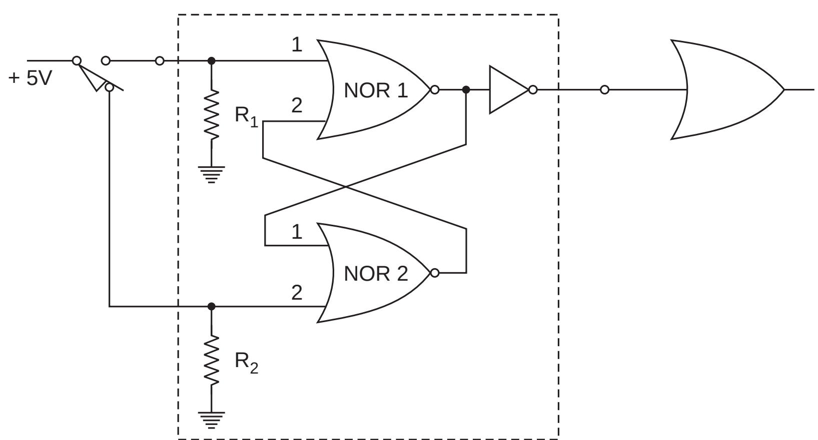


Fig. 11.22 Bounce eliminator built with digital logic gates

When the limit switch contact closes the following action takes place in the bounce eliminator switch:

(*i*) The NC contact of limit switch opens first, causing the number 2 input of NOR_2 to be low. NOR_2 does not change state as its output 1 is still high.

(*ii*) The NO contact of limit switch closes momentarily on the first closure. This puts a momentary high pulse on input 1 of NOR_1 causing its output to go low. The inverter drives the final output high. The NOR_1 output feeds input 1 of NOR_2 and, therefore, NOR_2 now has two inputs. Its output therefore goes high which is applied to input 2 NOR_1. NOR_1 now has two high inputs.

(*iii*) When the NO contact of limit switch opens on first rebound, a low voltage appears at input 1 of NOR_1, but its input 2 maintains its high voltage. Therefore NOR_1 does not change states and the final output remains high.

(*iv*) Several more bounces of limit switch contact takes place, which changes the voltage level of input of NOR_1. However, NC contact of the limit switch does not close during bounces and a high input is maintained on input 2 of NOR_1 from the output of NOR_2. Thus the output of NOR_1 remains steady at high value.

(*v*) When the limit switch is released, the bounce eliminator reverses the above action resulting in one time transition of low level at the final output of the bounce eliminator switch.

11.9.3 Signal Converters

The function of a signal converter, as described earlier, is to step down a high (110 or 220 V) ac or dc voltage fed to information gathering devices to a suitable low dc voltage for feeding to logic elements. Brief description of different types of signal converters is given below:

In a dc to dc signal converter, high dc voltage (110 V) from the information gathering devices is given to a potential divider circuit. Low voltage (+ 5 or + 15 volts) is taken from the potential divider as shown in Fig. 11.23 (*a*). This simple circuit can be improved by adding a transistor circuit to the voltage divider network to make the output insensitive to electric noise and line disturbance.

A simple ac signal converter is shown in Fig. 11.23 (*b*). In this signal converter, electric isolation is provided between high voltage input circuit and low voltage logic circuit due to magnetic coupling provided by transformer windings. A center tapped transformer is used to step down ac voltage from the sensing switch, a limit switch in this case. Step down voltage is rectified and applied to a potenitial divider. The output voltage from the potentiometer is fed to a logic element. Transistor circuit can be used so that the output is not affected due to noise and line disturbance. The signal converter shown in Fig. 11.23 (*c*) uses a reed relay, to switch on and off the output logic supply to the signal converter output line. When limit switch *LS* closes, rectified dc voltage will energise realy *RR*. Its contact will close and switch + 5 V to the logic gate. The reed relay, in this case can provide electric isolation between high voltage and low dc logic circuit supply.

As the above two types of signal converters use a capacitor to smoothen the dc voltage from rectifier, no separate bounce eliminator is needed. The capacitor in the signal converter takes care of the bouncing of switches and line disturbance.

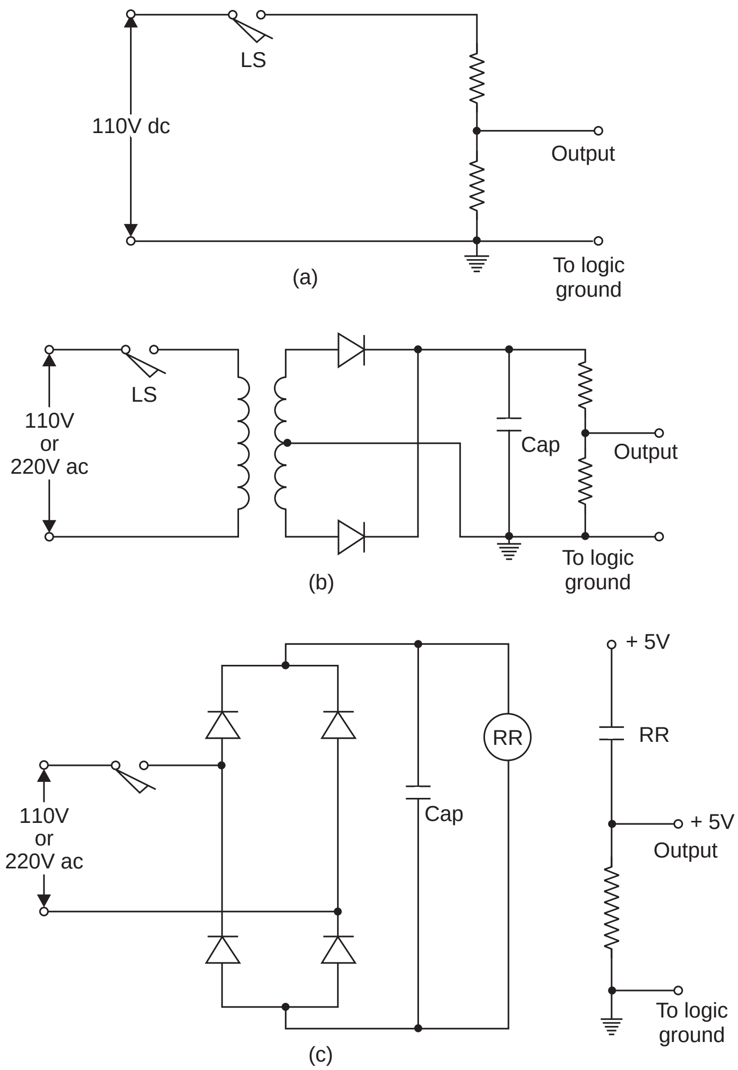


Fig. 11.23 Different types of signal converters (*a*) dc to dc converter (*b*) ac signal converter (*c*) ac converter using reed relay

In recent years, optically coupled signal converters have become very popular due to their light weight, low cost and more reliablility. The optically coupled signal converters work equally well on either ac or dc high voltage signals. They are therefore also referred to as the universal signal converters. In these converters no transformer or relay is required. One type of opto coupled signal converters, which is built using a light emitting diode and photo transistor, is shown in Fig. 11.24.

When limit switch *LS* is open, *LED* does not conduct. Photo transistor is cut off, while transistor T_1 is conducting as its base to emitter is forward biased due to voltage appearing across the photo transistor. As transistor T_1 is conducting, a low voltage appears at terminal V_{out}. When limit switch closes, *LED* will conduct and emit light which would fall on the base of photo transistor and it would start conducting. Due to the conduction of photo transitor, the base to emitter bias for transistor T_1 falls and it goes to cut off state. When T_1 is cut off, a high voltage *i.e.*, (+ 5 V) will appear at the output terminal V_{out}.

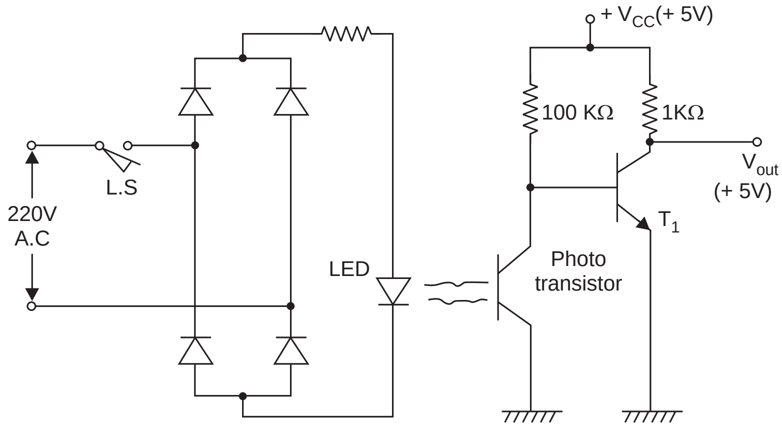


Fig.11.24 Opto coupled signal converter

11.10 OUTPUT DEVICES FOR SOLID STATE LOGIC

The actuating devices like solenoids, motor starter coils etc. can not be energised directly from gates as they are low voltage, low power devices. Thus, an output amplifier is required between the logic gate output and the actuating devices. The purpose of the output amplifier is to increase the low-voltage low current logic power to high voltage high current output power.

Most of the output amplifiers are designed to drive 110 V or 220 V ac load, since most industrial solenoid valves and starter coils are designed for this voltage. An output amplifier using a reed relay is shown in Fig. 11.25. In this circuit, when the output from the logic circuit is high, transistor T_1 will conduct and thus relay R will operate. Its contact R will close and energise the solenoid coil. This type of arragement provides electrical isolation between the logic circuit and the output circuit.

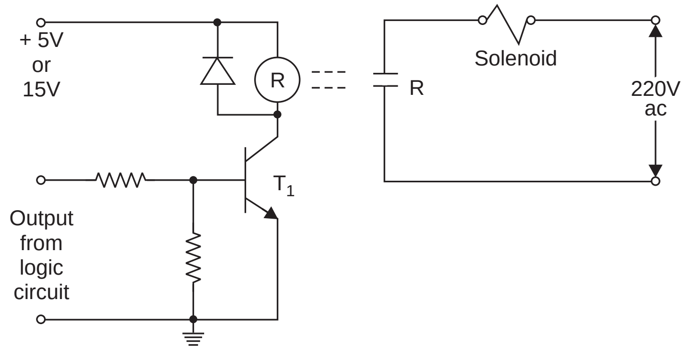


Fig. 11.25 Output amplifier using a relay contact to control current through output device

Modern output amplifiers are built using an SCR, triggered by a UJT. A typical design of such output amplifier is shown in Fig. 11.26. Due to the closing of limit switch, when a high input appears at *RC* potential divider, a capacitor starts charging. At a particular value of capacitor voltage the UJT is turned on and capacitor gets discharged through it. A pulse thus gets applied to the primary of a pulse transformer connected to the base of UJT. This pulse is transferred to the secondary side of the transformer and gets applied between gate and cathode of SCR. The SCR will trigger on and will start conducting if its anode is positive with respect to cathode. To achieve current flow through load on both half cycles of ac voltage, a bridge rectifier is used to provide a continuous dc supply to the SCR.

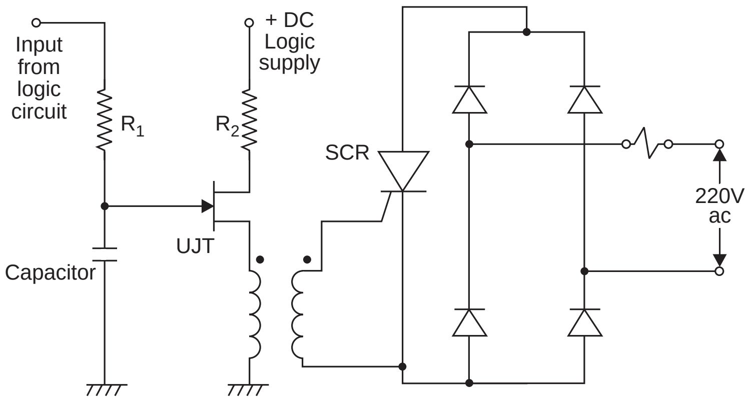


Fig. 11.26 Logic output amplifier using a UJT and an SCR

11.11 SOLENOID VALVE OPERATED CYLINDER PISTON ASSEMBLY

A cylinder piston assembly is used to get to and fro motion of a machine part. It is a very fundamental operation in any industry. Thus, before more complicated machine circuits are discussed, it will be worthwhile to study the control circuit for solenoid valve operated cylinder piston assembly, shown in Fig. 11.27.

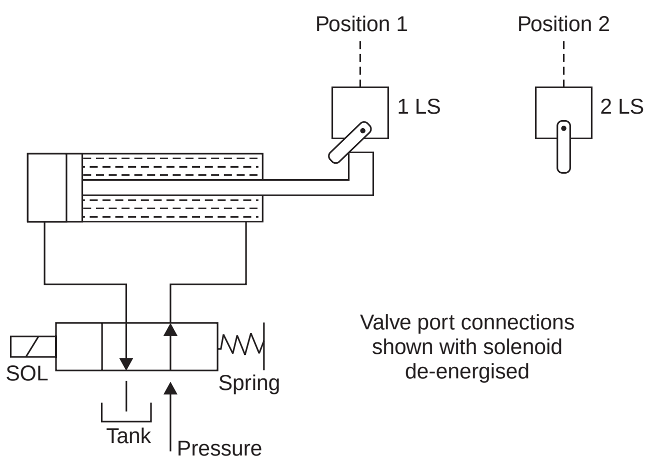


Fig. 11.27 Cylinder piston assembly operated by a solenoid valve

A single solenoid spring return valve is used to supply fluid power to this cylinder. Various control requirements for this cylinder piston assembly are as follows:

Piston has to move between two extreme positions 1 and 2 determined by the locations of limit switches 1 *LS* and 2 *LS*. The initial or starting position of piston is position 1 in which limit switch 1 *LS* is actuated as shown in Fig. 11.27. On giving the starting command, the piston should move to the right until it actuates the limit switch 2*LS*. Thus, at position 2, on actuation of 2*LS* the piston should immediately move backward to position 1. There should also be provision to return the piston back from any point in its forward travel (from left to right). Control circuit shown in Fig. 11.28 fulfills all the control requirements listed above.

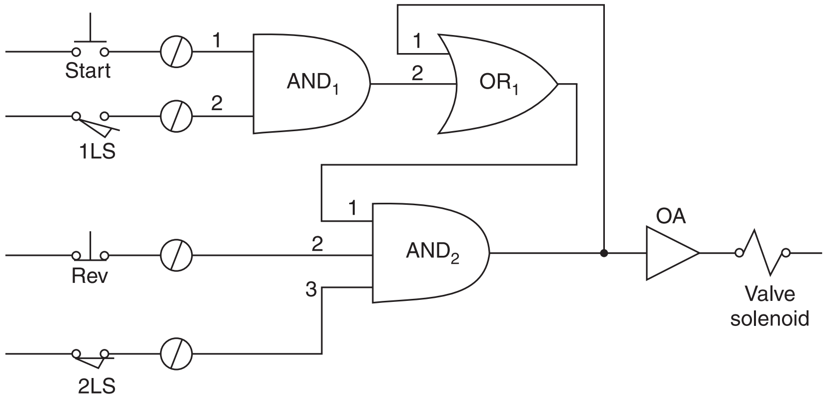


Fig. 11.28 Logic circuit for piston movement

In this control circuit normally open (*NO*) contact of limit switch 1*LS* and normally closed (*NC*) contact of limit switch 2 *LS* have been used. A Reverse push button is used to bring back the piston to position 1 from any point in its forward travel. Working of the control circuit is as follows:

When piston is in position 1, limit switch 1*LS* is actuated, its normally open (NO) contact is closed, thus providing a high signal to input terminal 2 of AND_1. On pressing the START-push button a high signal appears at terminal 1 of AND_1. Its output therefore goes high which appears at input terminal 2 of OR_1. Thus, output of OR_1 goes high which is fed back to the terminal 1 of AND_2. Terminals 2 and 3 of AND_2 already have high signals as Reverse push button and contact of 2*LS* are closed. Thus when START-push button is pressed, all three inputs to AND_2 become high and it gives a high output. This output is amplified and applied to the solenoid valve coil. Valve shifts its spool and piston starts moving in forward direction from left to right towards position 2. Signal from output of AND_2 is fed back to terminal 1 of OR_1 for sealing, as the input at terminal 2 of OR_1 will disappear as soon as START-push button is released. Contact of limit switch 1*LS* will also open as soon as piston leaves the position 1. The output of AND_2 is maintained till limit switch 2 *LS* operates and cuts off the input at its terminal 3. Loss of one input to AND_2 brings its output low which leads to de-energisation of the solenoid. As the solenoid valve is spring controlled the spool will come back to its original position and the piston will move back to position 1.

The piston can also be made to reverse at any point from its forward movement by pressing the Reverse-push button. When the Reverse-push button is pressed the high signal at terminal 2 of AND_2 goes low which causes output of AND_2 also to go low. As output of AND_2 goes low, the solenoid valve is de-energised and sealing/holding of circuit is also broken. The piston thus moves back to position 1.

11.12 CONTROL OF THREE STAGE AIR CONDITIONING SYSTEM

A simple air conditioner system consists of a single compressor motor which gets switched off when temerature of the space being controlled falls below the setting on the thermostat. Thermostats are provided with differential setting to avoid frequent switching ON and OFF of the compressor motor.

A three stage air conditioning system is used for conservation of electrical energy and optimum utilisation of the installed capacity of the compressor. There are two compressor motors in this system. One motor is of smaller horsepower, and the second one is of higher horsepower rating. These motors are designated a comp. 1 and comp. 2 in this case. The system is installed in a cinema hall for maintaining the hall temperature between 20-24° C. Depending upon the number of viewers in the hall and the ambient atmospheric conditions, comp. 1 and comp. 2 motors can be run in three different combinations. The three combinations described below are also the control requirements of the air conditioning system.

(1) Compressor 1 and compressor 2 should run when the temperature in the hall is above 28°C.

(2) Only compressor 2 should run if temperature in the hall rises above 24°C but is below 28°C.

(3) Only compressor 1 should run if temperature in the hall is above 20°C but below 24°C.

A pre-condition for running any compressor is that chilling water flow switch FS_1 should be closed. Chilling water flow is necessary to take away heat from the compressed cooling gas.

Three thermostats with different settings are used for the control of compressor motors running in three different stages described above. The three thermostats T_1, T_2, T_3 are set at 20°C, 24°C and 28°C respectively.

The control of three stages with three thermostats and flow switch (FS_1) of air conditioning system can be understood from the control circuit shown in Fig. 11.29. The START-push button, STOP-push button, and over load contacts for compressor motors have not been shown in the circuit for sake of simplicity.

Working of the control circuit is as follows:

(1) When chilled water flow is maintained, flow switch FS_1 will actuate and close its contacts. Closing of contact FS_1 causes application of a high logic signal to terminal 2 of all AND gates.

(2) When temperature in the cinema hall is above 28°C, contacts of all the three thermostats T_1, T_2, T_3 close. Closed contacts of T_1 will give a high input to terminal 1 of AND_1 but closed contact of T_2 will give low logic signal to terminal 3 of AND_1 as there is a NOT gate in series. The output of AND_1, therefore, becomes low.

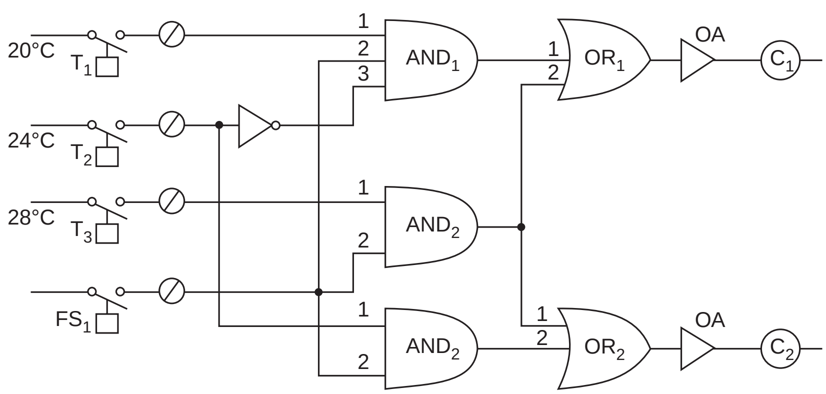


Fig. 11.29 Control circuit for three stage air conditioning system

(3) Closed contact of thermostat T_3 will give a high signal to terminal 1 of AND_2 while its other terminal 2 is already high due to closure of FS_1. AND_2 thus gives a high output which is applied to both OR_1 and OR_2. As one terminal each of OR_1 and OR_2 is now high, their outputs are also high. Output from OR_1 leads to energisation of contactor C_1 and output from OR_2 leads to energisation of contactor C_2 through their repsective amplifiers. Thus, compressors 1 and 2 will run when temperature in the hall is above 28°C.

(4) When the hall temperature is below 28°C but more than 24°C, contact of thermostat T_3 will be open while contacts of T_1 and T_2 are closed. Due to open contact of T_3 there is low signal at terminal 1 of AND_2 and therfore its output is low. Output of AND_1 is also low as closed contact of T_2 gives a low signal at terminal 3 due to a NOT gate in series. In this case AND_3 will have high output as its input terminal 1 has high signal from the closed contact of thermostat T_2. It is to be noted that supply to terminal 1 of AND_3 is taken prior to the NOT gate. High output from AND_3 goes to terminal 2 of OR_2 which then gives a high output. This output energises contactor C_2 through the amplifier. Thus compressor 2 will run only when the temperature is above 24°C but below 28°C.

(5) When temperature falls below 24°C contact of thermostat T_2 opens and output of AND_3 will then go low due to a low signal at its input terminal. The open contact of T_2 will however give a high signal to terminal 3 of AND_1 (due to the NOT gate in series). It will get switched ON as its terminal 1 and 2 are already high. The high output from AND_1 then goes to terminal 1 of OR_1 which then gives a high output to energise contactor C_1. Thus, one compressor will run when temperature is below 24°C but above 20°C. When temperature falls below 20° C, contact of thermostat T_1 also opens and terminal 1 of AND_1 goes low and it is switched off. Thus compressor 1 also stops when temperature falls below 20°C.

Compressor 1 continues to run if temperature in the hall remains between 20-24°C. If due to more viewers in the hall, compressor 1 is unable to maintain temperature below 24°C, compressor 2 will be switched ON while compressor 1 will be switched off. If the load is still more and compressor 2 alone can not cope up and temperature goes above 28°C then compressor 1 will also start to bring down the temperature.

11.13 SPEED CONTROL OF WOUND ROTOR INDUCTION MOTOR

Let us consider a wound rotor induction motor which is to run on three different speeds. Separate push buttons are used to select the speed of operation. The motor accelerates automatically to the selected speed. For example, if the second speed is selected, the motor first starts running on low speed and then accelerates to the second higher speed. If the third speed is selected, the motor must start in first speed, accelerate to second speed and then accelerate to third speed. The various control requirements for the control circuit are as follows:

(1) One STOP-push button to stop the motor regardless of the speed of rotation of the motor.

(2) An overload protection for the motor.

(3) Three separate push buttons to select the first, second or third speed.

(4) A 5 seconds time delay between acceleration from one speed to another.

(5) If the motor is in operation and a higher speed is desired, it should be obtained by pushing the respective push button. On the other hand if the motor is running and a

lower speed is desired, the stop button should be pressed before pressing the required speed push button. Recall that speed control for a wound rotor motor is obtained by placing a resistance in the rotor circuit as shown in Fig. 11.30.

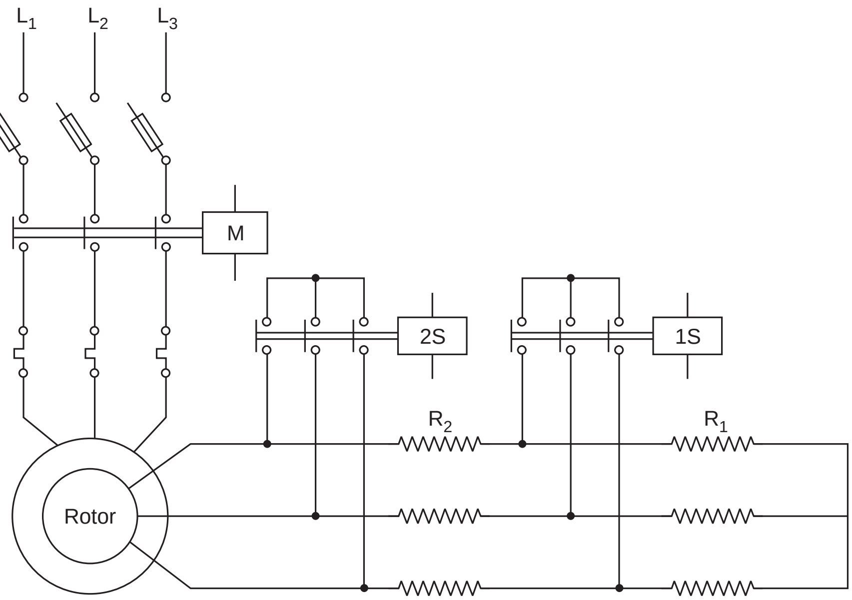


Fig. 11.30 Power circuit for a three speed wound rotor induction motor

In this starter contactor M is used to connect the stator windings of motor to the supply mains. When contactor M is energised the motor starts with all resistances in the rotor circuit, and accelerates to its first speed. For the second higher speed, contactor $1S$ closes and shorts resistance bank R_1 from rotor circuit. Third speed can be obtained by closing contactor $2S$ which cuts R_2 also from the rotor circuit. This shorts the rotor winding terminals and the motor operates as a squirrel cage motor at third speed. Control circuit for the above mentioned operation is shown in Fig. 11.31.

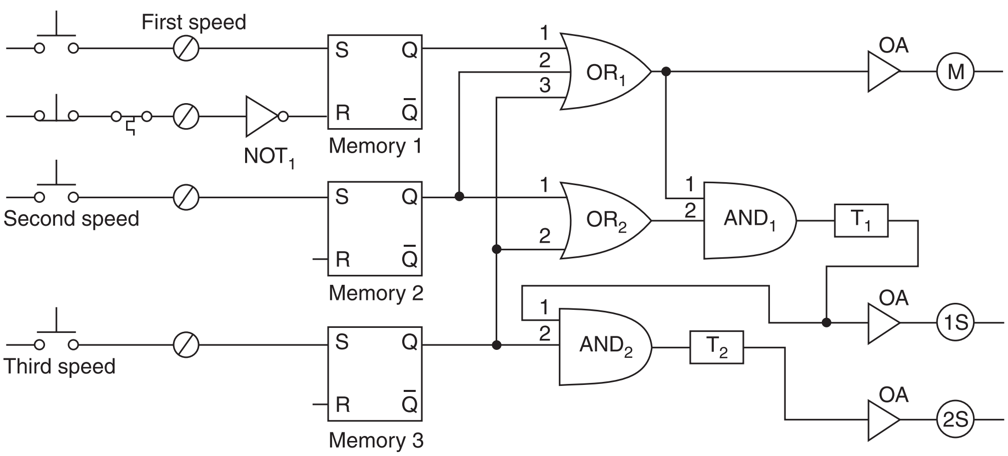


Fig. 11.31 Control circuit for a three speed wound rotor induction motor

Working of the circuit is as follows:

(1) When push button for the lowest speed is pressed, memory element 1 goes into set mode, its output Q becomes high which appears at terminal 1 of OR_1. Output of OR_1 thus becomes high and contactor M is energised through the amplifiers. Motor starts with all resistances in rotor circuit at a slow speed.

(2) When the motor is desired to run in next higher speed, the corresponding push button is pressed which brings the memory element 2 in set mode. Its output appears at input terminal 2 of OR_1 and also at terminal 1 of OR_2. Output of OR_1 goes high and energises contactor M while OR_2 output goes high and appears at input terminal 2 of AND_1. Besides energising contactor M, output of OR_1 also appears at terminal 1 of AND_1. Now both the terminals of AND_1 are high, thus output of AND_1 becomes high and timer T_1 is energised. After a pre set delay, timer output goes high and energises contactor 1S. Energisation of 1S shorts one bank of resistance R_1 from the rotor circuit and thus motor accelerates to second higher speed.

(3) When the third speed push button is pressed, memory element 3 goes into set mode and its output goes high and appears at terminal 3 of OR_1 and energises contactor M. Then, as described earlier, contactor 2S gets energised after a fixed delay, set by timer T_1. When T_1 has timed out its output energises contactor 1S and also appears at input terminal 1 of AND_2. Output of AND_2 goes high as its terminal 2 is already high due to output from memory element 3. Output of AND_2 energises timer T_2 and its output goes high after a fixed delay. This energises contactor 2S, which shorts resistance R_2 from the rotor circuit. The motor thus accelerates to the final *i.e.,* the third speed.

(4) When STOP-push button is pressed or over load relay trips the output of NOT_1 goes high which appears at reset terminal R of all the three memory elements and resets them. This leads to the dropping of all the three contactors M, 1S and 2S.

11.14 CONTROL OF PLANER MACHINE

The machine has already been discussed in the chapter on industrial applications of magnetic control. Here it will be shown how the same machine is controlled using digital logic elements. Schematic representation of a planer machine is shown in Fig. 11.32.

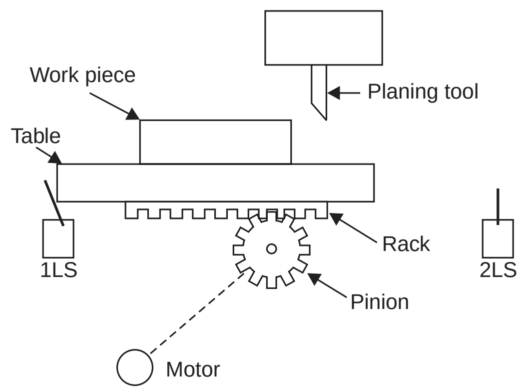


Fig. 11.32 Schematic diagram for a Planer machine

In this machine, the work piece or the job placed on the table moves to and fro by rack and pinion arrangement mounted on the shaft of a squirrel cage motor. The cutting tool is fixed while the job placed on the table is worked upon by movement of the table. Movement of the table is controlled between two limits on left and right by limit switches 1*LS* and 2*LS*. When table moves from left to right, tool works on the job while it remains ideal during right to left motion of the table. At the end of right to left motion, tool gets feed for the next cut on the job. Various control requirements for the machine are as follows:

(1) The motor is to be started manually by pressing START-push button. Once the motor starts it is reversed automatically at the end of right or left stroke by limit switches 2*LS* and 1*LS*.

(2) There should be provision for jogging the motor by a Jog-push button.

(3) If the machine table is lying in between extreme positions, machine should fail to start. Selection of initial direction of travel should be possible through right and left traverse push button, PB_R and PB_L.

(4) There should be a delay in starting the motor in left to right stroke so as to allow the tool to get the feed for a fresh cut on the job.

(5) The machine should stop on pressing of STOP-push button or on over-load tripping of motor.

(6) Interlocking of coolant pump motor (running) should be provided as a pre-condition for starting of the machine.

Control circuit for the machine adhering to the above mentioned control requirements is shown in Fig. 11.33.

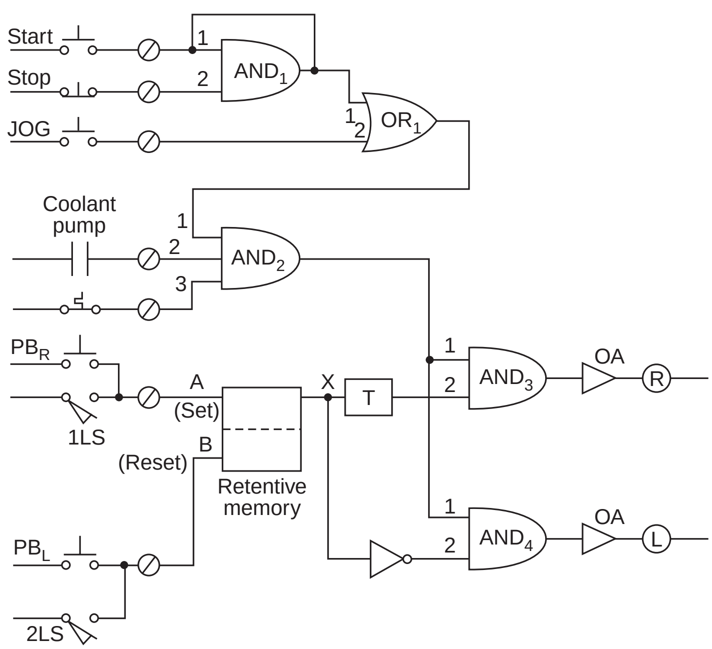


Fig. 11.33 Logic control circuit for a planer machine

There are two major sectors of this control circuit. One is the control of the starting and stopping of the motor, and the other is the automatic reversing control.

Working of the circuit is as follow:

(1) When START-push button is pressed, input terminal 1 of AND_1 becomes high. Its output also goes high as its input terminal 2 is already high due to closed contact of STOP-push button. Output is fed back to terminal 1 for holding the output high.

(2) Output of AND_1 appears at terminal 1 of OR_1 making the output of OR_1 high which appears at terminal 1 of AND_2. If motor overload relay contact is closed and coolant pump motor is running, then terminals 2 and 3 of AND_2 also have a high signal. Thus all the three input terminals of AND_2 are high and so its output goes high.

(3) Output of AND_2 appears at terminal 1 of AND_3 and AND_4. Depending upon the condition of memory element *i.e.,* whether it is in set mode or in reset, either AND_3 or AND_4 output will go high and will energise the respective contactor R or L. Desired direction of travel may however be selected by pressing the right or left traverse push buttons PB_R or PB_L before pressing the START-push button.

(4) To understand the reversing action of circuit, it is assumed that initially the machine table is in extreme left position so that the limit switch 1*LS* is in actuated condition and its normally open (NO) contact is closed. Thus, a high signal appears at terminal A of the retentive memory through closed contact of 1*LS*. Memory element gets set and its output terminal X goes high.

(5) High output from terminal X appears at terminal 2 of AND_3 after some delay set by the timer T while at terminal 2 of AND_4, a low signal appears because of the NOT gate being in series with the output from X.

(6) As both the terminals 1 and 2 of AND_3 are now high, its output becomes high which energise motor contactor R through the amplifier. Machine table thus moves in right direction.

(7) When extreme right position is reached, limit switch 2*LS* gets actuated. Its normally Open (NO) contact closes and resets the memory element. Output at terminal X goes low and thus terminal 2 of AND_3 also becomes low. Output of AND_3 therefore goes low and contactor R is de-energised.

At the same time when memory element gets reset, terminal 2 of AND_4 goes high due to a NOT gate inverting the low output from X.

(8) Thus, due to actuation of limit switch 2*LS* terminal 2 and AND_4 goes high while its terminal 1 is already high. Hence, a high output appears which energise motor contactor L through the amplifier. Motor now runs in reverse direction to move the table from right to left.

(9) When the table reaches extreme left position, limit switch 1*LS* gets actuated and memory element is set and thus terminal 2 of AND_4 goes low and its output becomes low. Contactor L is therefore de-energised. After a delay set on timer T, again contactor R is energised as output of AND_3 becomes high. The to and fro motion, due to setting and resetting of memory elements by actuation of limit switches, continues till the STOP-push button is pressed or overload trips to make the terminal 1 of AND_3 and AND_4 low.

(10) If the machine table is required to be moved slowly in steps for adjustment of the tool with respect to the job position then Jog-push button alongwith the required traverse push button PB_R or PB_L is used. As seen from the control circuit, Jog-push button output is connected to terminal 2 of OR_1 and there is no feedback for holding the

output of OR_1. Therefore, output of OR_1 remains high as long as Jog-push button is kept pressed. Thus the table can be moved as desired in steps by the Jog-push button. Students are advised to trace out the energisation of contactor R and L when the Jog-push button is used.

11.15 CONTROL OF THREE CONVEYORS

A conveyor system, discussed here, consists of three conveyors used to transfer sand from silos (large container) to the sand hopper of a mould making machine used in a foundary. The arrangement is as shown in Fig. 11.34.

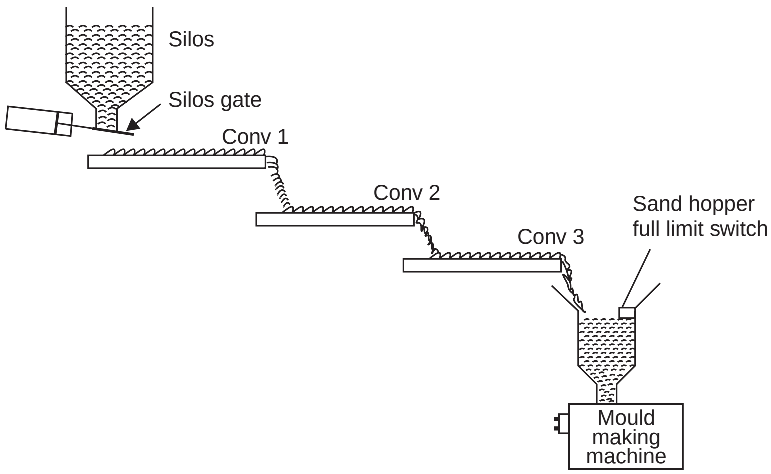


Fig. 11.34 Schematic diagram for three conveyors

Sand is fed to conveyor 1 by opening the gate of silos which is operated by a pneumatic cylinder. The gate opens only when all the three conveyors are running. Conveyor 1 dumps sand on to conveyor 2 which in turn dumps sand onto conveyor 3. Sand from conveyor 3 falls in the sand hopper. Conveyor can be started and stopped through the ON or OFF push button provided near the mould making machine. Conveyors stop automatically when the sand hopper is full. Various control requirements for this system are as follows:

(1) ON-push button is to start all conveyor motors in sequence from 3 to 1, *i.e.,* from the last to the first.

(2) Sand gate of the silos should open automatically when all the three conveyors are running.

(3) An over-load on any of the conveyors should stop all these conveyors.

(4) When sand hopper of the machine is full, a limit switch should actuate and stop all the conveyors.

(5) Stopping of the conveyors should follow the sequence 1, 2, 3 *i.e.,* from first to last.

(6) An additional requirement during stoppage is that there be a delay of 2 minutes between the stopping of subsequent conveyors, in order that the sand on the following conveyor might clear before it is stopped.

(7) A STOP-push button near the mould making machine should also be able to stop the conveyors.

Control circuit for the above requirements is shown in Fig. 11.35.

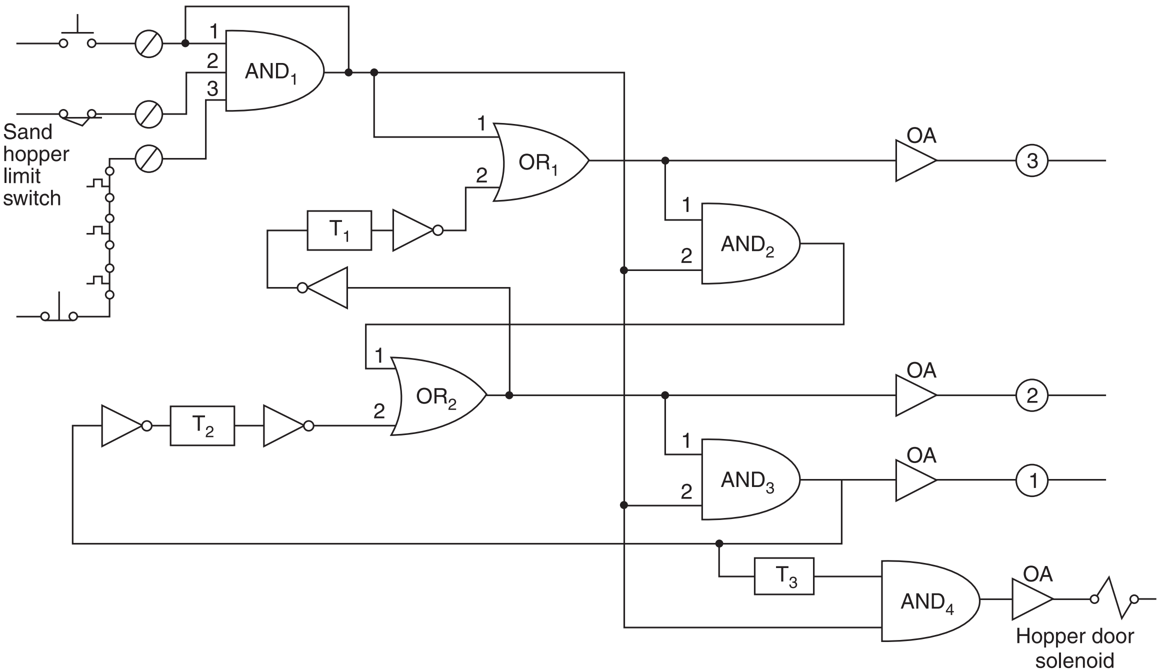


Fig. 11.35 Control circuit for three conveyors

In this control circuit, timer elements T_1 and T_2 have been prefixed and post fixed by NOT elements to make the timer action equivalent to an OFF-delay timer with a normally open delayed contact. Students are advised to clearly understand the operation of an OFF delay timer, if they have any doubt, before proceeding further.

Operations of the control circuit is as follows:

(1) The conveyors can be started if the contact of the sand hopper limit switch LS_1 is closed (*i.e.,* sand level is lower than the limit in the sand hopper) and all the overload relay contacts are closed. If the above two conditions are true then there will be high signals at input terminal 2 and 3 of AND_1.

(2) On pressing the ON-push button, a high signal appears at input terminal 1 of AND_1 and its output goes high. This output is fed back to terminal 1 for sealing. High output from AND_1 appears at terminal 2 of AND_2, AND_3 and AND_4.

(3) Output of AND_1 also appears at input terminal 1 of OR_1. Its output therefore goes high and energises contactor 3 to run conveyor 3. Output of OR_1 also appears at input terminal 1 of AND_2 and its output becomes high and appears at terminal 1 of OR_2. Output of OR_2 thus also goes high and energises contactor 2 to run conveyor 2.

(4) Output from OR_2 appears at input terminal 1 of timer T_1 and its output immediately goes high (off delay timer action) and appears at input terminal 2 of OR_1.

(5) Output from OR_2 also appears at input terminal of AND_3 and makes its output high to energise contactor 1.

(6) Output from AND_3 also appears at input terminal of timer T_2 and its output immediately goes high and appears at input terminal 2 of OR_2.

(7) Output of AND_3 also appears at input terminal 1 of AND_4 after a small delay through timer T_3. Output of AND_4 therefore goes high and energises the solenoid to open the gate of the silos. Thus, sand from silos starts falling on conveyor 1 after a small delay from the starting of conveyor 1.

(8) Now, when output of AND_1 goes low either due to pressing of OFF-push button or tripping of some over-load relay or actuation of sand hopper limit switch, the input at terminal 1 or OR_1 goes low, but its output remains high as its input terminal 2 is high (output from timer T_1). Similarly, output of OR_2 remains high due to a high signal at its input 2 although its terminal 1 goes low. Thus, conveyor 3 and 2 continue to run. Conveyor 1, however, stops immediately when AND_1 output goes low as input terminal 2 of AND_3 goes low. Silos gate also closes immediately as output of AND_4 goes low due to output of AND_1 going low.

(9) As output of AND_3 goes low, input to timer T_2 becomes low. Timer output goes low only after a delay of 2 minutes and makes the input terminal 2 of OR_2 also low. The output of OR_2 thus also becomes low. This leads to stopping of conveyor 2 after a delay of 2 minutes from the stopping of conveyor 1.

(10) As output of OR_2 goes low, input of T_1 also becomes low, and therefore its output becomes low after 2 minutes. This makes the input terminal 2 of OR_1 low and its output also becomes low. As a result contactor 3 gets de-energised. Conveyer 3 thus stops after a delay of 2 minutes from the stopping of conveyor 2.

11.16 SHIFT REGISTER

Shift register consists of *JK* flip flops connected in series which transfer their contents from one to another. Schematic diagram of a shift register having four flip flops is shown in Fig. 11.36. Output of the first is connected to input of the second and so on. Clock and clear terminals of all are connected in parallel.

Working:

When a low clear signal is applied, all flip flops get reset *i.e.*, Q_1, Q_2, Q_3, Q_4 becomes low while $\overline{Q_1}, \overline{Q_2}, \overline{Q_3}, \overline{Q_4}$ becomes high. The state of the register is Q_1, Q_2, Q_3, Q_4 = 0000.

Now suppose a high signal is applied to J terminal of the first flip flop FF_1 and is maintained. When clock pulses, also called shift commands are applied to the *CK* terminals of all flip flops, then on negative edge of first pulse, FF_4, FF_3, FF_2 remain in reset mode as their J input terminal is low. Flip flop FF_1, however gets into set mode and its output terminal Q_1 becomes high. Thus state of the register after first pulse becomes 1000. When second negative edge appears, FF_2 will go into set mode as it has a high at its J terminal. FF_1 remains in set mode since a high is maintained at its input terminal J. FF_4 and FF_3 remain in reset mode as they have a low at their J terminal. Thus after the second pulse the state of register becomes 1100. If high input at J terminal of FF_1 is maintained, then on application of third negative edge to *CK* terminals FF_3 will also go into set mode and the state of register becomes 1110. Similarly on fourth negative edge the state of the register becomes 1111. On subsequent pulses the state of register remains unchanged as 1111, if constant high is maintained at J terminal of FF_1. Registers continue to lose 1 from the extreme right flip flop while another 1 is added in the extreme left flip flop FF_1. Hence, the information in the flip flops is shifted one place to the right whenever a shift command occurs, while an external circuit keeps feeding 1's into the leading flip flop FF_1.

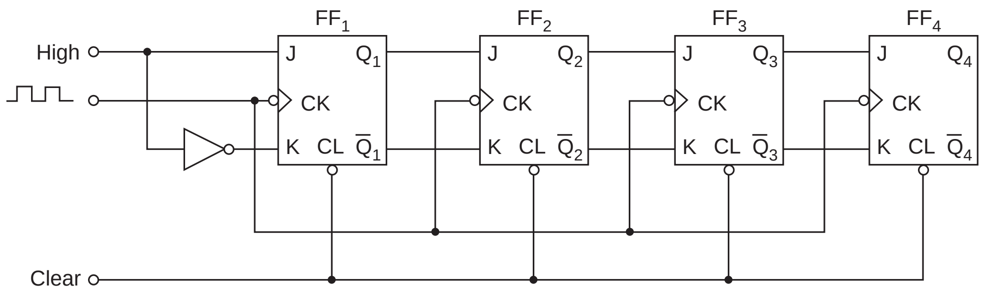


Fig. 11.36 Shift register built with JK Flip-flops

The schematic diagram of flip flop represents how pre-packaged shift registers are internally built however, they are illustrated in a different way as shown in Fig. 11.37 (*a*).

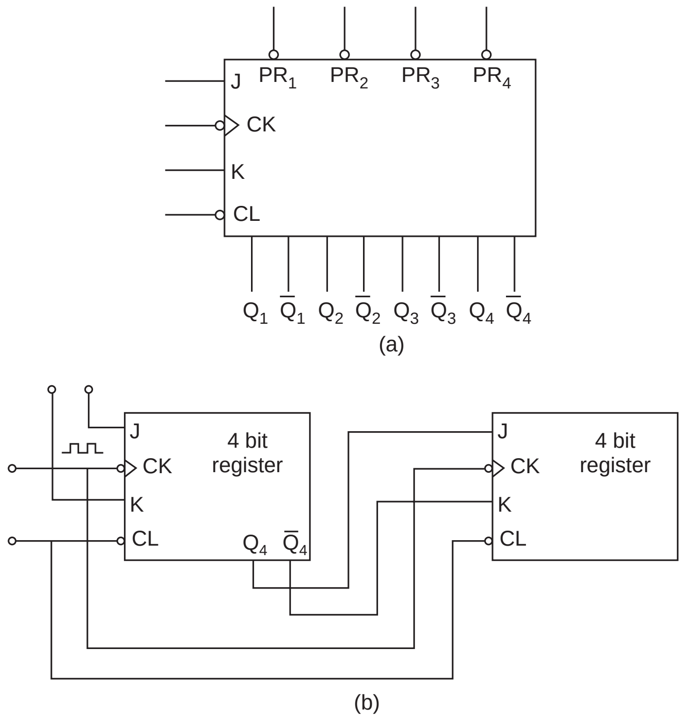


Fig. 11.37 (*a*) Symbol for prepackaged register (*b*) Cascade connection of two shift registers

Most common length for pre-package shift registers are 4, 5 and 8 bits. If a longer shift register is required, two or more small ones can be cascaded as shown in Fig. 11.37 (*b*). There are many different types of shift registers but the basic function of all is to shift binary bits from one location to the next. To avoid confusion only the type discussed above will be used subsequently.

11.17 CONVEYOR SYSTEM USING A SHIFT REGISTER

Shift registers are widely used in industrial applications involving conveyor systems. Each flip flop in shift register represents one zone on the conveyor system. The state of a particular flip flop, ON or OFF, stands for some characteristic of the piece in that zone. The most obvious example which can be represented in binary 1 or 0 is pass or fail, *i.e.,* either the piece passes inspection and is routed to the next zone or it fails inspection and is rejected.

Let us discuss a practical application of shift register in control of a production set-up in which evenly spaced parts come down a conveyor for inspection. Schematic representation of the system is shown in Fig. 11.38.

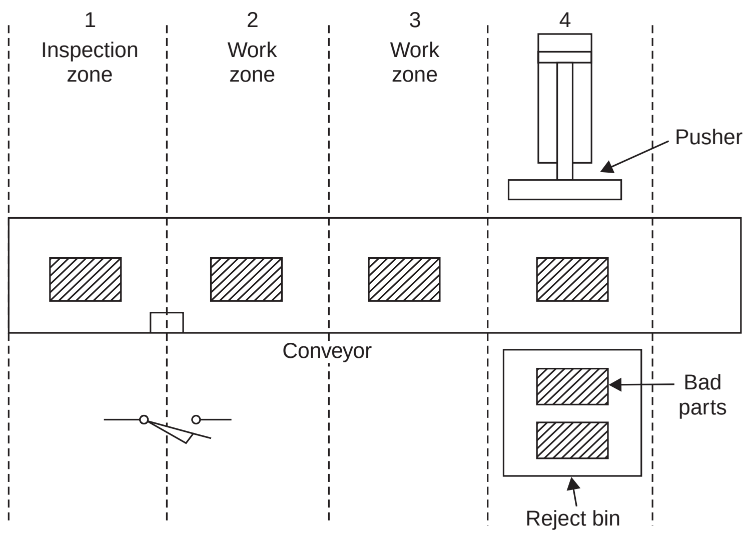


Fig. 11.38 Plan layout of a conveyor inspection system

Assume that the conveyor is divided in four zones. Inspection of the piece is done in zone 1. In zones 2 and 3 some work is done on the piece if it passes inspection, while the piece which fails, is allowed to pass through unattended. For identification of the rejection piece, it is marked with paint by an inspector of zone 1 for the benefit of workers of zones 2 and 3. A reject push button is also pressed while the rejected piece is still in zone 1. When the piece reaches the fourth zone, a pneumatic pusher extends and pushes the rejected piece into the reject bin while the good parts move past the fourth zone.

Control circuit for the above system is shown in Fig. 11.39. Shift register in the circuit has been used to keep track of the progress of a bad piece on the system and to operate the pusher when the bad piece reaches zone 4.

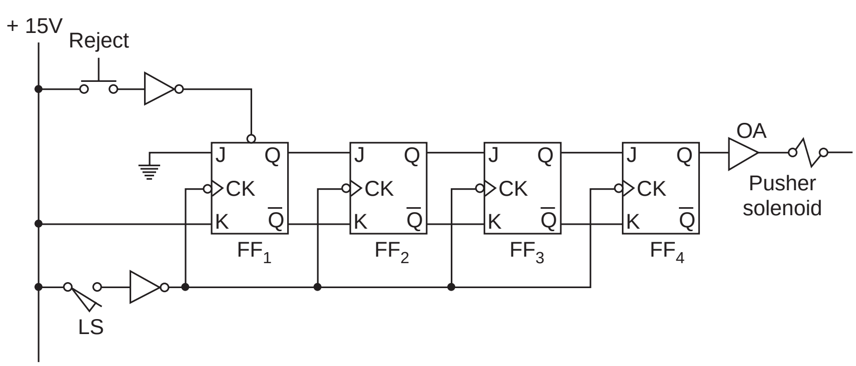


Fig. 11.39 Control circuit of conveyor inspection system using a shift register

Working of the circuit is as follows:

(1) If the Reject-button is pressed while the bad piece is in zone 1, the preset terminal of flip-flop FF_1 becomes low and it goes into set mode (assuming that the flip flop responds to low preset signal). Its output Q_1 becomes high and appears at input terminal J of FF_2.

(2) When the rejected piece leaves the zone 1 and enters zone 2, a limit switch is actuated. The limit switch gives a low signal to all CK terminals. Flip flop FF_2 goes into set mode and its output Q_2 becomes high while FF_1, FF_3 and FF_4 get reset. FF_1 gets reset due to its J terminal being grounded. Thus we see that as the rejected part moves into zone 2, the information about its non-acceptance enters flip flop 2.

(3) When the rejected piece enters zone 3, limit switch is again actuated, by the piece following it *i.e.*, by the one entering zone 2. Shift command thus appears at all the CK terminals.

(4) On application of signal to CK terminals, FF_3 gets in set mode as its input is high (Q_2 = 1), the information of a bad piece in zone 3 enters flip flop FF_3. Similarly, when a bad piece enters zone 4 the limit switch is again actuated and another shift command occurs, which turns on FF_4.

(5) When output Q_4 of FF_4 goes high it energises the solenoid which applies a push to the work piece. Pusher moves forward and the bad piece is thrown into the reject bin.

(6) When the next piece enters zone 4, FF_4 gets reset if the part is good and the pusher immediately moves backward before the part can run into it.

11.18 COUNTER

A digital counter can count the number of pulses appearing at its input terminal. Counting, however, is done in Binary coded decimal number since the counter circuit is made of flip flops and logic gates. Schematic representation of a decade counter is shown in Fig. 11.40 (*a*).

Input count pulses apear at terminal CK and the count number in binary code appears at terminal $DCBA$ with corresponding numerical values of 8, 4, 2, 1. Input count pulse number versus the corresponding BCD output is given below:

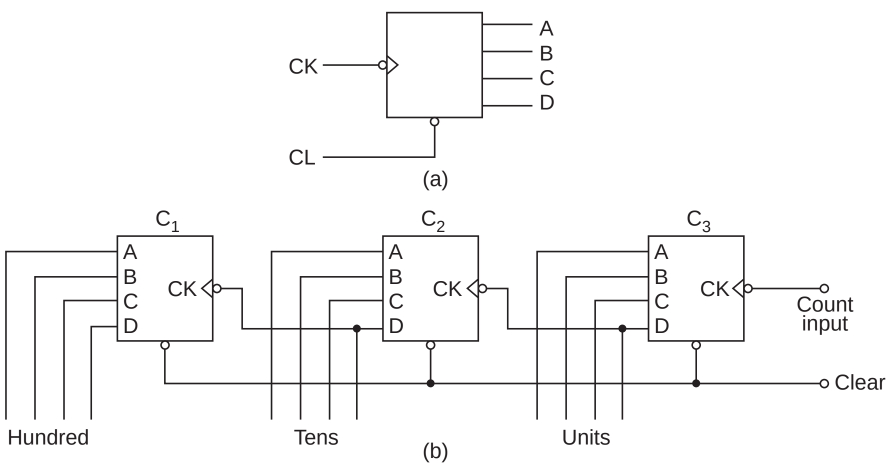


Fig. 11.40 (*a*) Symbol for counter (*b*) Cascading of counters for measurement in terms of tens and hundreds

CK	*DCBA*
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

When clear terminal *CL* goes to its active low, all four bits clear to 0. The counter output becomes 0000.

From the above table, it is clear that a decade up-counter counts upto 9. However, counting pulses greater than 9 is done by cascading the counters as shown in Fig. 11.40 (*b*). At the tenth pulse all the bits *DCBA* of counter 1 clear to 0. As the terminal *D* of the unit counter is connected to *CK* terminal of counter 2, the negative going edge of *D* triggers the counter and its output becomes 0001. Thus second counter registers, tens, and similarly, third counter will register hundreds. For example, when 15 number of pulses have appeared the output of counter will be :

Counter 3	Counter 2	Counter 1
(hundreds)	(tens)	(unit)
BCD number 0000	0001	0101
Numerical number 0	1	5

i.e., 00010101 = 15

11.19 DECODER

A counter records pulses in binary coded decimal numbers. But this information is not understood by a layman. A decoder is thus required which converts *BCD* number into decimal number. Schematic representation of a Decoder is shown in Fig. 11.41 (*a*).

If the binary information represents the decimal digit 3 (*DCBA* = 0011), the decoder drives the output line No. 3 high.

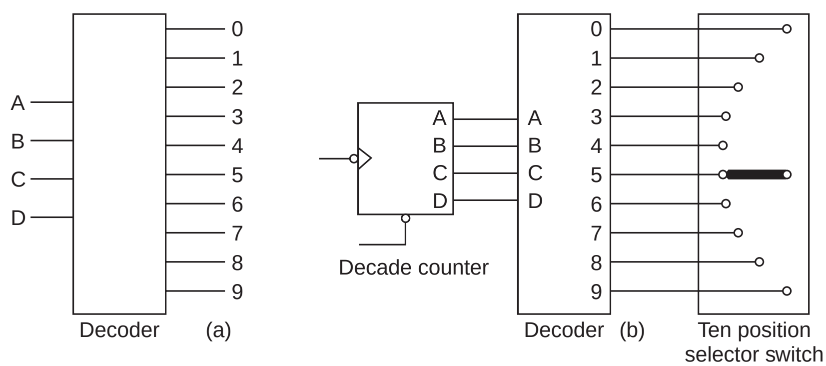


Fig. 11.41 (*a*) Schematic representation of a decoder (*b*) Combination of a decade counter, decoder and a 10-position selector switch

In many industrial applications, where a certain action has to be taken after a fixed, count, a ten position selector switch is connected to the output of decoder as shown in Fig. 11.41 (*b*). If it is desired to initiate some action after a count of say 5, selector switch is placed in position 5 as shown in Fig. 11.41. After 5 number of count pulses, *DCBA* of counter will be 0101, which would also appear at *DCBA* terminals of Decoder. Decoder terminal 5 will go high and a high output will appear at common terminal of the switch to initiate the desired action. Here, the *BCD* number has been referred to the decimal decoder. There are other types of decoders available such as *BCD* to seven segment, grey code to decimal, excess three code to decimal etc. In this text, the term decoder will refer to the *BCD* to decimal decoder. Interested students may refer to a text book on digital electronics for study of inbuilt structure of a decoder.

11.20 LOADING OF CASTINGS INTO ANNEALING FURNACE USING DECADE COUNTER AND DECODER

The schematic arrangement for the system is shown in Fig. 11.42.

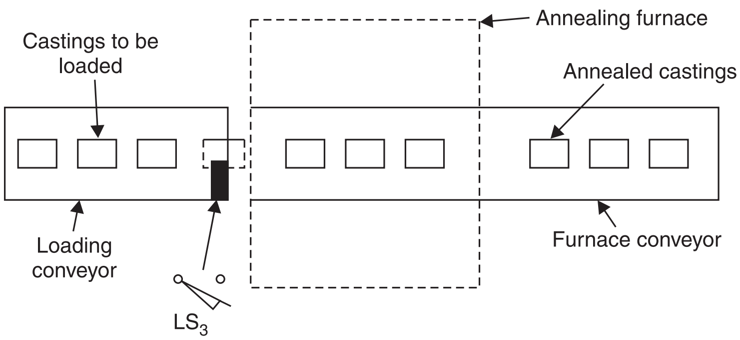


Fig. 11.42 Plan layout of automatic loading of castings into Annealing furnace using conveyors

In this system a number of castings are loaded on a metallic roller conveyor passing through the annealing furnace. On pressing the loading/unloading push button, annealing furnace door opens. When doors are fully open annealing furnace conveyor (conv. 2) and loading furnace conveyor (conv. 1) will start. As the conveyors start, annealed castings come out of the exit side, while fresh castings are loaded on to the annealing furance conveyor from loading conveyor. When the selected number of castings enter the annealing furnace, both the conveyors stop and furance doors close. Annealing of the castings can then be done for required time.

The number of castings to be admitted in furnace can be changed depending upon their size. Selector switches are used to select the number of castings to be admitted. Number of castings entering the furance is counted with the help of a limit switch LS_3 mounted on the end of the loading conveyor. Every time a casting de-actuates the limit switch while leaving conv 1 and entering conv 2, the *CK* terminal of units counter becomes zero. The negative going edge causes the counter to produce a pulse at its output in binary coded decimal form. Control circuit for the system is shown in Fig. 11.43.

Explanation of the control circuit is as follows :

(1) Suppose 12 castings are to be loaded into the furnace. This number being greater than 9, two decade counters are cascaded as shown in the diagram. Output *D* of the units counter is connected to the *CK* terminal of tens counter. Clear terminals of both the counters are connected to the output of AND_3 through a NOT gate as shown in the control circuit. Units counters selector switch is set at 2 while Tens counter selector switch is set at 1 to get a total setting of 12.

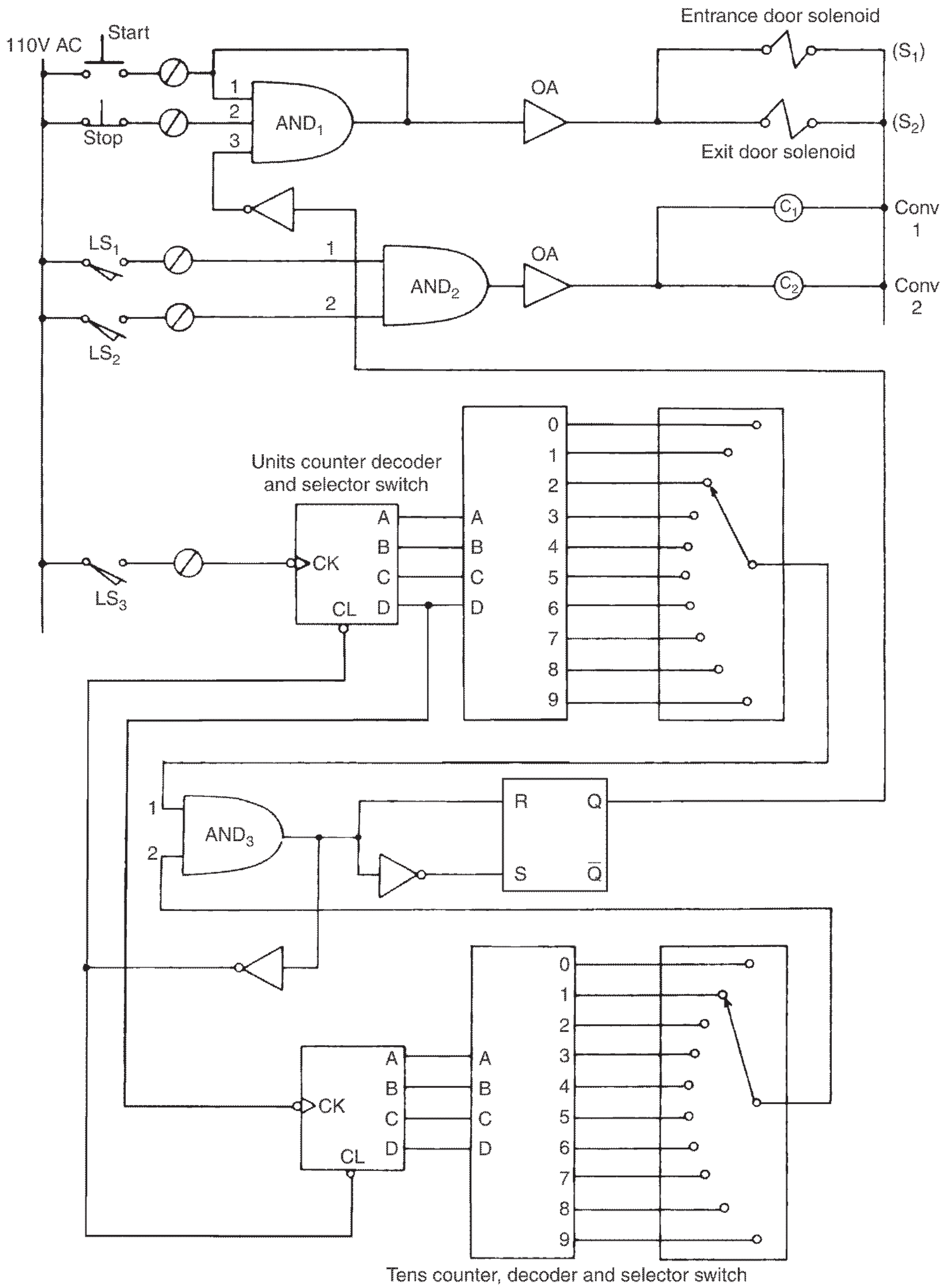


Fig. 11.43 Control circuit for loading of castings in an annealing furnace

(2) For loading, Start loading/unloading push-button is pressed. Output appears at AND_1 gate as its input terminal 2 and 3 are already high.

Terminal 3 is high as *R-S* flip-flop is in reset mode. Output is fed back to terminal 1 for sealing the circuit.

(3) As soon as the AND_1 output goes high, entry and exit door opens due to energisation of solenoids S_1 and S_2.

(4) When both the doors are open, LS_1 and LS_2 get actuated and AND_2 output goes high. This output runs the furnace conveyor and loading conveyor by energising contactor C_1 and C_2 respectively.

(5) As the conveyors start, the castings placed on loading conveyor also move and are shifted over to the furnace conveyor. Number of casting loaded on the furnace conveyor is counted by de-actuation of limit switch LS_3 installed on the end of the loading conveyor. Every time LS_3 is deactuated, *CK* terminal of units counter goes low and registers the count at its output-binary coded decimal form. Decoder converts it into decimal form. At the second count the ouput of units selector switch will go high and appear at input terminal 1 of AND_3 but no further action takes place as the other input terminal 2 of AND_3 is low.

(6) Units counter will count upto 9 and when 10th count pulse appears, its output resets to 0000 from 1001 (9). Negative going transition of terminal *D* causes the tens counter to register a count and its output becomes 0001.

Thus a high signal appears at input terminal 2 of AND_3 on the 10th, count, but now the input at terminal 1 of AND_3 is absent as unit counter is reset.

(7) From 11th count, units counter again starts counting from 1 onwards. At the 12th count pulse, common terminal of Decoder selector switch goes high. Now both the inputs of AND_3 are high so its output becomes high. This brings the *R-S* flip-flop in set mode and its output becomes high. This causes the input terminal 3 of AND_1 to go low due to the presence of a NOT gate in series. Thus AND_1 output goes low. Conveyors 1 and 2 stop immediately and furnace door starts closing due to de-energisation of door solenoids.

(8) As the output of AND_3 goes high, a low signal appears at *CL* terminal of units and tens counter due to the presence of a NOT gate in series with output of AND_3 gate.

11.21 MONO SHOT

Mono shot is a very useful digital element used in industrial controls. Its formal name is monostable multivibrator. The symbol for a mono shot is shown in Fig. 11.44 (*a*).

It has two outputs Q and $\overline{Q}$ similar to a flip-flop. In this text, it is assumed that mono shot are triggered by a negative edge at trigger terminal *T*. However, they can be triggered by a positive edge also. When one shot is triggered, the Q output goes high while the $\overline{Q}$ output goes low.

After a preset period of time, called firing time t_f, the output Q returns to low and Q returns to high. Triggering of the mono shot by a short pulse and the resulting output Q and $\overline{Q}$ are shown in Fig. 11.44 (*b*). This way, a mono shot may be used as a pulse stretcher, or for delaying the negative edge of a pulse by a firing time t_f.

Mono shots are frequently used to reset a counter or a flip-flop in circuits where the conditions are such that a long term level change cannot be used to reset the counter or the flip-flop (since the counter is to resume counting again after a short duration). Long term level change as compared to a small time change by a mono shot, is shown in Fig. 11.44 (*c*). Suppose the counter is to reset at instant *A* when V_{in} changes to low, and has to resume counting at instant *B*. If V_{in} is used to clear the counter by negative going edge at instant *A*, then even at instant *B*, the counter will remain reset and hence cannot resume counting. Thus V_{in} cannot be used to clear the counter. Instead, if a mono shot is triggered by V_{in} and its $\overline{Q}$ output is used to clear the counter, then counters can be resumed at instant *B,* since by that time $\overline{Q}$ of the mono shot will be back to its high state after firing time t_f (refer Fig. 11.44 (*c*)). The above will become more clear when a practical industrial circuit is discussed.

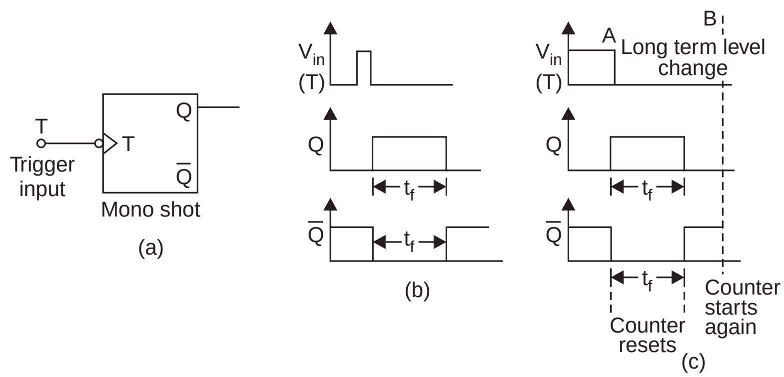


Fig. 11.44 Symbol and waveforms of a mono shot

11.22 CLOCK

The formal name of a clock in digital text books is astable multivibrator or free-running multivibrator. A clock generates a continuous train of pulses which may be utilised to synchronise various digital devices in an industrial circuit. It may also be required to provide count pulse to an industrial system which does not generate count pulses naturally. Symbol of a clock is shown in Fig. 11.45.

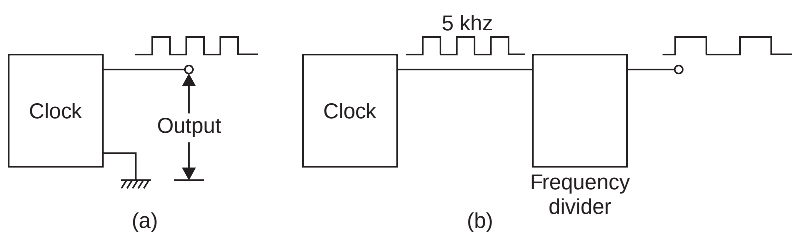


Fig. 11.45 (*a*) Symbol for a clock (*b*) A clock combined with a frequency divider

The frequency of the waveform is set by values of resistor, capacitor, and inductor which are internally connected to the circuit. A lower frequency can be obtained by connecting a frequency divider circuit as shown in Fig. 11.45 (*b*). A frequency divider divides the clock pulse by an integer and produces a lower frequency pulse train. Some systems require clock pulses of different frequency in order to synchronise various events properly.

11.23 AUTOMATIC FILLING OF SILOS USING A CLOCK AND A MONO SHOT

The schematic diagram for the system is shown in Fig. 11.46.

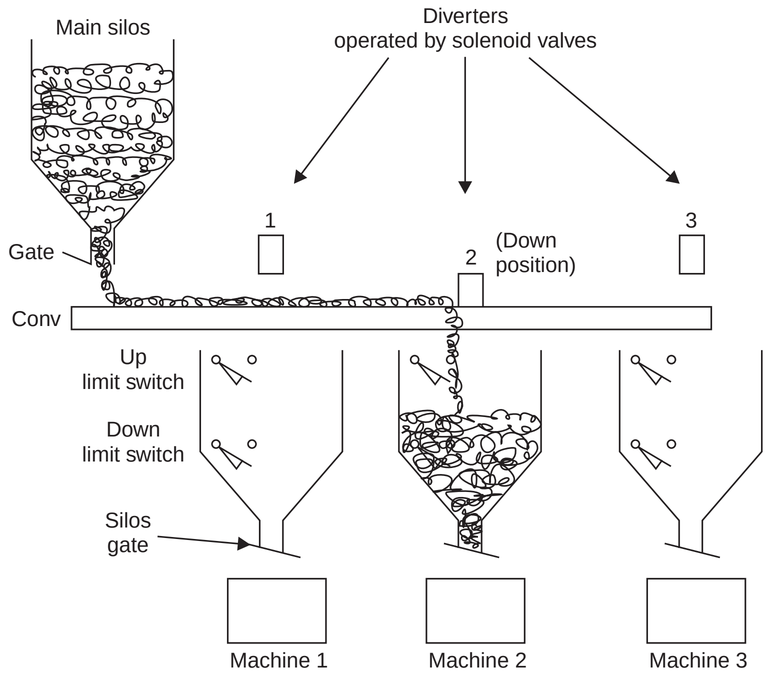


Fig. 11.46 Schematic diagram for an automatic machine filling a number of silos

In this system, certain material is to be distributed in three small silos 1, 2, 3 which feed individual machines 1, 2, and 3.

Material is fed to silos from the main silos through a belt conveyor and diverters. Level of material in small silos is sensed by a lower level and an upper level limit switch as shown in the figure. Filling of any of the silos starts when the level of material in it falls below certain level as determined by the position of the lower level limit switch. When material in all the silos is above the upper level, conveyor is at standstill and diverters are in up position. Gate of main silos is also closed.

When level of material in any of the silos falls below the lower limit, the conveyor starts moving and gate of the main silos opens. Diverter above the particular silos falls down so that material is diverted into that silos from the conveyor. When level rises to the upper limit, up limit switch gets actuated which causes the conveyor to stop, gate of the main silos to close, and the diverter to go up. In the diagram, diverter 2 is shown in down position and material is shown falling in to silos No. 2.

In the diagram, the diverters are shown connected in series, so that only one silos may be filled at a particular time.

Gate of main silos and diverter 1, 2, 3 are operated by solenoid valves. Special limit switches are used for sensing low and high level in silos.

Material for processing in machines can be taken out from the silos by manual operation of the gate of a silos by the operator of a particular machine.

Control circuit for the above system is shown in Fig. 11.47, and the explanation for the circuit is as follows:

(1) If the level in all the silos 1, 2 and 3 are above the upper limit, FF_4 remains OFF. Its $\overline{Q}$ output is high, and so, input 1 of AND_4 is high. At its terminal 2, clock is delivering square-wave pulses and, therefore, the output from AND_4 is also a square-wave of same frequency as the clock. These pulses appear at *CK* terminal of decade counter and it starts counting.

The counted number appears in BCD form at its output which is given to the decoder. Thus, terminal 1 of decoder goes high first and then 2, 3 and 4. When 4th output goes high it appears as a negative going edge at trigger terminal *T* of OS_4 due to a NOT gate in series. OS_4 fires for a few microseconds, applying a low signal to *CL* terminal of the counter, and counter immediately resets to zero. Counter again starts counting from 1. This is because when count pulse appears through AND_4, the clear pulse has long departed from counter terminal *CL*. This is the example of a mono shot resetting the counter and then removing the clear signal in time for the counter to resume counting again. Thus the counter continuously counts from 1 to 3.

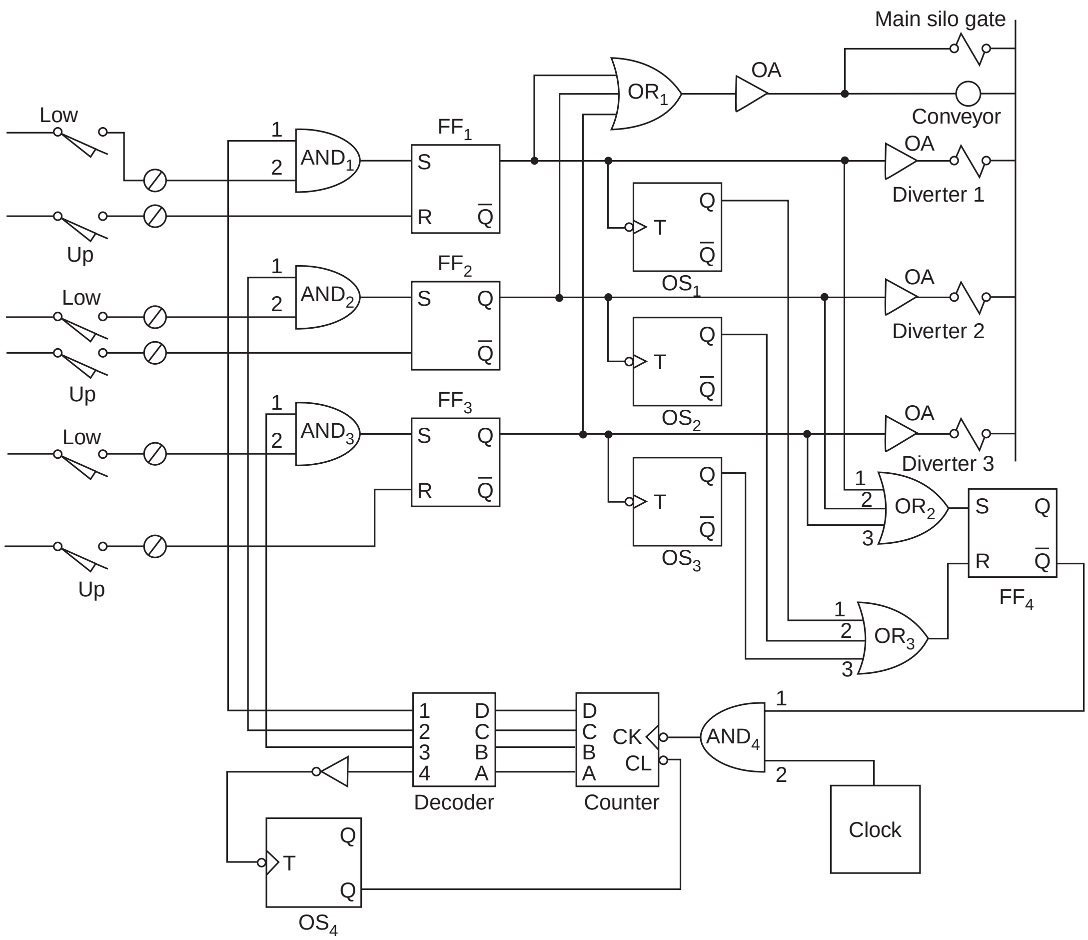


Fig. 11.47 Control circuit for an automatic machine filler

(2) In case the output, 1 to 3 of the decoder goes high in succession, AND_1, AND_2 and AND_3 are enabled partially in succession, as their terminal 1 goes high in succession. If low level limit switch of any of the silos is closed, then the corresponding AND gate will be fully enabled. Let us assume in this case that lower limit switch of silos 2 is actuated and thus AND_2 is enabled. Its output therefore goes high and brings FF_2 in set mode. Now due to output Q of FF_2 going high, three actions take place.

(*i*) Gate of main silos opens and conveyor also starts running with material falling from main silos on it.

(*ii*) Diverter 2 falls down so as to divert material from conveyor into silos 2 due to energisation of diverter 2 solenoid.

(*iii*) Q output of FF_2 also appears at terminal 2 of OR_2 and its output goes high which brings FF_4 in set mode. Thus $\overline{Q}$ of FF_4 goes low and AND_4 is disabled and counter does not receive count pulses. The counter therefore freezes in its present state.

(3) When the level in silos 2 rises, lower limit switch opens, thus disabling AND_2 but FF_2 remains in set mode due to its memory ability. Thus filling of material continues till upper level limit switch is actuated which resets FF_2. FF_2 output Q goes low which disables OR_1 and OR_2 and de-energises the solenoid of Diverter 2. Disabling of OR_1 stops the conveyor and main silos gate also closes. Disabling of OR_2 removes high state from the S terminal of FF_4.

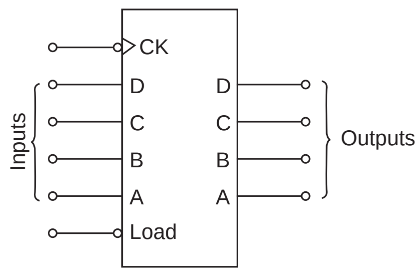
(4) Also, when Q of FF_2 goes low, it delivers a negative edge to the trigger terminal of OS_2 causing it to fire. Its output goes high for a few microseconds enabling OR_3. The output of OR_3 goes high and resets FF_4 thus high state appears at terminal 1 of AND_4 and thus clock pulses again appear at *CK* terminal of the counter. The counter starts counting from where it had stopped.

In the above circuit, observe the utility of using mono shots, 1 to 3 for resetting FF_4. Suppose, if FF_4 is reset by the output $\overline{Q}$ of flip-flops from FF_1 to FF_3 then if FF_4 is reset due to $\overline{Q}$ of FF_2 going high it will remain in reset mode even if $\overline{Q}$ of FF_1 or FF_3 goes low as $\overline{Q}$ of FF_2 will hold in reset mode. Thus it is necessary to temporarily apply a high to the terminal R of FF_4 when any of the flip flops, FF_1 to FF_3 goes into reset mode.

11.24 DOWN COUNTER

In a down counter every time a count pulse is delivered the number stored in the counter decreases by one. This type of counter is especially required in circuits where an output signal after a preset number of counts, and another signal earlier to a fixed number of counts, is desired. Symbol and table showing states of down counter after each input pulse are shown in Fig. 11.48.

Down counters have input terminals DCBA, in addition to the output terminals, so as to preset a number into the counter in BCD form. When the load terminal of the counter goes low, BCD number at input is loaded into the counter and it appears at output terminals DCBA. Assuming that number 9(1001) is present at input terminals when load terminal goes low, the output is preset to 1001 as shown in the table of Fig. 11.48 (*b*). When the first pulse appears at CK terminal, output becomes 1000(8). At 9th pulse the output becomes 0000. At 10th pulse the counter again resets to 1001(9).



(a)

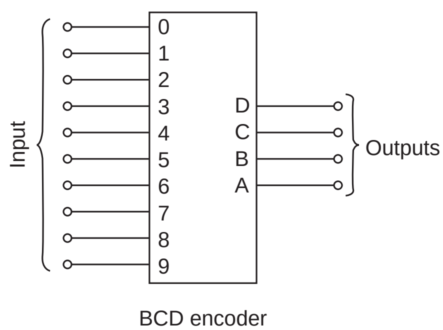
Initial pulse at CK	Preset BCD number				Decimal number
	1	0	0	1	9
1	1	0	0	0	8
2	0	1	1	1	7
3	0	1	1	0	6
4	0	1	0	1	5
5	0	1	0	0	4
6	0	0	1	1	3
7	0	0	1	0	2
8	0	0	0	1	1
9	0	0	0	0	0
10	1	0	0	1	Preset

(b)

Fig. 11.48 (*a*) Symbol for decade down counter (*b*) Truth table

11.25 ENCODER

An encoder is the inverse of a decoder. In this, input is in the decimal form and output appears in a binary equivalent number. There are various types of encoders, but in this text only 1-of-10 decimal input to BCD output type is discussed. Symbols for Encoders with active low inputs is shown in Fig. 11.49 (*a*).



(a)

Input terminal low ↓	Output			
	D	C	B	A
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

(b)

Fig. 11.49 (*a*) Symbol for 1-of-10 decimal encoder (*b*) Truth table for encoder

In an active low input encoder any one of the lines 0, 1, 2, 3 etc. going low is considered to be the desired input number. When input 0 is low while all others are high, output of the encoder is 0000, and when 1 becomes low while others are high, output becomes 0001. Truth table shown in Fig. 11.49 (*b*) indicates the output states for various inputs. Generally, the encoders receive their input from a 10-position selector switch. Selector switch can be set at any desired number by the operator and equivalent BCD number will appear at the output. This output is then loaded into a down counter when its load terminal goes low. Arrangement of selector switch, encoder and decade down counter is shown in Fig. 11.50.

The encoder discussed here is supposed to belong to the logic family which interprets a floating input as High *i.e.*, when all terminals from 0 to 9 except 3 appear as high to the encoder (terminal 3 being connected to a low). Active high input encoders may also be used from logic families which interpret floating input as low.

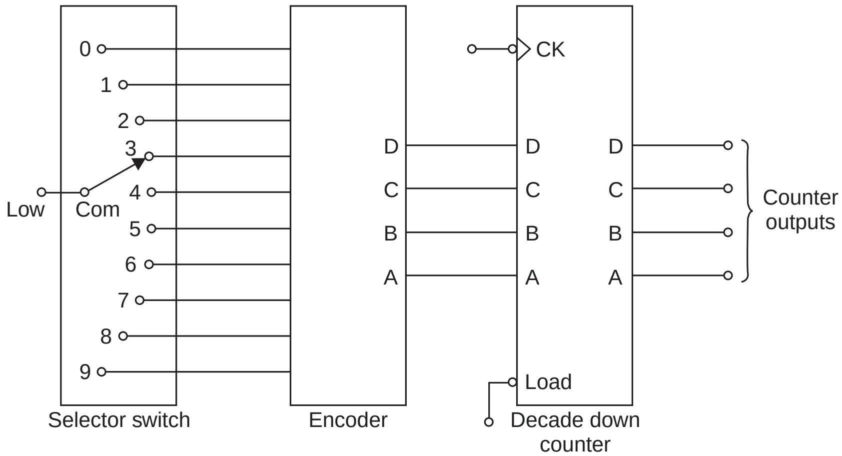


Fig. 11.50 Combination of a 10-position selector switch, a decimal-to-BCD encoder and a decade down counter

In this text, active low convention has been followed.

11.26 PRODUCT DISPERSION CONVEYOR SYSTEM USING A DOWN-COUNTER, AN ENCODER, A MONO-SHOT AND A TIMER

The conveyor system, used for dispensing a product to any desired zone is illustrated in Fig. 11.51.

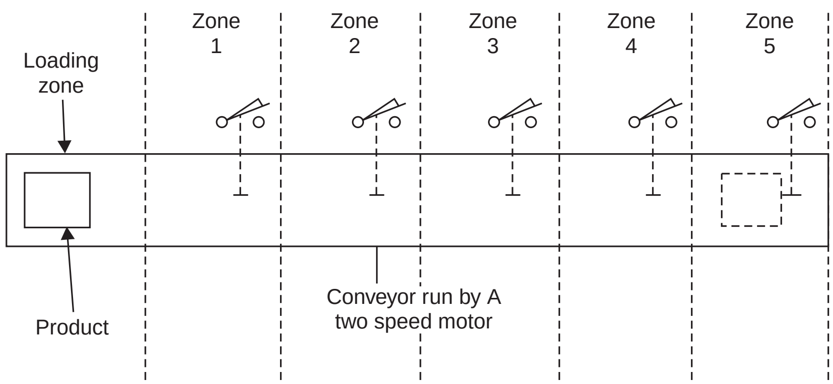


Fig. 11.51 Plan view of a product dispersion system

In this system, a product is loaded on the conveyor in the loading zone by the operator. Depending upon the zone in which this product is desired, operator selects the zone number on the selector switch. After selecting the zone, operator presses the conveyor START-push button. First, the conveyor runs in slow speed for a small time as set by a timer. Then it runs in fast speed, and again it becomes slow when it reaches a zone prior to the zone set on the selector switch. In each zone, limit switches are provided for sensing the product in that particular zone. As seen from Fig. 11.51 there are five zones and LS_1 to LS_5 are provided in these zones. There is an interlocking in the system due to which the conveyor cannot be started if a product is lying in any of the zones and has not been picked by the workers of that zone. Another provision in the control circuit is that if the product is desired in zone 1 then conveyor does not shift to fast speed but continues to run in slow speed. Control circuit for the above system is shown in Fig. 11.52.

Explanation of the circuit is as follows :

(1) Suppose it is desired to take the product to zone 5. First of all, the operator will set the selector switch to position 5. Terminal 5 of encoder thus goes low and binary coded decimal number 0101 appears at the output terminal of the encoder. This number also appears at the input of decade down counter.

(2) When operator presses the conveyor START-push button, terminal 1 of AND_1 goes high. If all the limit switches from LS_1 to LS_5 are in de-actuated condition, a high state appears at terminal 2 of AND_1. Its output goes high. This causes terminal T of OS_1 to go low. Its output $\overline{Q}$, which is connected to load terminal of decade down counter, also goes low. Decade-down counter thus gets loaded to 0101 (5) which is present at its input terminals. Output of the down counter gets connected to the decoder. Thus, decoder's terminal 5 will be high.

(3) As soon as AND_1 output goes high it also turns on FF_1. Its output Q goes high and energises the main contactor of conveyor motor. A high also appears at terminal 2 of NAND gate but its terminal 1 is low so its output will be high and appear at terminal 1 of OR_1 causing its output to go high. Slow contactor gets energised through the amplifier and thus the conveyor motor runs in slow speed. After some time delay, the timer T output goes high and appears at terminal 1 of NAND gate. As both the inputs of the NAND gate are now high, its output goes low. OR_1 is disabled as its terminal 2 is already low. Slow contactor of the motor is de-energised while the fast contactor gets energised and the conveyor runs at fast speed with the product loaded on it.

(4) When LS_1 is actuated a low appears at CK terminal of the down counter and its output decreases from 0101(5) to 0100(4). Now the decoder output terminal 4 goes high. As the product on the conveyor proceeds further, limits switches LS_2, LS_3 and LS_4 are actuated in succession. The decoder output terminals 3, 2 and 1 become high in succession. When terminal 1 of decoder becomes high, it appears at terminal 2 of OR_1 and thus its output goes high. Fast contactor is de-energised and slow contactor is energised. Conveyor again shifts to slow speed. When limit switch LS_5 is actuated, fifth count pulse is delivered to the down counter and its output becomes 0000 and decoder terminal 0 becomes high. Immediately trigger terminal T of OS_2 goes low and its output Q becomes high which resets flip-flop FF_1. When FF_1 resets, its Q goes low and conveyor main contactor M is de-energised. Conveyor thus stops. Now the product can be lifted from the conveyor for further work on it in zone 5.

(5) Similarly the product can be taken to any zone by selecting the required position on the selector switch.

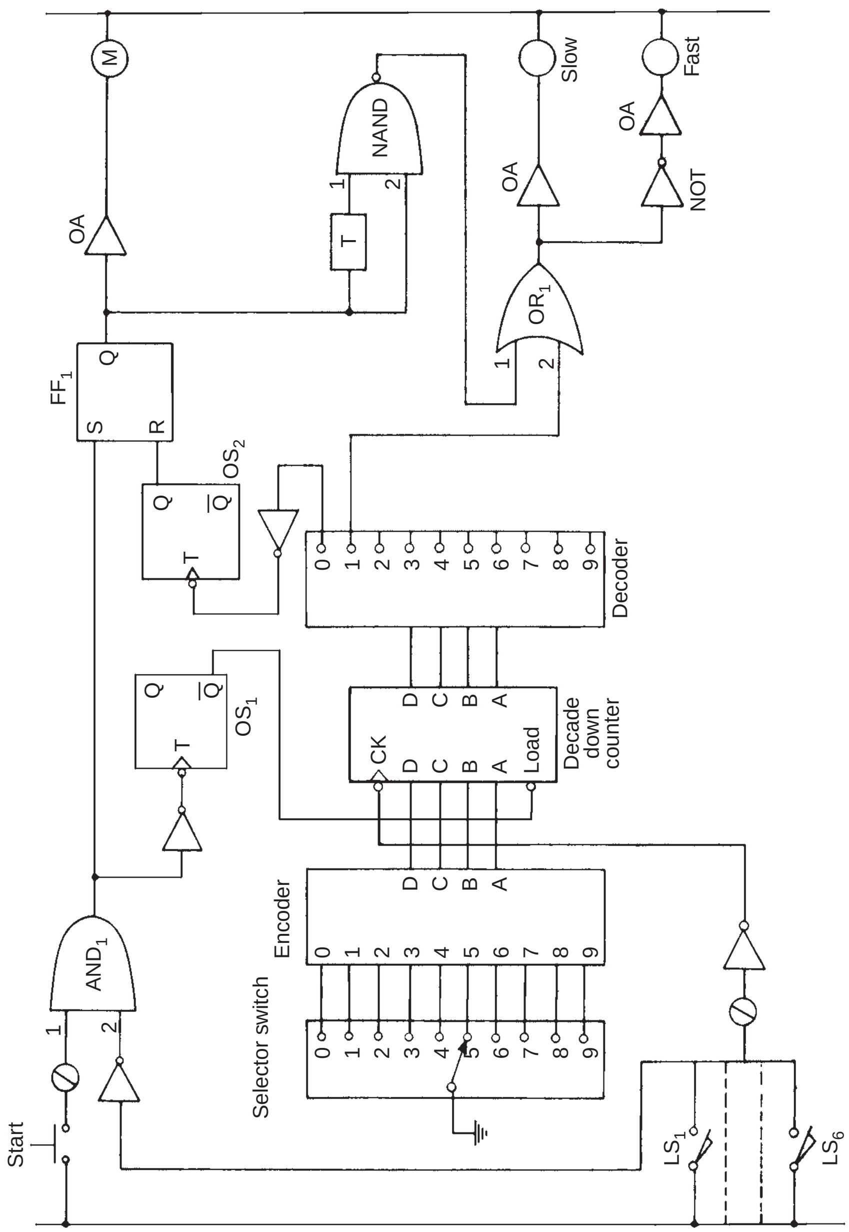


Fig. 11.52 Control circuit for a product dispersion system

REVIEW QUESTIONS

1. Enumerate various advantages and disadvantages of static control as compared to magnetic relay control.
2. In what way the static control differs as compared to magnetic relay control.
3. List the logic gates used in building control circuits. Draw their symbols and explain their working in brief.
4. Draw the USAI symbols for Relay coil, Relay contact, Time delay relay, and Limit switch,
5. Draw the internal circuitry of AND and OR gate using TTL logic and also explain its working.
6. Discuss solid state timer and its various modifications which are analogous to ON and OFF delay time delay relays.
7. Discuss OFF-return memory. Draw the internal circuitry and explain its working.
8. Explain how *RS* flip-flop can be built by using NAND gates and NOR gates only.
9. How does a clocked *RS* flip-flop differ from an ordinary *RS* flip-flop. What is negative edge triggering and positive edge triggering as aplicable to clocked flip-flop.
10. Discuss in detail the working of JK flip-flop.
11. What is Retentive memory ? How is it built ? Draw its symbol and equivalent relay circuit.
12. Enumerate various steps which are useful in designing a control circuit.Develop holding circuit using AND gate, RS flip and using both AND gate and OR gate.
13. What is the necessity of signal converters in static control ? Discuss different types of signal converters.
14. What is a Bounce Eliminator ? Discuss Bounce Eliminator circuit using NOR gates.
15. Discuss the working of a modern output amplifier using a UJT and SCR.
16. Draw schematic arrangement of a solenoid value operated cylinder piston assembly. Discuss the motion of piston between two extreme positions by drawing the control circuit.
17. Explain how the speed of a wound rotor induction motor can be controlled using logic elements.
18. Draw control circuit for Planer machine and discuss its working.
19. Explain working of a shift register using JK flip-flops.
20. If it is desired to build a 10-bit shift register, how many packaged 4 bit shift registers are needed ? Draw a schematic diagram showing all the interconnections between the packages.
21. Explain the action of a BCD-to-decimal decoder.
22. What is the formal name of a mono-shot ? Explain what a mono-shot does.
23. What is the function of clock generator in industrial circuits ?
24. Draw symbols for down-counter and Encoder and explain their working.

12

Programmable Logic Controller

12.1 INTRODUCTION

The control requirements of industry were served well for many generations by relays, drum switches, mechanical (physical) timers and counter etc. The relay control circuits had a disadvantage that when the control requirements change, relays had to be added or removed and rewiring was required to be done. This was time consuming and tedious process. In extreme cases, such as in Auto industry with the change in the model of the automobile being manufactured, complete panels had to be replaced, since it was not economically feasible to rewire the old panels. Also some control functions required could not be easily achieved using relay circuits. Also the increasing sophistication and complexity of the control systems in industry required more faster acting control elements. The electronic industry responded to this need of the industry and developed modular solid state electronic devices. These devices were faster, had low power consumption and eliminated much of the hand-wiring, but brought with them a new language. The language consisted to AND gates, OR gates, NOR gates, OFF return memory, J-K flip flops, and so on.

Static control circuit using logic gates and other solid state devices also had some disadvantages. Although the circuits were faster but reliability was not as expected. Noise signals could cause the control circuit to malfunction. Solid state devices did not work well at high temperatures encountered in industry. Also static control was economically not feasible for small control requirements. Alteration or modification in an existing circuit was not easy. It required the change in copper track connections and addition or removal of solid state devices. Trouble shooting was difficult as compared to the relay circuits. The above mentioned disadvantages and the reluctance of the technicians to learn a new language comprising AND, OR gates etc. and the advent of microprocessor gave industry what is now known as Programmable Logic Controller (PLC). Internally there are still AND gates, OR gates, and so forth in the processor but the design engineers have preprogrammed the PLC so that program can be entered using RELAY LADDER LOGIC.

The first PLC was invented in 1969 by Richard Dick E. Morley, who was the founder of the Modicon Corporation.

The PLC consists of a programming device (Keyboard), processor unit, power supply and input/output interface. At this point you will wonder, "is PLC a computer ?". The answer to this is 'Yes' PLC is a computer but designed for specific application. There are thus similarities and also some major differences between a PLC and a computer. Some differences between PLC and computer are:

1. PLCs are designed to be operated in industrial environment with wide range of ambient temperature, vibration and humidity conditions. It is not effected by the electrical noise present in the industrial environment.
2. In computer, the inputs are floppy drives and CD Roms and output is a printer, but in PLC the inputs are signals from control elements like push-buttons, limit switches, temperature switches, pressure switch and transducer etc., installed on the machines to be controlled. Also the output are final control elements like contactors, solenoids, positioning valves, indication lights, an so forth.
3. The PLC is not a disc based system like PC. With a disc based system there is a continuous checking of what to do next. With a PLC the answer of what to do next is inherent, there is no consulting. The PLC program is stored in battery backed RAM or EPROM.
4. Another important difference between PLC and PC is that the PLC contains the operating systems and application programs in ROM memory. The operating system does not have to load an application program, as it is already in ROM. It is difficult to differentiate between PLCs, 'BIOS', operating system and application program.
5. PLCs are designed to be operated in industrial environment with wide range of ambient temperature, vibration and humidity conditions. It is not effected by the electrical noise present in the industrial environment.
6. Another major difference between PLC and computer is the programming language. PLC is not programmed in one of the high language used for programming a computer. As PLC is designed to be operated by plant engineers and maintenance personnel with limited knowledge of computers, it is designed to be programmed using RELAY LADDER LOGIC. However some PLCs are available which can be programmed using FORTRAN and BASIC, but relay ladder logic programming is the most popular. Some PLCs are also programmed using, Boolean Algebra, Satement lists and Control system flow chart languages.
7. Another major difference is that troubleshooting is simplified in most PLCs because they include fault indicators, blown-fuse indicators, input and output status indicator, and written fault information that can be displayed on the programmer.

From the above discussion, the programmable logic controller (PLC) can thus be defined as follow:

It is a solid state system, with a programmable memory for storing instructions to implement specific functions such as logic, sequencing, timing, counting and arithmetic to control machine and processes.

A typical PLC can be divided into five components. These components consist of the processor unit, memory, power supply, input/output section (interface) and the programming device. Some manufacturers refer to the processor as a C.P.U. or central processing unit. The components are shown in Fig. 12.1.

The power supply is required to convert 240 volts AC voltage to the low voltage DC required for the logic circuits of the processor and the internal circuits of the input and output modules. DC power for the input and output devices, if required is generally provided from a separate source.

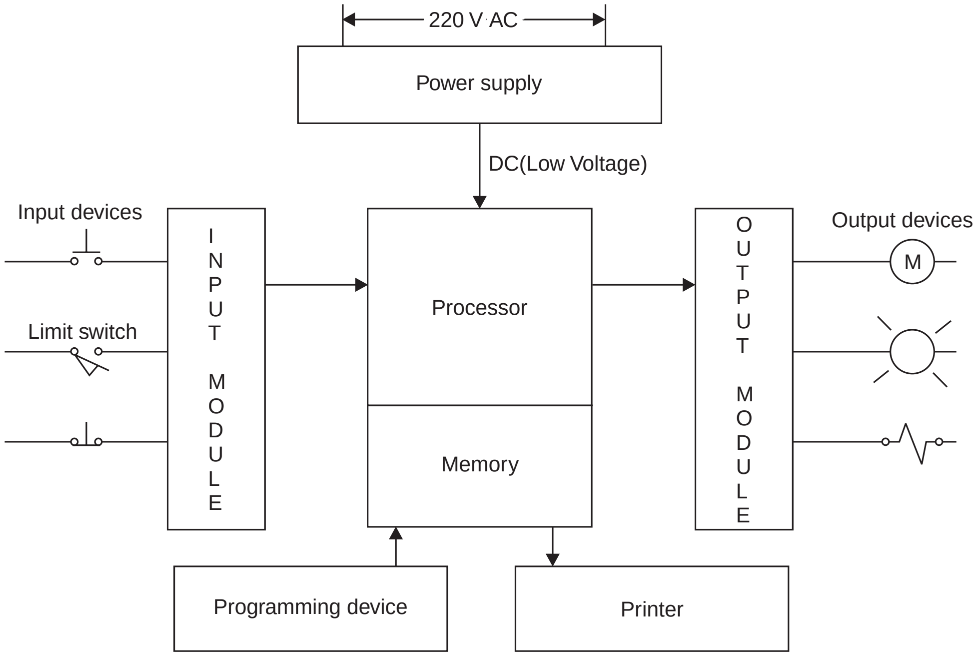


Fig. 12.1 Components of a programmable logic controller

The input module and output modules are referred to a I/O section (I for input and O for output). The real word input devices like push buttons, limit switches, analog sensors are wired to input module and real word output devices like contactors, solenoid valves indicator lights, positioning valves etc., are wired to the output modules. Real word input and output devices are of two types: discrete and analog. Discrete I/O devices are either ON or OFF (open or closed), while analog devices have infinite number of possible values. Examples of discrete input devices are pushbutton and limit switch while analog input device are temperature probes, Pressure transducers etc. which gives varying voltage and current. The input from the analog input device is converted by the analog module called Analog-to-Digital Converter (ADC) into a proportional binary number and stored in memory of the PLC for further use by the processor.

Discrete output devices like contactors, solenoid valve coils, indication lamps are either energised or de-energized, but Analog output devices require varying current or voltage to control the output. Example of analog output device is the positioning valve, which gives variable opening of the valve depending upon the variable voltages/current applied to the valve which is obtained using the Digital-to Analog Converter (DCA) as the output module.

The processor unit operates on low DC voltage of 5 volts. Input modules thus contains circuitry that converts input voltages of 120-240 V AC or 0-24 DC, etc., from discrete input devices to low level DC voltage typically 5 V DC. Analog input modules converts the 4-20 millampere signals from sensors to low-level DC voltages for the processor unit. Similarly, the output modules change low level DC signals from the processor to 120-240 AC or low level DC voltages or give output currents in range 4-20 millampere.

The programming device for a PLC can be a Hand-held programmer, Dedicated programmer or Personal computer. The program is entered using Relay Ladder Logic, Statement Lists or Control System flow charts but the most popular method of programming is the Relay Ladder logic.

The hand-held programmer uses either LED (light emitting diode) or LCD (liquid crystal display). The hand-held programmers are small, light weight and convenient to use in the field. They just look like a small calculator with small display windows. The small display capabilities limits its use for reviewing the program and trouble shooting.

Dedicated programmers use a standard video display terminal (VDT) and keyboard for entering and displaying the program. Large video screen makes the viewing, and trouble shooting of program easier. They however are even more expensive than the personal computer, as they are designed-to operate in the industrial environment.

Personal computers have become the most popular programming device today due to its lower cost and more versatility than the dedicated programmers. A personal computer can be used to program a PLC using a special software installed on it. Some PLCs require only a software to communicate with PC while others require a special hardware communication card also in addition to the software installed on PC. Nowdays these software are windows based and are very user friendly. Using a PC for programming offer other advantages also as number of programs can be stored in the hard disk of the PC and other softwares like spread sheets, word and graphics can also be used.

12.2 INPUT/OUTPUT SECTION

The processor in PLC operates at a control voltage of 5 V DC. It is thus essential that input signals to the processor from input devices be of 5 V DC. We however cannot energies the input devices at 5 V DC because, the input devices may be at a appreciable distance from PLC. Thus there would be a voltage drop. Thus input devices are energized generally at higher DC or AC voltage. The input signals from the devices thus are required to be stepped down to 5 V DC. This is accomplished by using input modules.

The output devices to be energised like solenoid coils, indicator lights etc. are to be energized generally at 110V/220V A.C. The output signals from processor however will be 5VDC. Thus to interface the processor with output devices, output modules are required. Output modules will convert the low voltage signals from processor to proper voltage level required to energise the output devices. Thus all the different types and levels of signals (voltage and currents) used in the control process are interfaced in the I/O section.

The I/O section generally can be divided into two categories; fixed I/O and modular I/O.

12.2.1 Fixed I/O

PLCs with fixed I/O come in a complete unit that contains the processor, I/O section and the power supply. The I/O section contains a fixed number of inputs and outputs, all of which have the same voltage level (120V AC, 24V DC, or 230V AC). For example the Allen Bradley SLC 150, PLC shown in the Fig. 12.2 has 10 discrete inputs and 12 discrete outputs of 24 V DC. As mentioned earlier discrete type I/O signals are ON or OFF and do not vary in level. When a limit switch connected to 24 V DC is ON, the signal to the input section will be 24 V and when the switch is open it will be OV. Discrete I/O is sometimes also referred to as Digital I/O as digital signals also have two levels, high and low. Once digital signal is high, its level remains constant and it does not change. An analog type signal on the other hand will vary in magnitude and will be constantly changing based on control variables in the process. A pressure transducer that sends a 20 milliampere signal at 500 psi or a 10 milliampere signal at 250 psi is an example. Many manufacturers offer analog expansion units that can be added to their fixed I/O, PLCs.

The cost of PLCs are nowadays so competitive that any control process which uses a small number of relay and timers can now be controlled using a small PLC. Fixed I/O PLCs are also referred as "Shoebox" or "brick" by manufacturers due to their shape and size. The SLC 150 PLC shown in Fig. 12.2 also has the provision for adding a analog module.

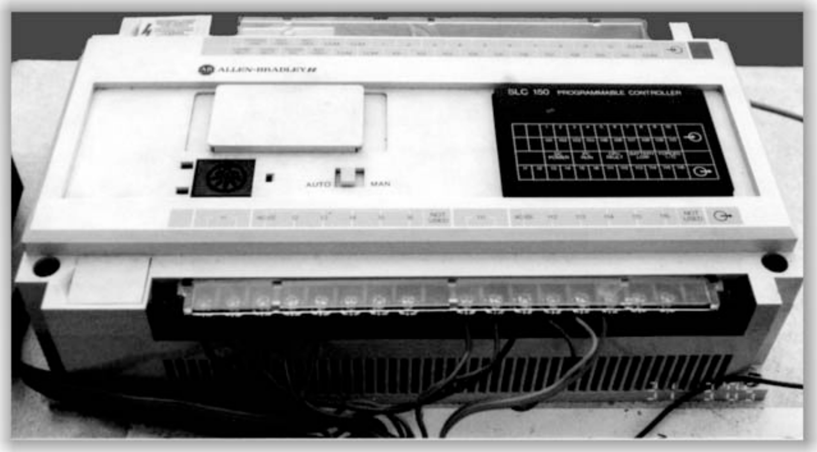


Fig. 12.2 Photographic view of a PLC with fixed input/outputs

12.2.2 Modular I/O

In modular type of I/O, different types of module, discrete, analog or special are housed in a Rack or chasis having a number of slots. Each module is inserted in a slot. Rack or chasis come in many size for example 4, 8, 12 slots. Generally the first slot contains the power supply and is numbered 0, the second slot contains the PLC and in the rest of the slots, different types of input and output modules are inserted. The back panel of the I/O rack contain a printed circuit board having connectors for each slot, into which the individual I/O modules are inserted. The proper alignment while the modules are inserted is provided by guides in the slots on both upper & lower side. Racks that contain I/O module and the processor are referred to as local I/O. Racks that contain I/O modules, power supplies, remote I/O communication cards and located away from the local I/O are refered to as remote I/O. The number of remote I/O racks that a

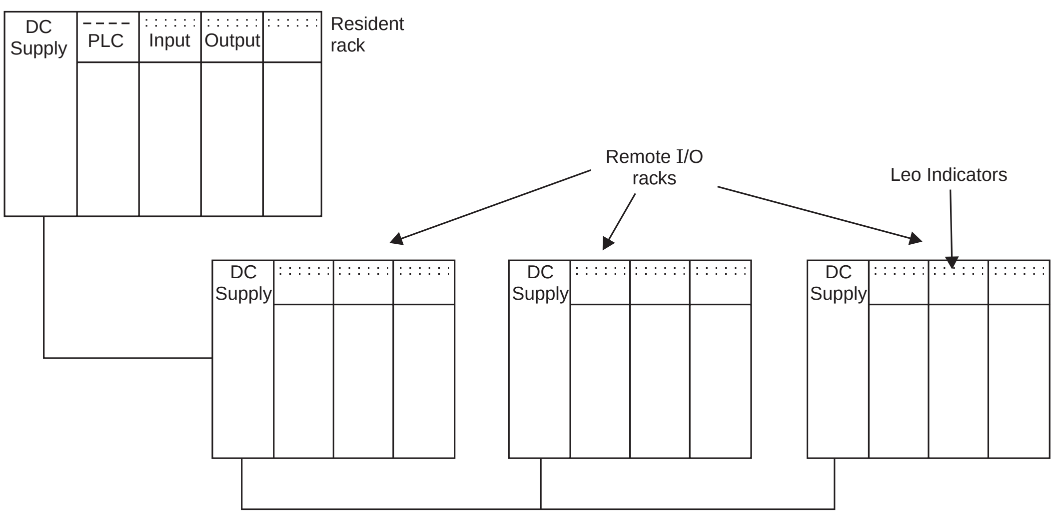


Fig. 12.3 Local Rack with processor and three Remote I/O racks

processor can control varies with each manufacturer. The communication between the remote rack and the processor is accomplished using several different types of communication methods like co-axial cable, twin axial cable, shielded-twisted pair or by fibre optical cable if distance is more and electrical noise is also a consideration. Fig. 12.3 shows a local rack and three remote I/O racks.

An Allen Bradleys modular type of PLC is shown in Fig. 12.4. The first slot contains the power supply, second one contains the SLC 500 PLC, third one contains discrete input module, fourth slot contains discrete output module, fifth and sixth slots contain analog input and analog output module while slot number 8 is empty.

Fig. 12.4 Photographic view of Allen Bradleys Modular type PLC and Input/Output modules.

Input and output devices connected to input and output modules must have a address so that the processor knows where which input and output device is located. Within each rack individual input and output device connections must have a distinct address. Allen Bradley for example uses the rack number, location of a module in the rack (i.e., slot number) whether input or output device is connected, to determine the device address. Racks normally have jumpers or switches that have to be set or configured in order for rack to communicate with the processor. A common type of switch used for rack configuration is called DIP switch (Dual-in-line package), which are intended for use on printed circuit boards. These switches are either ON or OFF. These switches when set in proper sequence, are used to assign an address to a rack, such as Rack 1, Rack 2. etc. DIP switches are used for other processor functions also. For example a Analog current input module can be configured as Analog voltage input module by changing the DIP switch positions provided on the printed circuit board of the module. DIP switch settings are specified in the installation manual supplied by the PLC manufactures.

12.3 DISCRETE INPUT MODULES

Discrete input modules are available in wide range of voltages for various applications. Some more common voltage modules are 120V AC, 240V AC, 24VDC. The cost of a input module depends upon the number of input terminals available for connecting the real word input devices like push-buttons, Limit switches etc. Common sizes available are 8, 16 and 32 point. Nowadays, optically coupled input and output modules are used as they provide isolation of processor circuit from the real word input and output devices which may be energized on higher level voltages.

12.3.1 AC Discrete Input Module

A typical AC input module for 8 inputs is shown in Fig. 12.5. L1 is the hot terminal of AC supply and L2 is the neutral.

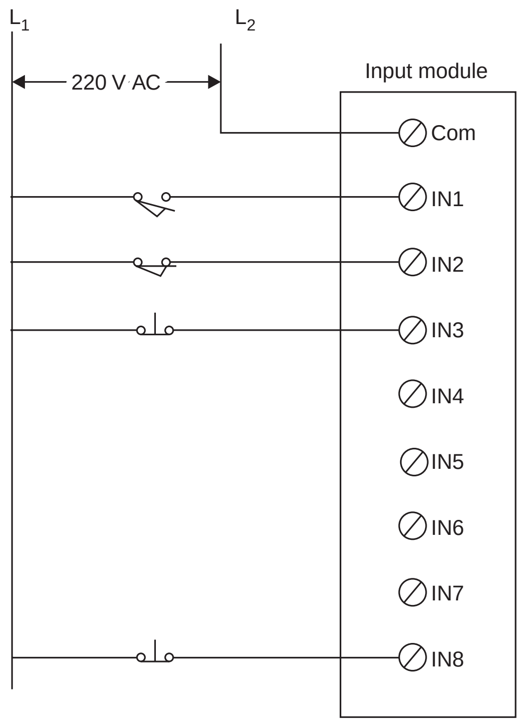


Fig. 12.5 Connection for an 8 input AC discrete input module

The enclosure of the input module shown contains a printed circuit board on which eight number of circuits shown in Fig. 12.6 are there for each of the eight individual inputs.

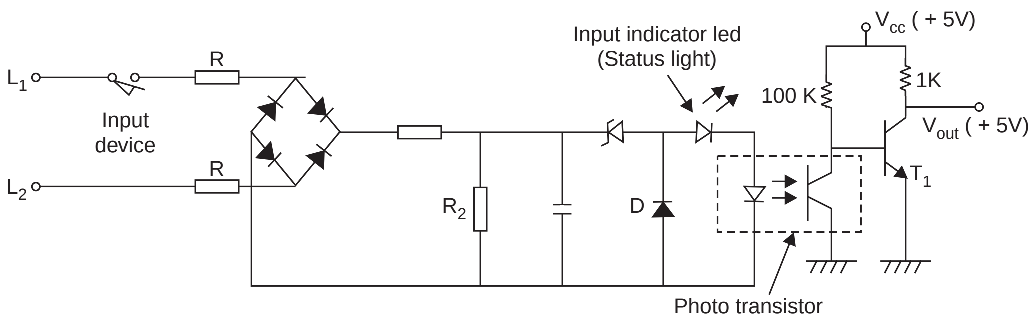


Fig. 12.6 Simplified AC input module circuit with indication light for on input terminal

The input module has a common connection for the neutral or grounded potential (L_2) for AC modules and the negative (–) for DC modules. To wire the input devices to AC input module one terminal of all the input devices are connected to hot terminal (L_1) of the ac supply and the other terminal of each input device is connected to the input terminal on the module.

Resistors are used to drop the incoming voltage, then a bridge rectifier is used to convert the AC input voltage of DC. Next a filtering circuit is used to condition the DC and also to provide a delay in sending the signal forward. The delay is required to safeguard against electrical noise signals generated due to bouncing action of limit switch.

When the input device closes, LED emits light which falls on the photo transistor and turns it ON. Turning ON of photo transistors will switch OFF the transistor T_1, thus + 5V appears at the Vout terminal of logic circuit, which is communicated to the processor and the information is stored as binary 1 in the memory location assigned for the status of input device. By employing this type of optical coupling, or isolation, there is no actual connection between the input device and the processor. This eliminates any possibility of the 240V input voltage from coming in contact with and damaging the low-volage DC section of the processor. Optical isolation also protects the processor from electrical noise, voltage transients or spikes.

Status indication, whether the input device is ON or OFF is provided by another LED used in the optically coupled circuit. All the eight LED for this purpose are provided on the top of the input module (see Fig. 12.6). The status light is lit, when the input device is closed and is OFF when the input device is open. Status lights are very helpful for troubleshooting, as just looking at the status lights, technicians know the status of all input devices.

12.3.2 DC Discrete Input Module

A typical DC input module wired to input devices is shown Fig. 12.7(*a*).

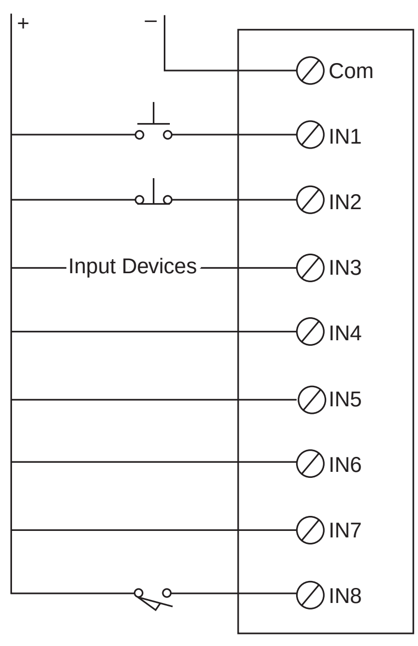


Fig. 12.7 (*a*) Connections for a discrete DC input module

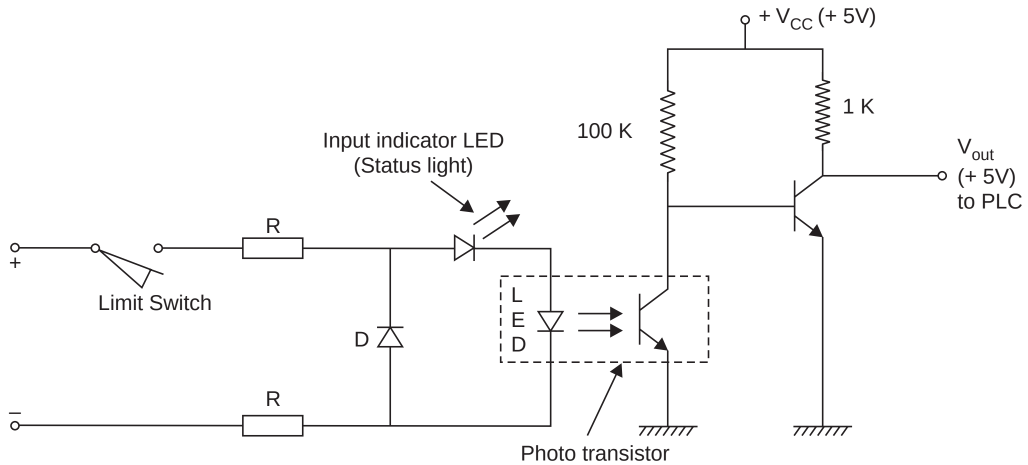


Fig. 12.7 (*b*) Simplified circuit for one terminal of a DC discrete input module

The enclosure shown in the Fig. 12.7 will contain eight number of electronic circuits as shown in Fig. 12.7(*b*), which are similar to the circuit shown in Fig. 12.6 except that there is no bridge rectifier required, as the voltage used to energize the input device is DC.

12.4 DISCRETE OUTPUT MODULES

Discrete output module can be AC or DC type. Both types are available in a wide range of voltages. The function of discrete output module is to energies the output device such as motor starter coil, pilot lights, solenoids valve etc., connected at its terminal, when the processor places a binary 1 in the memory location assigned for that particular device.

The cost of a output module is proportional to the number of terminals provided for connecting output devices. The standard terminals available are 8, 16 and 32. Output module has a continuous current rating for each terminal as well as continuous overall rating for the module. A surge rating is also specified, indicating the maximum current that can be allowed to flow for a specific time. A typical current rating of a 240 V AC output module would be 1 amp maximum, continuous duty with a surge current rating of 3 ampers.

The output module are provided with fuse to protect against over current, short circuits and ground faults. The number of fuse used vary with each manufacturer. In some modules only one fuse is provided for all the outputs while in others individual fuses are provided for each output. Some manufacturers do not provide any fuse, so external fuses must be connected. Blown fuse indication is also provided on most PLCs. Some PLCs have only one blown-fuse indicator while others have blown-fuse indicator for each individual output thus simplifying the troubleshooting.

Status lights are also provided in the modules to indicate the status of any particular output. Some modules have two status lights for each output point. One is referred to as the logic light, and the other as the output light. When the logic lamp is lit, it indicates that logic to turn on the output device has been sent from the processor. When the output light is on, it indicates that current is actually flowing to the output device. Status lights are thus very important tools in troubleshooting, but it should be ascertained what the status lights indicate.

12.4.1 AC Output Module

AC output module standard voltages are 120 V or 240 V as most industrial solenoid valves and starter coils are designed for this voltage. A 8 circuit AC output module for 240 volts is shown in Fig. 12.8. One wire of each output device is connected to the neutral (L_2) of the AC supply.

The other terminals of output devices are connected to the output terminals of the module. The hot wire (L_1) of the AC supply is connected to the common terminal available on output module.

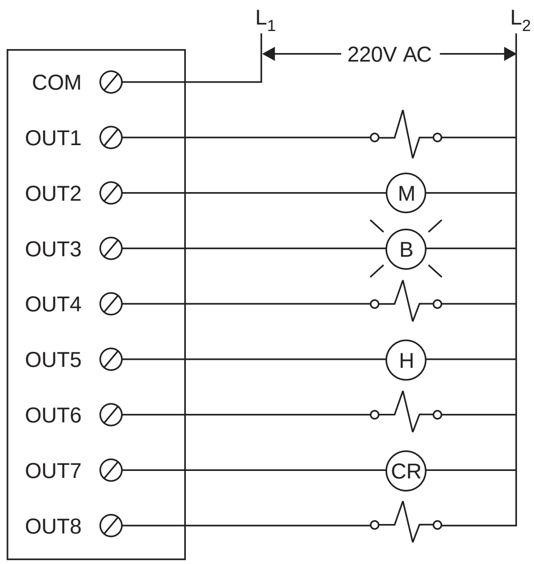


Fig. 12.8 Connection of output devices to a output module

The internal circuit for one terminal of the output module is shown in Fig. 12.9. In a 8-Point module, there will be 8 such type of circuits mounted on a printed circuit board. Either a SCR or a TRIAC is used as the switching device.

A circuit using SCR is shown in Fig. 12.9, when a signal from processor appears for energisation of a solenoids coil, the RC potential divider is energized and capacitor will start charging. At a particular value of capacitor voltage, V, T is turned on and capacitor gets discharged through it. A pulse thus gets applied to the primary of a pulse transformer connected to the base of UJT. This pulse is transferred to the secondary side of the transformer and gets applied between gate and cathode of SCR. The SCR will trigger on and will start conducting if its anode is positive with respect to cathode. To achieve current flow through load on both half cycles of ac voltage, a bridge rectifier is used to provide a continuous dc supply to the SCR. Instead of a pulse transformer an optically coupled photo transister can also be used to energies a TRIAC for switching on the supply to output device.

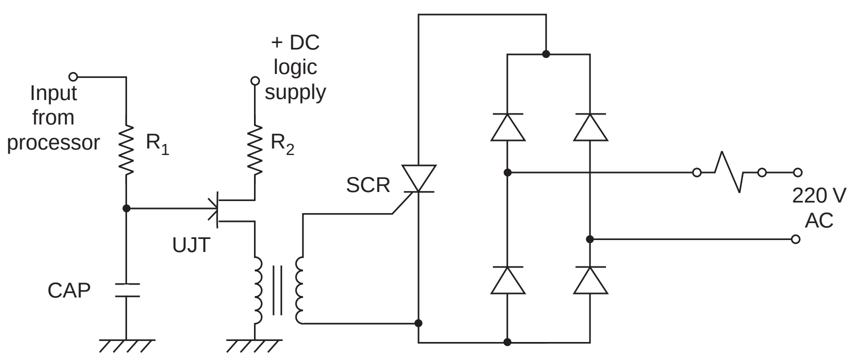


Fig. 12.9 Simplified circuit for one terminal of an output module

12.4.2 DC Output Modules

DC output modules are available in ranges from 12-240VDC. Suitable voltage & current range has to be selected by the consumer according to the load requirements. The operation of a DC output module is similar to that of an AC module, except that instead of SCR or TRIAC, power transistor will be used to switch on power to the output device. When connecting the output device to the output module, one terminal of all the output devices are connected to the negative of the DC supply and +ve terminal is connected to the common terminal on the module. A typical DC output circuit for each terminal of the output module will be as shown in Fig. 12.10.

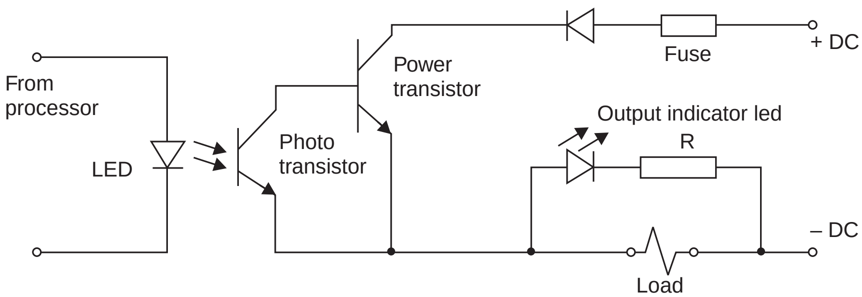


Fig. 12.10 Simplified DC output module circuit

The power transister has a quicker switching capability than the SCR and TRIAC used in AC output modules; therefore the response time of DC modules is faster than the AC modules.

12.4.3 Rating of Output Modules

Output modules have limited current ratings. Thus, when larger loads are to be energized, a interposing relay is used, which is a standard control relay, having small inrush and continuous current value. The contacts of the control relay are generally rated at 10 amp. The contacts of the relay are used to energise a larger size contactor used for motor starter or heating loads. The connection for energising a large motor using interposing relay is shown in Fig. 12.11.

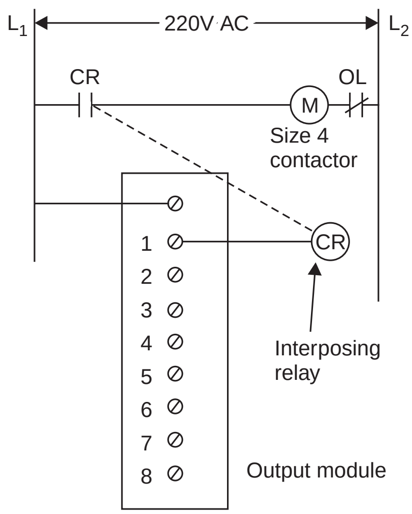


Fig. 12.11 Interposing relay connections

12.5 ANALOG I/O MODULES

Analog input and output modules are used in process control where variables such as temperature, light intensity, speed, pressure, position and flow measuring instruments etc have to be read and output devices like positioning valves, strip chart recorders, actuators, displays and variable drive systems have to be energized. Most of the todays analog I/O modules are available in three ranges:

(1) 0 to 10 volts (DC) also called unipolar

(2) –10 to +10 volts (DC), also called bipolar and

(3) 4 to 20 milliampers (mA DC), also refered to as current.

The last version can, many times be expressed as 1 to 5 volts (DC) with a simple reconfiguration of the module.

Input modules are available in configuration of two, four and eight channels. Output modules are available in configuration of four or two channels. Newer analog I/O modules provide the mixing of analog input and output on one module.

In analog input module, the analog signal from the sensing device is converted to 8 bit or 16 bit binary values for storage in the PLC processor memory with the help of a analog to digital (ADC) converter. The analog output module changes the 8 bit or 16 bit binary from the PLC memory to analog value using the Digital to Analog (DAC) converter. A typical mixed type of analog I/O module having two input and two output channels is shown in Fig. 12.12.

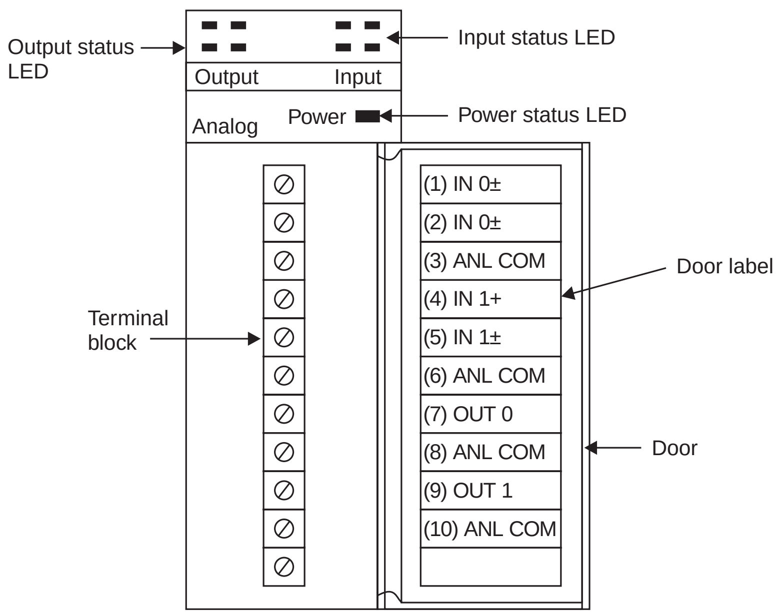


Fig. 12.12 Analog input/output module

The module shown contains a openable door exposing the terminal block to provide connection for the analog input and output channels. It is specifically designed to interface with analog current and voltage input signals. The channels can be wired as either single-ended or differential inputs. There are DIP switches on the circuit board of the module for selecting voltage or current input.

Analog modules are generally classed by their resolution, which is their ability to convert the analog information to digital form in the case of an input, the reverse for an output. This resolution is expressed in bits: for examples 16 bit or 8 bit resolution. It should be clear that higher the resolution, the more accurately an analog value can be represented digitally.

Here we have discussed some basic input/output modules for a basic understanding only. Each PLC manufacturer however has a long list of modules they market for common or specialized applications. An example of specialized module is high speed counting and position sensing module, A PLC manufacturer representative should be contacted for a full and complete list of modules that are available.

12.6 SAFETY CIRCUIT

PLCs of today are though very rugged and dependable, but where safety is concerned, it is recommended by the manufacturing associations not to solely depend on the solid-state devices or PLC program for removal of power to output devices on emergency stop. It is thus recommended, that a hard-wire emergency Stop push button should de-energies the power to output module. Thus safety circuit as shown in Fig. 12.13 is recommended.

A control relay designated as master control relay (MCR) is used to de-energies the output devices when emergency stop push button is pressed. The contact of MCR relay in the neutral will de-energise all the output device on emergency stop and MCR contact in line will de-energise all inputs and power supply to output module. The MCR contact in line is however optional as normally the inputs are kept energized for ease in troubleshooting.

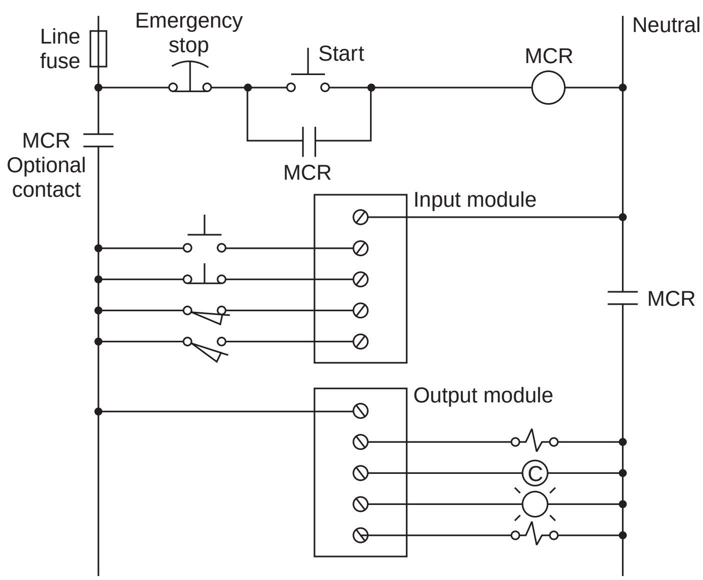


Fig. 12.13 Safety circuit using physical master control relay

12.7 PROCESSOR UNIT

The processor consists of a microprocessor, memory chips, circuits necessary to store and retrieve information from the memory, and communication circuits required for the processor to interface with the programmer, printer and other peripheral devices. Block diagram for Processor unit is shown in Fig. 12.14. Memory of the Processor has been shown divided into subsections for easy understanding. Microprocessor and its associated circuits have been referred to as Central Processing Unit (CPU).

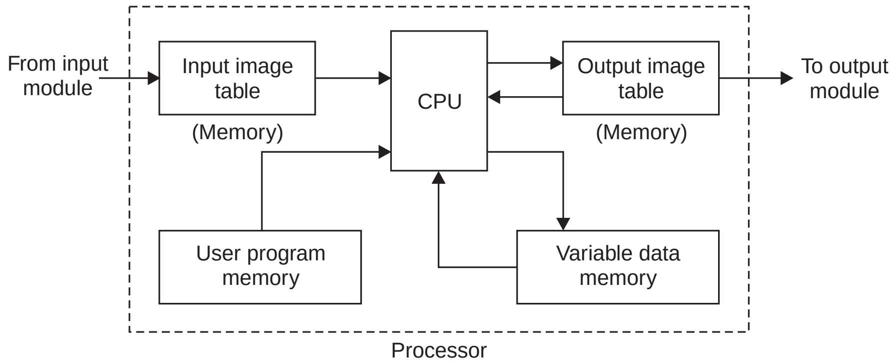


Fig. 12.14 Block diagram representation of a processor unit

The processor may be part of the self-contained unit housing processor, input and output modules and power supply. A Allen Bradley make SLC 150, is a self-contained PLC (refer Fig. 12.2). The porcessor may be modular in design and plug directly into the I/O rack (refer Fig. 12.3). In the extreme left is the dc power supply. The processor is inserted into the first slot of the rack. The Fig. 12.3 shows a SLC 5/02 CPU in the first slot. In other slots modular input and output modules are installed. This whole assembly of power supply, processor and input/output module comprise the programmable logic controller.

The processor is the brain of programmable logic controller. It is the decision maker and controls the operation of the machine to which it is connected. The processor controls the output devices connected to output modules based on the status of the input devices and the program that has been entered into the PLC memory. The processor is also referred to as central processing unit or CPU by some authors. Here the sub-section of the processor which actually performs program execution is called CPU.

The microprocessor used in the processor depends upon the number of inputs to be monitored and number of outputs to be controlled. Larger the number of inputs and outputs, and more complicated the control functions to be performed, the more powerful the microprocessor required. Various functions of micro processor are:

1. Monitors the status (ON or OFF) of the input devices.
2. Solves the logic of the user program stored in the memory.
3. Controls the output devices (ON or OFF) based on status of input devices and user program.
4. Communicates with other devices like hand held programmer, personal computers etc.
5. Manages memory and update timers, counters and internal registers.

When the micro processor executes the above task in sequence given above it is called the processor scan.

When a PLC is powered up, the processor runs an internal self-diagnostic or self-check, prior to entering the mode, it was left in, when power was last shut down. During the diagnostic test, if it is detected that any part of processor is not functioning such as faulty memory, improper communication with I/O section etc., then a message is displayed on the display window of Hand-held programmer or VDT screen of programming terminal.

PLC can be put in various modes of operation. Some typical PLC modes of operation are:

1. CLEAR program memory Mode
2. PROGRAMMING Mode
3. RUN Mode
4. TESTING program mode
5. DIAGNOSTIC test mode
6. Enter/Change Access Code.

When PLC is put in CLEAR memory mode, the user program stored in PLC memory can be cleard. Now all the memory is free for entering a new program. A new program can now be entered by bringing the PLC into PROGRAMMING mode and then program instructions are entered one by one in sequence. After entering the program, the program execution can be checked by putting PLC in TEST program mode. In test mode, PLC executes the user program but does not energise the outputs, only LED displays for outputs are energised. Thus program working can be checked without actually energising the outputs. This avoids a prospective damage to machinery on account of incorrect program. The machine can be run continuously by bringing the PLC in RUN mode. In RUN mode, the PLC first reads the status of input devices and store them in the memory. Then it executes the user program instructions one by one and if any outputs are to be energized, the memory location for that output device is updated by storing binary 1 at that memory location. When whole of the program is executed, the output devices are energised. After this the PLC will communicate with any connected devices like hand-held programmer, personal computer, and will also perform any necessary memory management (housekeeping). Memory management will include updating timers, counters and internal registers etc. This four-step process called processor scan is repeated over and over. The scan time of PLC is in milliseconds. The scan time can vary from a fraction of a millisecond to 100+ milliseconds depending upon the size of the program. Each manufacturer lists the scan time based on the use of 1K (1024 words) of program memory. A typical scan time is 3-5 msecs per 1K (1024 words) of memory used. A typical processor scan is shown in Fig. 12.15.

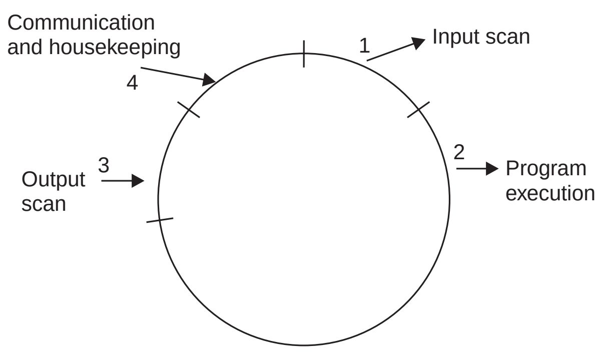


Fig. 12.15 Typical processor scan

It must be noted that output devices are energized all together during the output scan rather than energizing them while the program is being executed. This is because, in general the load devices themselves are hopelessly slow compared to the scan cycle of the PLC. For example a real solenoid might require 30 to 50 milliseconds to get magnetically flushed and pull in its armature. This much time is enough for the PLC to scan its whole cycle several times. Thus, if during program scan, a solenoid is to be energized the signal has to be sent to the above said duration and program execution is halted. Thus under these circumstances, instead of delaying the program execution, the outputs are energized together in output scan after the whole of program is executed. Waiting for the output scan to energies outputs is soon enough in most of the industrial control applications.

In some rare applications, it may be necessary to energies an output immediately during user-program execution. To facilitate this, advanced PLCs have a instruction called immediate output instruction. This instruction temporarily suspends the normal business of the program, and energise the required output device. After the energisation of the output device, the normal execution of the user program is restored. This type of processor scan is shown in Fig. 12.16.

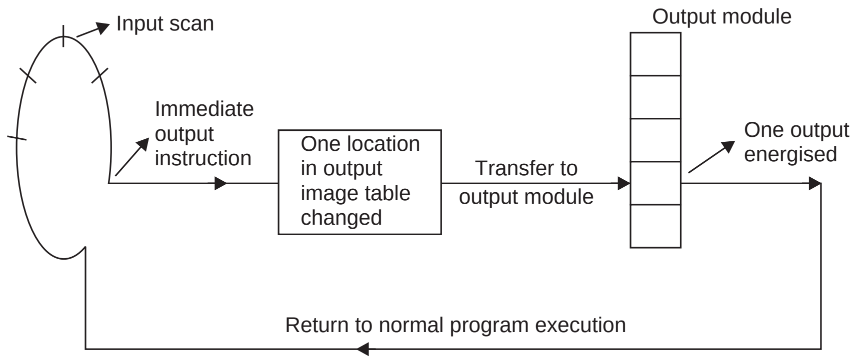


Fig. 12.16 Processor scan with a immediate output instruction

Similarly advanced PLCs also provide a special instruction called immediate input instruction, which can be used to update the status of a particular input device in the input image table, during the execution of the user program, just prior to the user program instruction which uses the status of that input. The use of this instruction is necessitated in a control situation, where it really matters if the input has changed during the few milliseconds that may have elapsed between the last input scan and the point in the user program, where the critical instruction is encountered. The input immediate capability during a processor scan is shown in the Fig. 12.17.

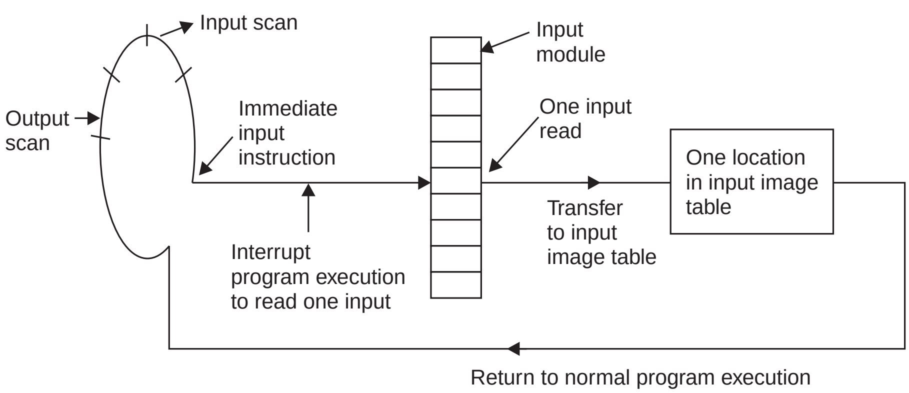


Fig. 12.17 Processor scan with a immediate input instruction

12.7.1 Internal Self Diagnostic System

During normal operation, the processor scan is completed and started again in an orderly predictable cycle. The processor should not stuck while scanning the user-program or for some other reason is unable to complete the current scan. Being unable to complete the scan means that the processor has no control over the real-word outputs. Real word outputs without control might be left running when they were to be stopped. This could spell disaster. A watch dog timer is used to insure that the processor complete each scan in a timely manner.

The watchdog timer is preset to an amount of time that is slightly longer than the scan time would be under normal conditions. At the start of each scan, the watch dog timer is turned ON and starts to accumulate time. If the program is correct, the program scan will be complete prior to the time set on the watchdog timer, and at the end of each scan, the watch dog timer is reset to 0 (zero). If for some reason the program scan is not completed in the allotted time, indicating that there is a problem with the program, the watchdog timer will time out, which puts the processor into a faulted condition and all outputs will be turned OFF. The range of the timer is software selectable (adjustable) on many PLCs.

A program that faults due to watchdog timer timing out may have become caught in an endless loop within the porgram. This could be the result of programming problems such as the use of too many uncontrolled backward jumps where there is no defined jump out of the loop. Using subroutines where too much time is spent within one or multiple subroutines, could also result in the program scan time exceeding the watchdog timer time value. In some instance, lengthening the watchdog timer preset value can solve the problem.

In addition to the scan time problem detected by watchdog timer, other processor errors that are detected by the internal diagnostic system are: processor hardware problem, processor memory problem, communication problem, expansion unit problem, EEPROM module problem. The problems related to programmer and programming are also detected by the internal diagnostic system which are as follows. Incomplete rung (no output instruction), invalid address for instruction, user memory exceeded, branch error (short circuit), branch error (incomplete branch), invalid access code (password).

12.7.2 Memory Types

Memory types will be discussed here in a generalized way for basic understanding. Memory chips used in the processor can be separated into two distinct groups: volatile and non volatile. A volatile memory is one that loses its stored information when power is removed. Even momentary loss of power erases any information stored or programmed on a volatile memory chip. A non volatile memory has the ability to retain stored information when power is removed accidentlly or intentionally.

The most common type of volatile memory is **Random Access Memory (RAM)** also refered to as read/write memory, as information can be written into, or read from this memory. Random access means, any memory location can be accessed or used easily. RAM is used for both, as user memory for storing the program and as storage memory for storing of status of input and outputs and other data required for execution of the program. As RAM is volatile, it must be backed up with a battery to retain or protect the stored program. Various forms of RAM are MOS, HMOS and CMOS-RAM (complimentary Metal Oxide Semiconductor) is one of the most popular type of RAM. CMOS-RAM is popular as it has a very low current drain when not being accessed (15 micro amperes) and the information stored in memory can be retained by as little as 2V DC. Back-up power for CMOS-RAM is provided by a replaceable battery assembly. The lithium battery provides back-up power for approximately 2-3 years. However in the absence of battery, there is a provision of a standard back-up power provided by a capacitor which can hold or protect the program for 1-2 weeks.

Non-volatile memories are memories that retain their information or program when power is lost, and they do not require battery backup. A common type of non-volatile memory is Read Only Memory (ROM). Read only means that information can be written only once and subsequently, that information can only be read but cannot be changed. In PLC processor, the ROM used contains the program for internal use, of the PLC. It is this program, which makes the PLC different from the ordinary personal computer. This programme cannot be changed. ROM chips can however be changed to upgrade the PLC. Other types of non-volatile memory are PROM, UVPROM, EPROM, EAROM and EEPROM.

EEPROM *i.e.* Electrically Erasable Programmable Read only Memory is also used with PLC to upload program from the RAM of PLC or for loading a program into the PLC. A special Pin Socket is available on the PLC for the EEPROM module. EEPROM is thus used as a nonvolatile backup for the user program RAM. If the user program in RAM is lost or erased a copy of the program stored on an EEPROM, chip can be downloaded into RAM. It is common in some PLCs for the processor to load the program from EEPROM chip into RAM memory each time the processor is powered up or after a power failure. EEPROM is a chip that can be programmed using a standard programming device and can be erased by the proper signal being applied to the erase pin.

Memory in PLC can be subdivided into sub-section for easy understanding. The subsections are input image table, output image table, user-program memory and variable data memory (refer block diagram for processor unit Fig. 12.14).

12.7.3 Input Image Table

It is a portion of the processor memory, where the status of input devices whether open or close is stored. Every single input terminal of a input module is assigned a particular location (address) in the portion of memory called input image table. This particular location is dedicated solely to the task of keeping track of the latest condition of its input terminal. If a particular input terminal has 220 volts fed to it, due to closing of input device connected to it, a binary (01) is stored in that memory location allotted to that particular input module. If there is no voltage at the input terminal then binary (0) is stored in that particular location. Thus only one bit is required to store the status of discrete inputs. In case the input module is a analog module then the memory assigned to each input is 8 bits or 16 bits depending upon the PLC.

The memory locations in the input image table thus store the image of the input devices, that is why it is named as input image table. The image of status of input devices is created in the input image table before the processor starts executing the user program, as the status of input devices are the deciding factors in the execution of user program.

12.7.4 Output Image Table

This is another portion of the processor memory, where the each output terminal of the output module is assigned a particular memory location (address). When the processor executes the user program and a particular output is required to be energized a binary (1) is stored in the memory location alloted to that particular output. Thus when the user program execution is complete the output image table updating is also complete. Now all the outputs which have binary (1) stored in their assigned memory locations are energized simultaneously after the last instruction of user-program is executed. This period of the processor cycle in which outputs are energized is called the output scan.

It may be noted that the processor can write to and also read from the output image table as the status of any output being energized may affect the user program in subsequent instructions of user program. However, the processor only reads from the input image table during the execution of the user program.

12.7.5 User Program Memory

This is the portion of the processor memory which is used for storing the program in the form of coded instruction which represents the logic of the functions to be carried out. This programming is done through a key board and the program can be seen on a VDU (Visual Display Unit).

As the instructions are entered through a key board, they are automatically stored as sequential location within the user-program memory. The total number of instructions can range from a dozen or so, for controlling a simple machine, to several hundreds, for controlling a complex machine or a process.

Central processing unit executes the User-program instructions step by step. During execution, if the instruction execution calls for a change at any of the output image table locations, it immediately updates the output image table.

The CPU executes subsequent instructions by taking into account the output conditions, since these often effect later instructions in the program.

It thus becomes clear that the output image table has two functions. Its first function is to receive immediate information from the CPU and pass it on to the output module. The second function is to pass on information backwards to the CPU when any instruction calls for the state (high or low) of a particular output, for its execution.

On the other hand, the input image table has only to acquire information from the input module of I/O section and pass on that information to CPU when the instruction execution calls for any input information. The dual nature of information flow for the output image table is shown by an arrow in the block diagram in Fig. 12.14.

12.7.6 Variable Data Memory

User program instruction can have time settings, counter settings, numeric comparison instruction (greater than, less than etc.). These types of instructions will require storage of data like setting of timers, counters, down counters, etc. The memory which keeps track of these variable data is called variable-data memory. There are five types of numeric data that can be present in the variable-data memory.

- Preset value of a timer—This is the number of seconds for which the timer must remain energized.
- Instant value of a timer—This is the number of seconds that elapses after the timer is energized.
- Preset value of a counter—This is the number that an Up counter must count or the starting number from which the Down counter starts counting down.
- Instant value of a counter—This is the number of counts recorded by an Up counter or the number of counts remaining for the Down-counter.
- Value of a physical variable in the controlled process—This value can be temperature, pressure, flow etc. Such a value is obtained by making measurement with the help of a transducer and converting the transducer's analog output voltage into digital form using Analog to Digital (ADC) converter.

When the CPU is executing an instruction for which a certain data must be known, it fetches that data from the variable data memory. Also, when CPU executes an instruction which produces a numeric value, it is stored in the variable data memory. This two way flow of information is shown by arrows in the block diagram of Fig. 12.14.

12.8 PROGRAMMING DEVICE

Programming device is the control console for the PLC. PLC is operated in different modes like Programming mode, Run mode, Test mode etc., through the programming device. It is through the programming device, that a program is entered into the PLC memory. Editing and troubleshooting of an existing program in PLC memory is also done through programming device. Once the program has been entered into the PLC memory and PLC is brought into Run mode, the programming device may be disconnected. It is not necessary for the programming device to be connected for the PLC to operate, but it can be used to monitor the PLC program while the program is running. Programming device or also called programmer can be of Hand held type, Dedicated desktop type or a computer can be used as programming device. Each of the above type of programmer has its own advantages and disadvantages.

12.8.1 Dedicated Desktop Programmers

A typical dedicated programmer consists of a keyboard, VDT (Video display terminal) and necessary electronic circuits and memory for developing, editing and loading program into the PLC processor memory.

In appearance, the dedicated programmers resembles the personal computer but not in their capabilities. They are not capable of computer functions like running software programs for word processing and spreadsheets. They are however rugged in construction and can withstand the mechanical shock associated with moving the programmer from machine to machine. They can function in the industrial environment under high humidity, high temperature, dust dirt and electromagnetic interference.

The keyboard of the dedicated programmer can be like the keyboard of a computer with raised keys or have sealed touchpad type keyboard suited for the industrial environment. Most dedicated programmer keyboards have electrical symbol keys for normally open normally closed contacts, timer contacts, output symbol, Relay, timer, counter etc. These dedicated keys pertaining to ladder logic program development make programming easier for the technician who are not much familiar with computers. The keyboard also has special function keys that are used for program development and numeric and alpha keys for addressing and labeling the program.

Video display terminals can have screen sizes from 5 to 12 inches, measured diagonally. They are also referred to as CRTs (Cathode ray tubes). When the PLC is put in program mode; and program is entered through the programmer keyboard, the program appears on the VDTs screen as it is entered. The video screen allows to display multiple lines or rungs of the program. This makes the entering and editing of program easy. After the completion of program, it is down loaded from the programmer memory to PLC processor memory. Once the program has been into user memory the PLC is placed in the RUN mode, and thus the program is activated. The programmers VDT now gives the visual display of the program execution. The program instructions which are true are highlighted either by making them brighter of by using reverse video. No matter which method is used this feature of dedicated desktop programmer is a powerful troubleshooting aid.

The above discussed advantages of dedicated desktop programmer are however obtained at a relative high cost. The other disadvantage is that limited models of PLC can be programmed with a particular programmer. It also has limited documentation and graphic capabilities. The physical size of the programmer makes it unsuitable for portability; which is very much required in an industry as PLCs installed on various machines are supposed to be programmed using a single programmer.

12.8.2 Hand-held Programmers

Hand-held programmers resemble a calculator in appearance and is only a slightly bigger. A Hand-held programmer for Allen Bradleys SLC is shown in Fig. 12.18.

Hand-held programmers are thus smaller, cheaper, and more portable than dedicated desktop programmer. They are most suitable for installations, where control functions have to be changed frequently. It is also much easier to connect the hand-held programmer to the processor for changing program parameters or for troubleshooting than to bring the heavier desktop programmer.

The main limitation of the hand held programmer is that, it has a limited display capability. Some hand-held programmer display a Rung of logic with up to four horizontal line, while others display only one line and some do not display any rung at all. The location of cursor in the program in such a programmer is made out from the LED glow for the type of instruction and liquid crystal display of its address and Rung number. The hand-held programmer takes more time to go through the program one contact or one rung at a time and also more keystones are required to enter the program. Fewer functions are possible and it works with only specific PLC model. It has limited access to memory and also has limited or no documentation capabilities.

Fig. 12.18 A hand held programmer

12.8.3 Computer Programmers

A PLC can be programmed using a Personal Computer with the help of a special programming software loaded on the PC and a special card installed on the PC for communicating between PLC and PC. However some PLCs may not require communication card to communicate with PC.

PLC programming software have been developed by PLC manufactureres themselves and also by other companies. The software's developed by a company other than the manufacturer of PLC are referred as "third party software". With softwares available for all major brands of PLCs, the personal computer has now become the most common programming device. These software programs can generally be used with most personal computers in either DOS or Window environment. For example Rockwell Automation, has developed a windows based program called RS logix 500 which can be used to program the Allen Bradleys PLC-5, SLC 500 and Micrologic 1000 and 1500 PLCs. Fig. 12.19 shows a PC with RS logix 500 program installed.

Programming using a Personal Computer provide many of the advantages of the dedicated desk-top programmer, but also provides features not available on most dedicated desktop programmers. The personal computer usually has a colour monitor (VDT), and the monitor shows multiple rungs of program logic, as well as highlighting the circuit elements to indicate status, just like the dedicated desktop programmer. When the program is first developed, it is done in the program mode or also called off line mode. Off line mode means program is being developed in the RAM of the computer memory and it has not yet been loaded into the processor memory. Once the program is developed it is downloaded into the processor memory for testing and verification. For testing, the PLC is put in test mode, in which the

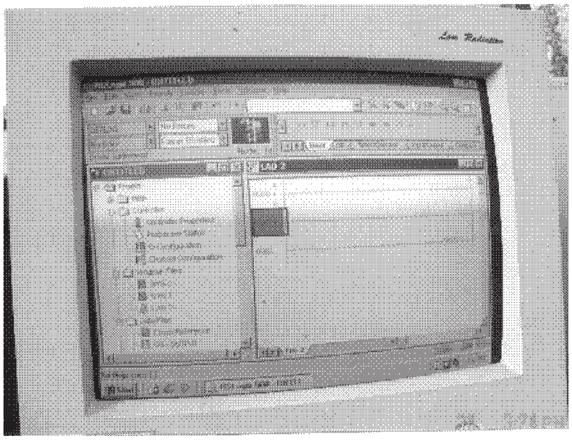


Fig. 12.19 Programming software on personal computer

program is executed but the output devices are not energized. After verifying the proper functioning of program, the PLC is put in RUN mode. If any changes to the program is done while PLC is in RUN mode, it is called ON-line programming. Making changes to the program while the program is running and the driven equipment is operational (ON line programming) must only be done by trained personnel who not only understand the PLC program, but also thoroughly understand the driven machinery or process. To prevent unauthorized access to the software, most of the softwares requires activation key, when the software is turned on. Activation key can be in the form of a hardware key, which is usually connected to one of the printer ports or it can also be in the form of a floppy disk or a password may be required when the software is first started. Some manufactures however do no copy-protect their software and encourage copying and widespread use of their software.

12.8.4 Advantages of Using Personal Computers for Programming

1. The foremost advantage of using personal computer for programming is that the program can be stored in its hard disc or in a floppy disc. If the program in PLC processor memory is lost due to any reason, the program can be restored easily from the hard disc or floppy disc of personal computer.
2. PLC programming software for personal computers provide more documentation capabilities than desktop programmers. Graphic capabilities of the software, provide for developing a flow diagram of the controlled equipment or process, and provide operator alarms and messages from the process information.
3. The software updating can be easily accomplished by loading the new software into the computer hard disk through floppy/CD disk drive. On the other hand a Dedicated desktop programmer requires changes in ROM chips to accomplish updates.
4. The computer has the added ability to interface the PLC software program with other software programs for "cut and paste" program development and editing.
5. PLC programming software used on personal computer have the feature of being able to display Rungs of logic in any order that may be helpful for troubleshooting. This feature though also available on few dedicated programmers but is a standard feature on all computer based software's.
6. Computer provides more flexibility and networking capabilities than the Dedicated Programmers for networking multiple PLCs.

7. Availability of small laptop computers provide an added flexibility in the use of computer for programming PLCs.
8. Low cost when compared to dedicated desktop programming.

12.8.5 Disadvantages of Using Personal Computer for Programming a PLC

1. The programming learning curve for programming using a computer based software is longer than the Dedicated programmer programming, as the keys using control component symbols are not used as in the case of a Dedicated programmer keyboard.
2. The computer is not designed for the industrial environment. It is affected by electrical noise, high temperature and humidity conditions in the industrial environment.

To overcome the shortcoming of personal computer in its use in the industrial environment has led to the development of Industrial-rated computer programmers. It is a mix of the Dedicated programmer and the personal computer. Allen Bradley, Siemens, Modicon and GE-Fanuc are several of the companies that offer these highbred programmers. This type of programmer, however, is more expensive than the Dedicated desktop programmer or a personal computer, but one gets the best features of both.

12.9 FUNDAMENTAL PLC PROGRAMMING

12.9.1 Introduction

The fundamental level, ladder logic programs for PLC are very similar to the relay control circuits, we have studied in this book. In this book, we have drawn the relay control circuits between two horizontal lines representing a phase and neutral of the control supply. If the same control diagram is drawn between two vertical lines, it is called ladder logic diagram, as the two vertical lines representing phase and neutral resemble two poles of a ladder and the control circuits drawn between the two vertical lines resemble the rungs of a ladder. A control circuit for starting two motors in a sequence is shown drawn in two different types of control circuit representation

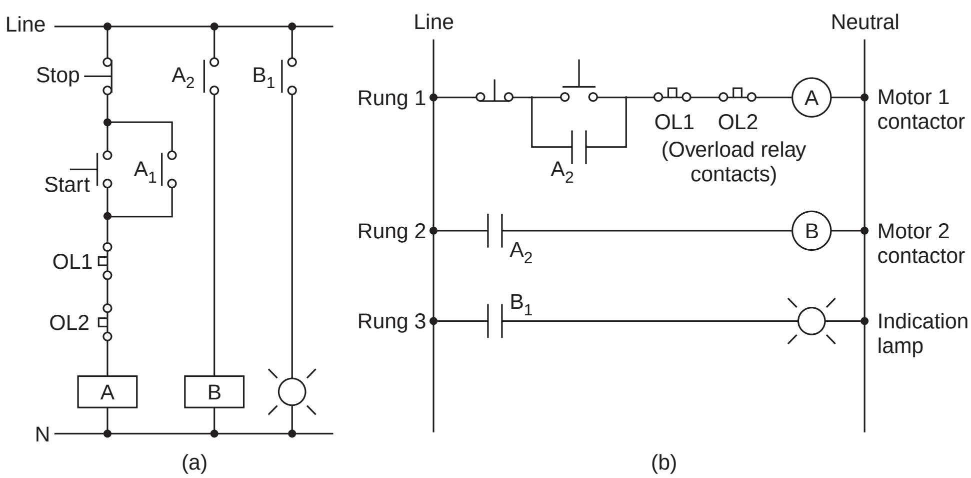


Fig. 12.20 Logic of sequence starting of two motors using relay ladder logic diagram

Ladder logic diagram is a graphical language that is based on relay ladder logic and is the most widely used language to program the current generation PLCs.

The first PLC was programmed with ladder logic. This decision to use the relay logic was a strategic one. This eliminated the need to teach the electricians, technician and engineers how to program. The ability of PLCs to accept programming in ladder diagram format is one of the reasons for the success of PLCs in industry. The many similarities between the ladder diagrams used to program PLCs and the relay ladder logic used to control industrial systems, eased the transition from hardwired relay system to PLC based systems for many people in the electrical industry. Also the ability to monitor PLC logic in ladder diagram format also made troubelshooting easier for those already familiar with relay based control systems. Although there are many higher-level languages now available for PLC programming, the majority of systems are still programmed in ladder diagram format because of these advantages. Ladder logic diagram is quite flexible and it is best used for

- Boolean operations
- Computer logical operations
- Message and communication processing
- Interlocks
- Troubleshoot a machine and process

When a PLC is to be used primarily to replace relays, timers and counters, it's hard to beat the simplicity and usefulness to ladder diagram programming. However it has a number of deficiencies also.

The basic ladder diagram instructions are fine for performing many simple tasks, but sometimes things get more complicated for example when a shift register, stack is to be programmed. Although these complex tasks can be programmed with combinations of the standard ladder logic instructions but PLC manufacturers have used function blocks to make programming some of the more common tasks easier. Many PLC manufacturers have now converted timing, counting and arithmetic instructions to the more use-friendly functions in the block format.

Function block diagram is another form of graphical language. The main concept is that the data flow start from inputs and passes in block(s) and generate output. Thus the program elements appear (*i.e.*, reusable software elements) as Functions blocks, which are connected together with lines that represent wires in a way, that look much like a circuit diagram. The ladder logic diagram shown in Fig. 12.21 shows the use of a function block.

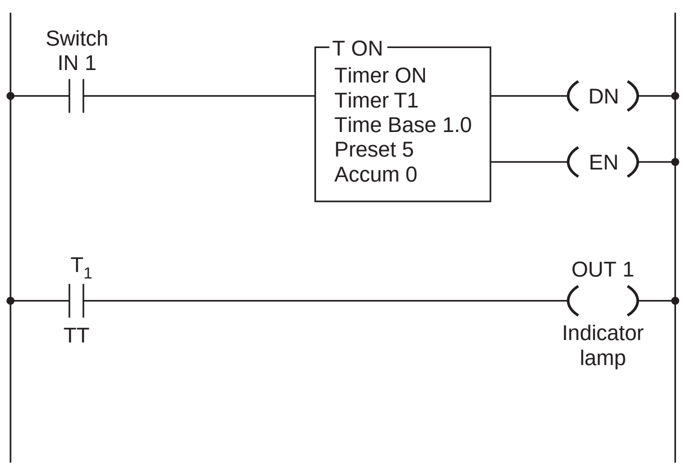


Fig. 12.21 PLC program using a function block

RS logix 500 a software for programming of Allen Bradly PLC-5, SLC 500 and micrologix family of PLSs use the combine of ladder logic and function block as the programming language.

12.9.2 Physical Components Versus Program Components

One of the most difficult concepts to grasp while learning PLC programming is the difference between physical components and program components. The physical components like switches, push-buttons, pressure switches, relays, solenoids are connected to the input/output terminals of the PLC. When the PLC is programmed, then the physical components connected to PLC are programmed as program components. The program component corresponding to a physical components will not have the same symbol as the physical component but will have the same name. All input physical components which have only two positions ON or OFF are represented by normally open and normally closed contacts. Similarly all output devices are represented by one symbol i.e., a relay or output symbol. The logic for the control is built using the internal program components like relays, latch relays, timers, counters, sequences and shift registers etc. It should be understood here that there are no such physical components in the PLC but the microprocessor simulates the function of a physical component which is programmed as a program component in the program.

Now, we take a simple relay circuit having two pushbuttons PB_1 and PB_2 connected in series to operate a lamp. The circuit is shown in Fig. 12.22.

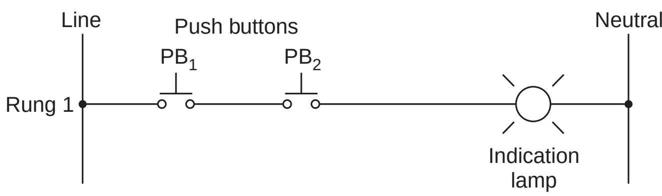


Fig. 12.22 A simple relay circuit using two pushbuttons

When we convert this circuit to run through PLC, we will remove the components from the circuit and wire them to the PLC as shown in Fig. 12.23.

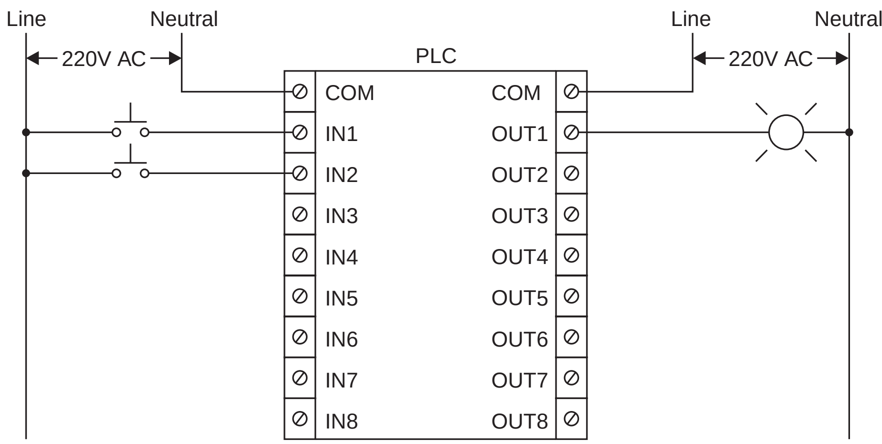


Fig. 12.23 Wiring of push buttons and indication lamp to input and output module

One major difference in this circuit is that the two switches are no longer wired in series. Instead, each one is wired to a separate input on the PLC. By providing each push button as a separate input to PLC, we gain the maximum amount of flexibility i.e., we can program them in any fashion in the ladder logic program.

Now we will see, how the logic is programmed in the PLC to get the same operation as is obtained by the hard wire circuit shown in Fig. 12.22. The push-buttons in the program will be designated by the input addresses to which they are connected on the PLC. The output in the program will be designated by the output address to which the output (indication lamp) is connected. Since push-button PB_1 is connected to input address IN1, it will be designated as IN1 in the program and will be represented by a normally open contact. Likewise push-buttons PB_2 will be designated IN2 in the program. Indication lamp will be represented in the program by the output symbol ( ) and will be designated by OUT1, i.e., the output address to which it is connected. The program to control lamp is shown in the Fig. 12.24.

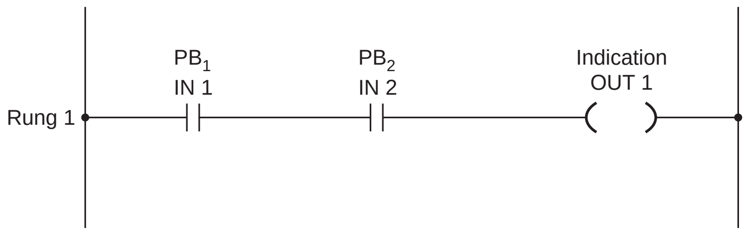


Fig. 12.24 PLC program for a simple control circuit

There is a provision in the PLC software to label the Program component with symbol (PB_1) and discription as Push-button as shown in Fig. 12.24. All input devices are represented by the same programming instruction i.e., (Examine ON instruction), if they are wired with normally open contact.

After entering the program of Fig. 12.24 into PLC, when the PLC is put in RUN mode, the PLC will first update the input image table (a portion of memory) by storing the values of the inputs on terminals IN1 and IN2 (it stores a 1 if an input is ON and a 0 if it is OFF). Then it solves the ladder diagram accordingly based on the contents of the input image table. For this program if there is supply at IN1 and IN2, then both instructions IN1 and IN2 are true and the output instruction will be made true i.e., address allotted to OUT 1, in the output image table is made true (1 is stored at OUT 1 location in output image table). Note : it does not turn on the output terminal yet ! When PLC has scanned the entire program, it performs another update. This update transfers the contents of the output image table to the output terminals. This brings supply of 220 V at terminal OUT1, which turns on the lamp. This whole cycle is repeated again and again.

For a simple circuit like the one we have discussed, it would be very uneconomical to implement this circuit on PLC. However, for extensive circuits requiring a lot of relays and timers, PLC can economise not only on wiring but on the complexity and cost of external components.

In the previous section, we discussed how physical control components connected to the input and output terminals of PLC are represented by various symbols in the programme. Now, we will study some of the the basic instructions, for writing the ladder logic program.

12.9.3 Examine ON Instruction

This instruction is represented by the symbol of a normally open contact -| |-. This instruction in a program instructs the processor to examine supply at the input address designated on the instruction. If there is supply at the designated address the instruction is read as true otherwise as false.

12.9.4 Examine OFF Instruction

This instruction is represented by the symbol of a normally closed contact ┤/├. This instruction in a program instructs the processors to examine the supply at the designated address and if there is no supply, the instruction is read as true. If there is supply at the designated address the instruction is read as false.

12.9.5 Internal Relay Instruction

Most important and a valuable programming instruction in a PLC is the internal relay. Internal relays are general purpose relays which can have any number of normally open and normally closed contacts for use in the program. It must be understood that they are not “real” relays in a physical sense, but instead are a digital bit of memory in an internal image register.

For programming, a relay is represented by a symbol consisting of two paranthesis–( )- and a designator address, which corresponds to internal memory address allotted to this relay. The relay contacts are represented by normally open and normally closed contacts having the same address as that of the relay coil (┤ ├, ┤/├).

All PLCs provide this programming instruction, however the internal addressing scheme and the maximum number of relays that can be used in a program depends on the PLC brand and model. Therefore the programmer must refer to the technical manual for the PLC in order to determine how to reference them in a program and the maximum allowable number that is available.

In some PLC brands, the internal relays are also reffered to a Flag or bit.

NOTE: The same symbols of normally open contact (┤ ├) and normally closed contact (┤/├) are used for Examine ON and Examine OFF instruction and also for the contacts of a internal relay. The golden rule to differentiate whether the normally open or normally closed contact in a program represents a Examine ON or Examine OFF instruction is to see its address. If the contacts bears the address of a input terminal of PLC, they are Examine ON or OFF instruction and if the address is of a relay, they are the contacts of that particular relay.

The internal relay instruction allows the programmer to perform more complex internal operations without needlessly using costly output relay. In the programming examples in this text all internal relays will be designated with a “CR” prefix followed by a number i.e., CR1, CR2 etc.

12.9.6 Latching Instruction

Latch and Unlatch instructions like their physical real-world counterparts are retentive during a power failure. When the PLC processor loses power or is switched to either the TEST or PROGRAM modes, or detects a major fault, outputs are turned OFF. However the state of latch instruction is retained in memory.

Latch and unlatch instruction can be used as an internal relay, if the address designated to this instruction is of the relay. If the Latch instruction is designated with an output terminal address, then the supply at that particular address is latched. When the supply to processor is restored after a power failure or processor is brought back to RUN mode after switching out to TEST or PROGRAM mode, the supply at the latched output terminal will be restored automatically. The symbol for programming a Latch and Unlatch coil is same as ordinary coil with letter L and U inserted between the parentheses.

-(L)-, -(U)-

12.9.7 Output Instruction

Output instruction is used to program the real word physical control components connected to the output terminal of the PLC. Irrespective of the type of physical output component connected, the output instruction is programmed by a symbol consisting of two parentheses and designated by the address of the output terminal at which the physical output is connected. The information of a particular output whether it is energized or not can be used in the subsequent rungs of the ladder program by using normally open or normally closed contacts having the same address as that of the output.

12.9.8 Programming Stop Push-buttons

Now we discuss the programming of a simple program for the direct on line starting of a motor as shown in Fig. 12.25(*a*). In the early days of programmable controllers it was common for the

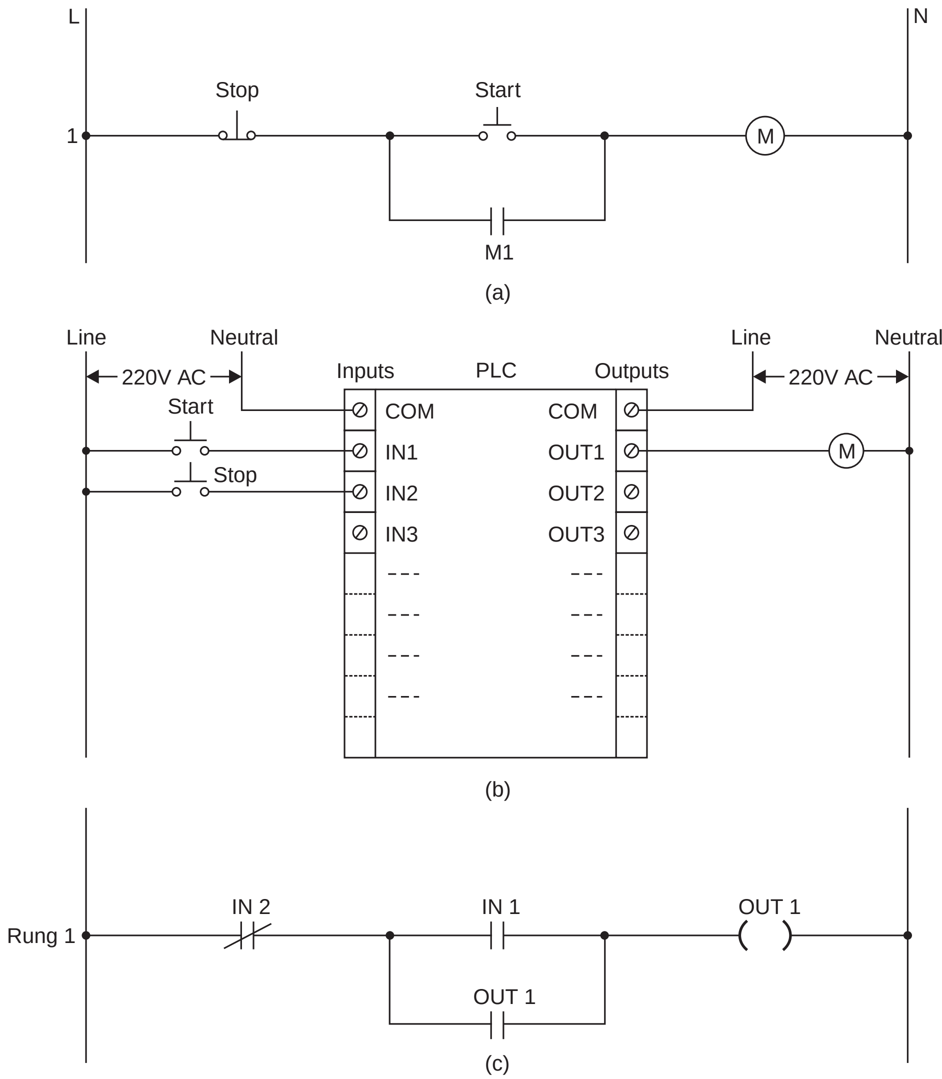
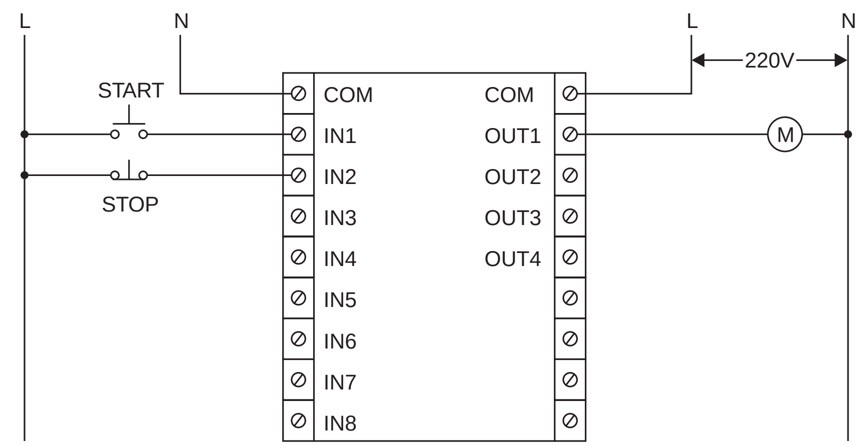


Fig. 12.25 (*a*) Standard STOP/START circuit (*b*) Wiring of input and output devices (*c*) PLC programmed STOP/START circuit

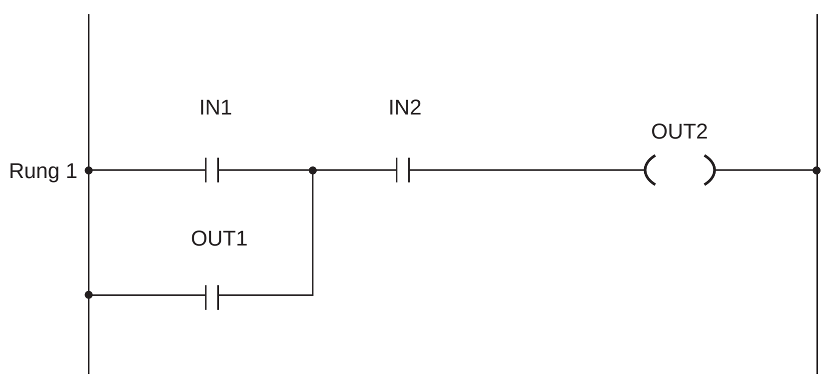
salespeople to use a demonstrator model that had the STOP push button wired normally open (N.O) to the input terminal of the PLC as shown in the Fig. 12.25(*b*). This resulted in the program very similar to the actual wiring circuit of the Start Stop circuit as shown in Fig. 12.25(*c*). By using a normally open contact of STOP push-button, the Examine OFF instruction is true as normally there will be no supply at terminal IN1 and the circuit will energies when start push-button is pressed. The output OUT 1 will hold due to relay contact instruction having address OUT1 getting true once OUT1 is energized. The only way to de-energies the output now is to push the STOP button. This will make the Examine OFF instruction IN1 false and the output OUT1 will be de-energized.

While this circuit will work, there is a built in danger that must be considered. If a STOP button is wired in a normally open (NO) position, and a wire opens from the terminal of the STOP button, it will be impossible to de-energise the circuit. With the wire broken, change in the status of the STOP button cannot be conveyed to the processor and the circuit or equipment cannot be de-energised.

The desirable way to connect a STOP button is as shown in Fig. 12.26(*a*) by using the normally close contact of the pushbutton. The program now will be as shown in Fig. 12.26(*b*). We will have to program a Examine ON instruction for STOP push-button.



(a)



(b)

Fig. 12.26 (*a*) Desirable input device connections (*b*) Resulting program

Note: For safety reasons, all STOP buttons must be wired so that a failure of the switch or a broken wire will automatically break logic continuity and turn the circuit OFF. A good programmer should always wire the devices and program the circuit so that if the real-world device fail, it creates a safe condition, not a safety hazard.

12.9.9 Logical Holding Instructions Versus Discrete Holding Contacts

In the stop, start program for motor discussed in the previous section, we have used the address of the output for the holding instruction across the start instruction. The output instruction will be held true once it is turned true due to start instruction getting true but there is no guarantee however that the actual motor starter connected to the output module has been energized.

The only way to guarantee, that the actual motor contactor has energized is to actually wire the holding contacts of the motor starter to an input module point, and use that address when programming the holding contacts. This is shown in Fig. 12.27.

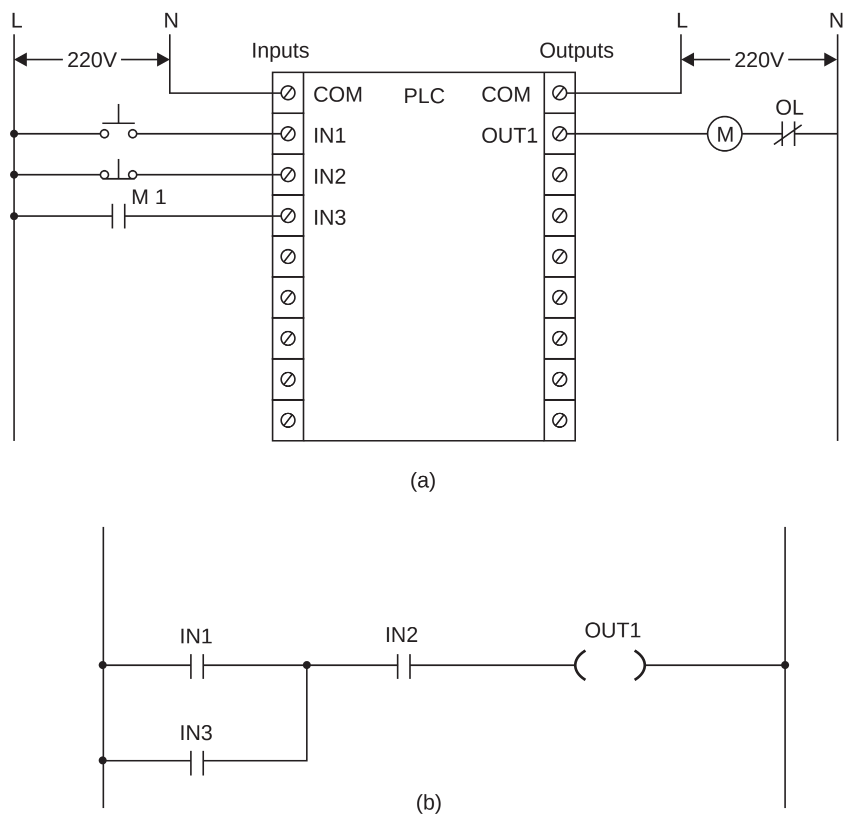


Fig. 12.27 (*a*) Use of discrete holding contact. (*b*) Program using discrete holding contact

12.9.10 Overload Contacts

It is common practice to wire the overload contact, in series with the contactor coil as shown in Fig. 12.27(*a*). When the over load contact opens, it will de-energies the motor contactor M. The holding contact M_1, connected to the input module and programmed in the PLC program as IN3 will break logic, which turn off the supply at OUT1, where the contactor coil is connected. This type of overload only works, if the holding contacts are wired to an input module and programmed into the PLC program.

If the holding contact is not wired to an input module but instead the output address is used for holding logic, then the tripping of overload relay will de-energise the contactor coil but PLC program logic is not broken and output address supply will remain ON. This can cause a safety hazard, that the motor will start automatically if the overload is reset. This type of wiring can also cause problems in sequential motor circuit or other automated circuits.

If the address of the output is used for logic continuity (holding circuit), then the actual overload contacts must be wired to an input module and referenced in the PLC program as shown in Fig. 12.28.

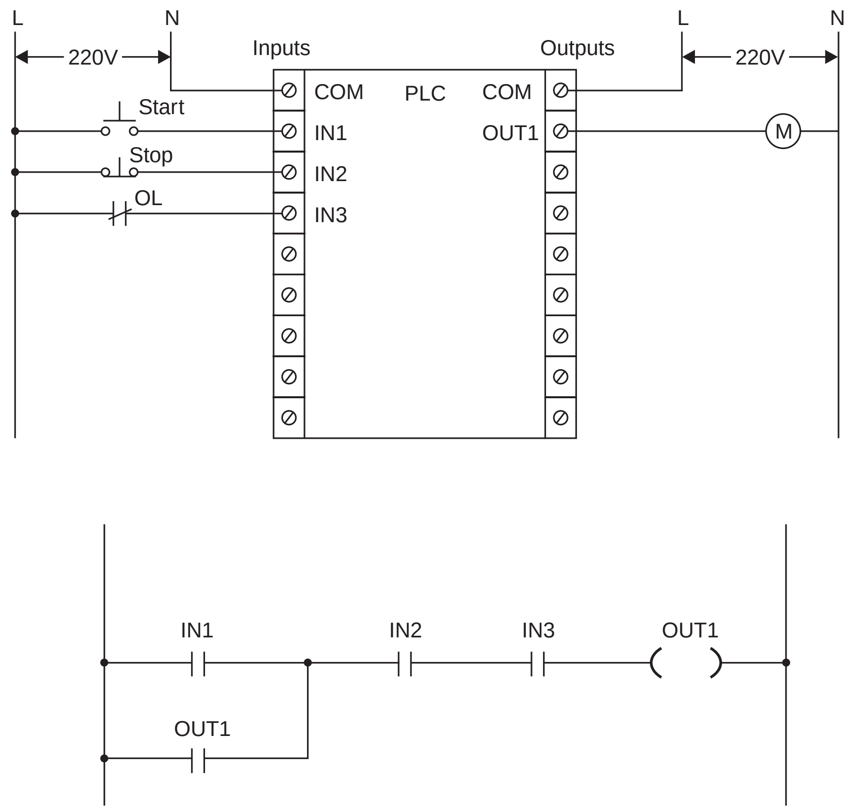


Fig. 12.28 Wiring of overload contact to an input module

Wiring of overload contact to input module has an added advantage in troubleshooting. As any address used in PLC program can be viewed for its ON or OFF status by viewing the LEDs meant for them or on the PLC or the input module.

12.9.11 Master Control Relay Instruction

In relay circuits, a relay is often used to control power to the entire control circuit or to a portion of control circuit. This relay is also referred to as start relay, control relay or Master control relay. Fig. 12.29 shows a typical hardwired master control relay that controls power for the whole control circuit. When the relay switches off power to the whole circuit, it is also referred as Emergency stop release.

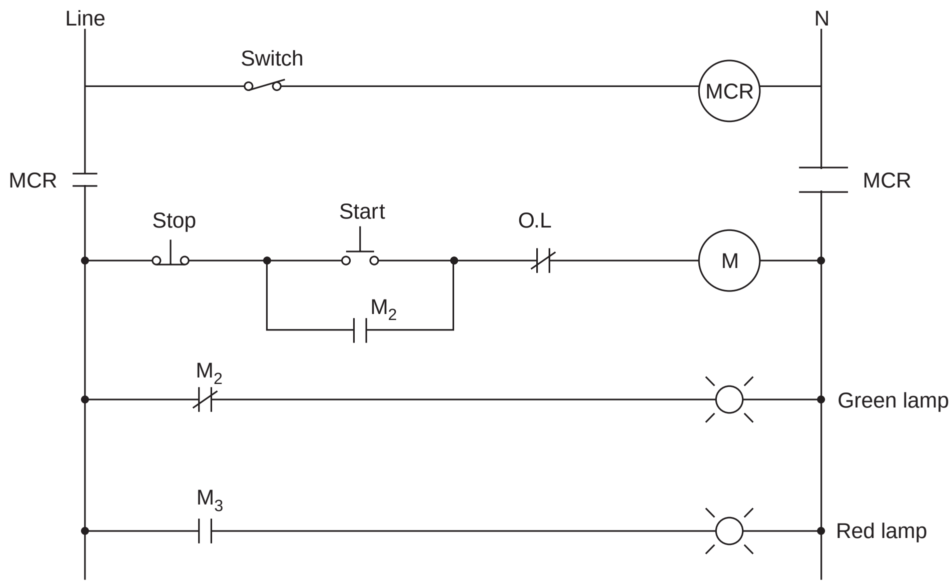


Fig. 12.29 Hardwired master control relay

All PLCs also provide Master Control Relay (MCR) instruction to control an entire program or selected rungs of a program. When the MCR instruction is programmed as shown in the Fig. 12.30, the portion of the program which is in between two MCR instructions is enabled only when the first MCR instruction is true. It means rungs 2 to 4 are enabled only when the instruction IN1 is true. Two MCR instructions are used to create a zone. In the circuit shown rung 5 is outside the areas of MCR zone created by two MCR instructions and thus works independently of the MCR instruction.

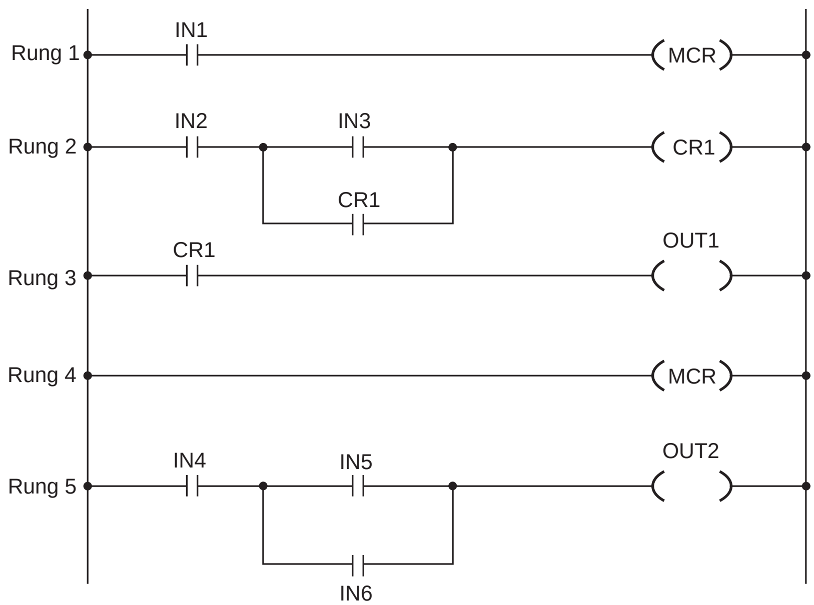


Fig. 12.30 Two MCR instructions used to create two different zones

Any number of zones can be created in a program but an MCR zone cannot be nested within another MCR zone.

Note : A programmed MCR must never be used to replace a hard wired master control relay that provides emergency shutdown. It is recommended that a hard wired emergency STOP push-button should remove power to the output devices. This is achieved by using the normally open contact of a physical MCR relay in the neutral to cut off power to the output module of the PLC as shown in the Fig. 12.31.

Another contact of MCR can be used in the line, but it is optional, as it is advantageous to keep the inputs energized for troubleshooting.

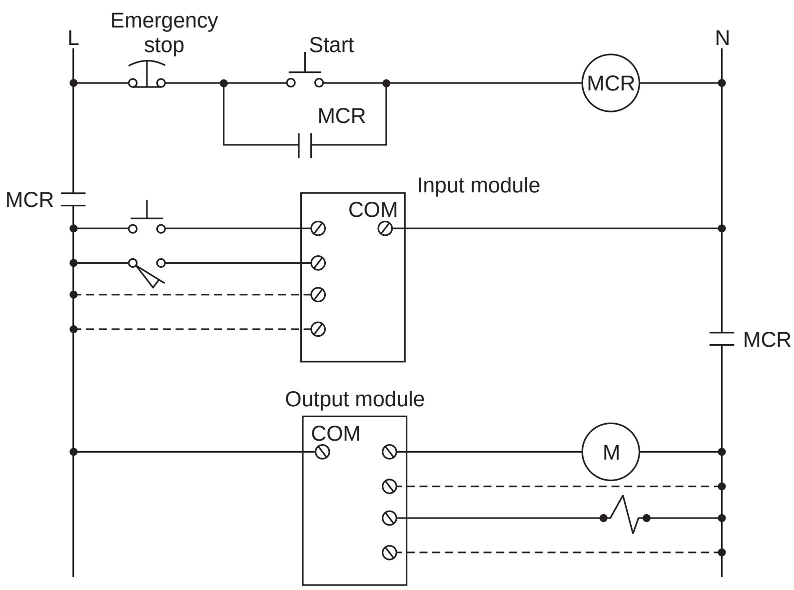


Fig. 12.31 Safety circuit using a physical MCR relay

12.9.12 Branch Open and Branch Close Instructions

Whenever two instructions are to be programmed in parallel (for example the holding circuit) Branch open & Branch close instructions are required to program the circuit into PLC memory. The circuit shown in Fig. 12.32 will be programmed using a branch open instruction (L) and branch close instruction by L entering the instructions as follows with the help of a hand held programmer in the Allen Bradleys "SLC 150" PLC.

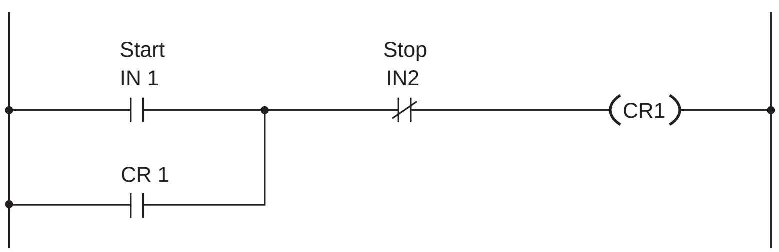


Fig. 12.32 A simple PLC program

Program Entry : Press symbol L(Branch open)

Press symbol ⊣ ⊢ (Examine ON) and give it address IN1

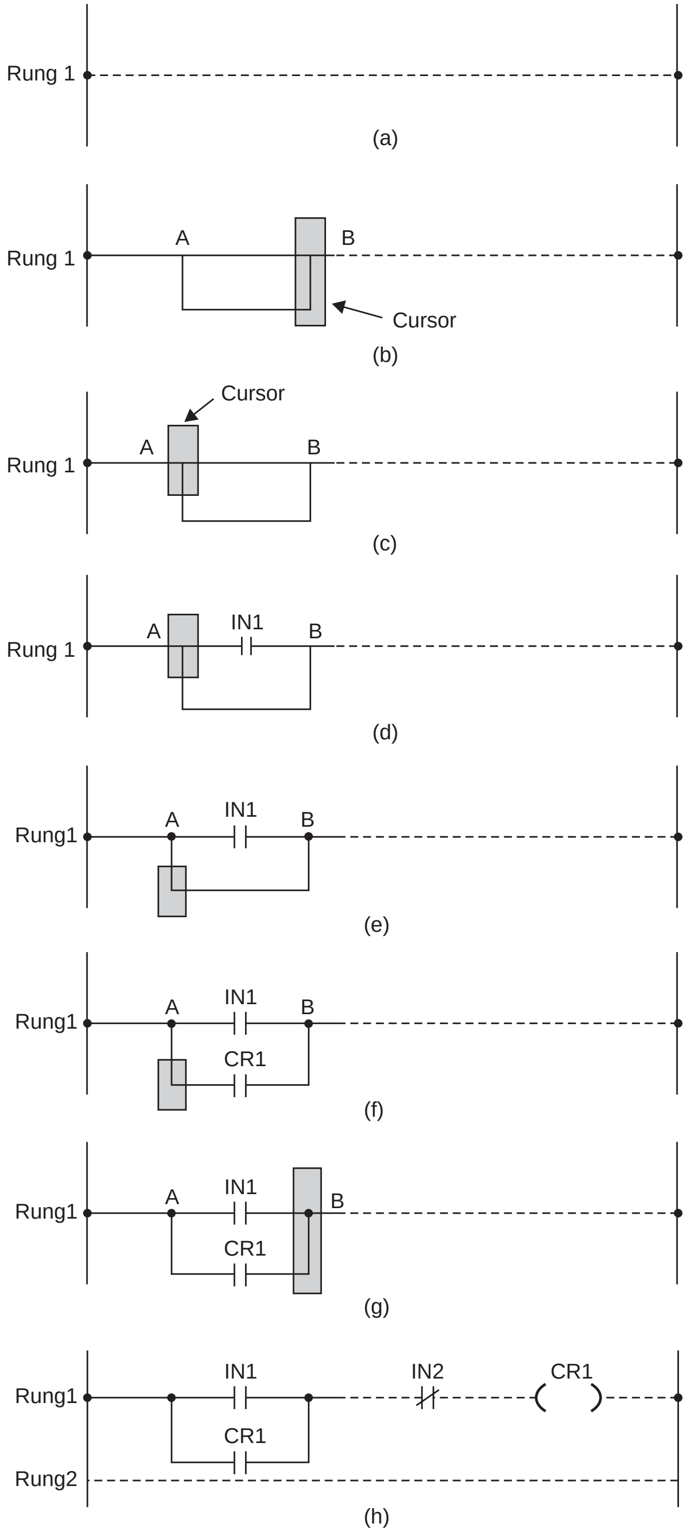


Fig. 12.33 Programming of a parallel branch using computer software

Press symbol L again (Branch Open)

Press Symbol -| |- (Examine ON) and give it address CR1

Press Symbol ⊑ (Branch close)

Press Symbol -| |- (Examine OFF) and give it address IN2

Press Symbol -( )- (Relay) and give it address CR1

Press Enter

If window based Personal computer software is used to program a PLC through Keyboard/Mouse of the PC, then a single instruction called Branch instruction is available in the software to program the instructions connected in parallel. The symbol used for branch instruction in RS logix 500 software for programming Allen Bradley make PLC is ⊏⊐, which is available on the tool bar of the window.

When the software is opened for programming a dotted line (rung) will appear in the working window where Ladder program is to be entered as shown in Fig. 12.33(*a*). When branch instruction available on the toolbar of the window based software is called by left click of the mouse, the rung 1 will be modified and the branch will appear on the rung as shown in Fig. 12.33(*b*) and the cursor is shown by a rectangle. To enter the instruction in the top branch, mouse is clicked at junction A as shown in the diagram. This will move the cursor to point A as shown in Fig. 12.33(*c*). Now clicking an Examine ON instruction on the tool bar will modify the circuit as shown in Fig. 12.33(*d*).

After entering the address IN1 for this instruction, mouse will be clicked at the starting of bottom branch, which will shift the cursor shown by rectangle as shown in Fig. 12.33(*e*). Now clicking again on Examine ON Instruction on the toolbar will add the instruction in parallel with the first instruction as shown in Fig. 12.33(*f*). This instruction is given address CR1.

Now again clicking the mouse at point B in the program, the rectangle will appear as shown in Fig. 12.33(*g*). Now the Examine OFF instruction can be added to the circuit by clicking its symbol on the toolbar and then its address is entered. Finally the rung can be completed by clicking the relay instruction -( )- on the toolbar and entering its address CR1 from the keyboard. The complete rung 1 will be as shown in Fig. 12.33 (*h*) and clicking a new rung instruction on the toolbar will enter a new rung as shown in the diagram.

12.9.13 Timer Instruction

Timer instruction is used to perform timing operations based on a precise internal clock, generally 0.1 or 0.01 seconds per clock pulse. In many PLC*s*, the time increment is user selectable, with the 0.1 sec incrementing the timer is called standard timer and the 0.01 sec incrementing timers are called high-speed timers. Timers generally fall into two different categories depending on the PLC manufacturers. These are retentive and non-retentive. Further the timer can be of two types, On-delay timer and OFF delay timer. Defference in working of ON and OFF delay timers has already been discussed in chapter on control components. Review it, if you cannot recollect. Most of the PLC manufacturers only provide ON-delay timer instruction. Thus we will discuss here the ON-delay timer only.

A non-retentive timer is the one, which has got only one control line as shown in Fig. 12.34. Timer is represented by a coil symbol or by a box symbol as shown in Fig. 12.34(*a*) and (*b*) respectively.

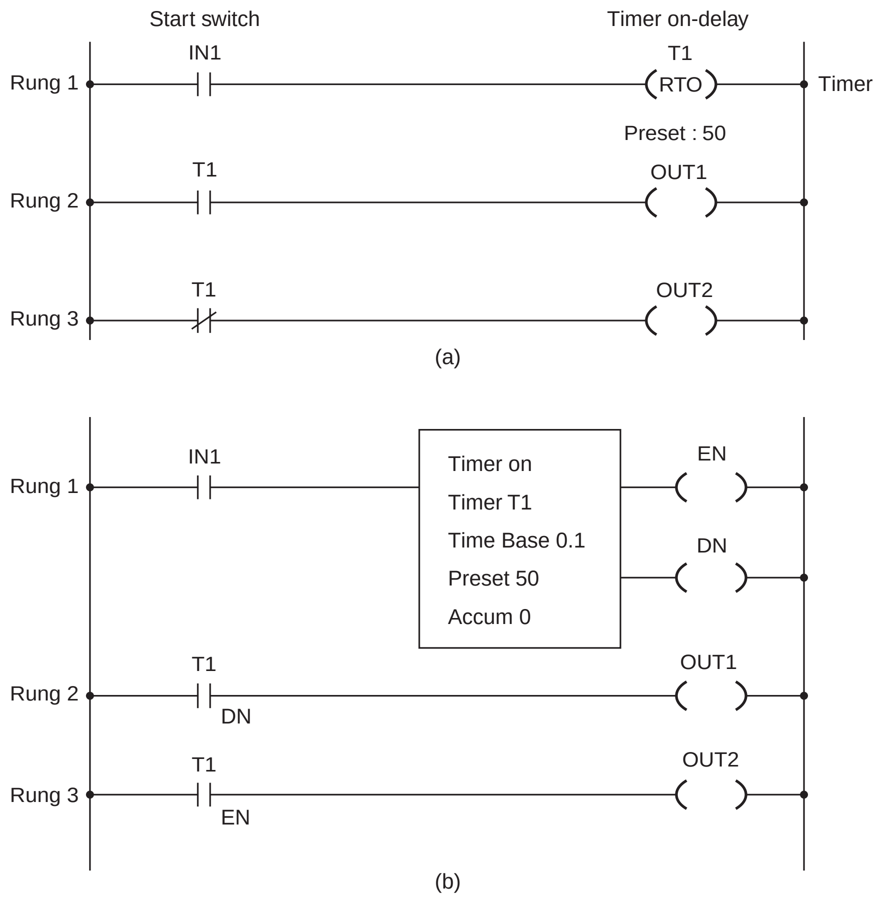


Fig.12.34 (*a*) Timer representation in ladder logic (*b*) Timer representation in functional block language

In the timer circuit, of Fig.12.34(*a*) when the Examine ON instruction IN1 is true, timer starts counting the time in intervals of 0.1 or 0.01 depending upon the time base. A preset of 50 for time base 0.1 sec means timer setting is 5 seconds. After 5 secs, the timer contacts, T1 will changeover their positions. Timer instruction in functional block language is more interactive. Time base selection is possible and time counted at a particular instant is shown against ACCUMULATED VALUE. Two coils EN and DN are shown. EN coil will remain energised as long as timer is ON. Thus contact T1/EN will changeover as soon as Timer is energised due to IN1 instruction getting true. The DN coil will energised/becomes true when the timer has timed out, that is when the ACCUMULATED VALUE = PRESET VALUE. Thus the timer contacts T1/DN will changeover. If the IN1 instruction goes false or supply fails at any time when timer is counting or has already timed out the ACCUMULATED VALUE will be reset to zero (0) and all timer contacts will come to their original condition. On restoration of power supply or closing of IN1 contact, timer will again start counting from zero towards the PRESET value.

Retentive type of timers have two control lines as shown in Fig. 12.35.

In this type of timer, the accumulated time at any instant is retained, if the power goes off or Examine ON instruction IN1 becomes false. Timer resumes counting from the accumulated value, when power is restored or when Examine ON instruction again becomes true. Once the

PRESET VALUE = ACCUMULATED VALUE, the timer contacts will changeover and remain so until the reset instruction for the timer becomes true due to Examine ON instructing IN2 becoming true. This will reset the timer contacts to their original position and accumulated value will be reset to zero.

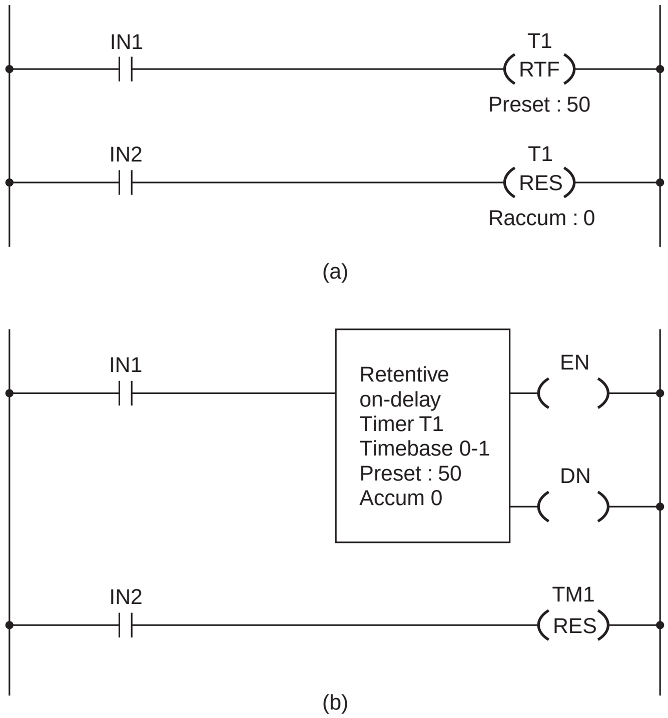


Fig.12.35 (*a*) Retentive timer representation in ladder logic language
(*b*) Retentive timer representation in functional block diagram language

Note : As long as the reset instruction is true, timer instruction will not work. In some PLCs, Reset instruction can be programmed to have the initial accumulated value called reset accumulated value other than zero (0). If the reset instruction is programmed to have a non-zero intial accumulated value, the time required to change the timer contacts will be equal to PRESET VALUE—RESET ACCUMULATED VALUE.

12.9.14 Counter Instruction

Counter instruction is similar to timer instruction, the only difference being that timer counts the internal pulses generated, by an internal clock while the counter counts internal pulses. A very common example of internal pulse generation is the counting of products moving on a conveyor system. A limit switch installed on the conveyor is actuated each time a product passes across the limit switch arm. Normally open, contact of limit switch, will close and open when a product actuates and deactuates the limit switch arm while passing through where the limit switch is installed. This closing and opening of contact is used to give a pulse to counter for counting the number of products passed. Counters are always of retentive type.

Some manufacturers have counter instructions using one coil instructions each in two rungs as shown in Fig. 12.36. In one rung, there is Up counter instruction (CTU) and in the other rung is the reset instruction -(RST)-. A preset value is given to counter instruction, which corresponds to the maximum count. The reset instruction by default has a reset accumulated value of zero (0). Reset instruction can however be programmed to have any Reset value upto the preset value of the counter in case of a Up-counter.

In the program shown in Fig. 12.36, note that the IN1 instruction going true and then false will increase the accumulated value of counter C1 by one. When the accumulated value becomes equal to the preset value of 5, the counter contact C1, will close energizing the OUT1. If however the RAC value of counter C1, is programmed to say 2, then the counting will start from 2. The counter contact C1, will become true (close) after three counts i.e., (5 – 2 = 3).

Some manufacturers represent the counter instruction in a box with two inputs and two coil in its output as shown in Fig. 12.36 (*b*), CTU at the top of the box represents that it is a Up-counter. The CU relay is true, when the IN1 instruction is true. Thus for each count, the relay becomes true and its contact C1/CU will close and then open for each count. When the Accumulated value = Preset value, the DN relay will become true and its contacts C1/DN will change their positions.

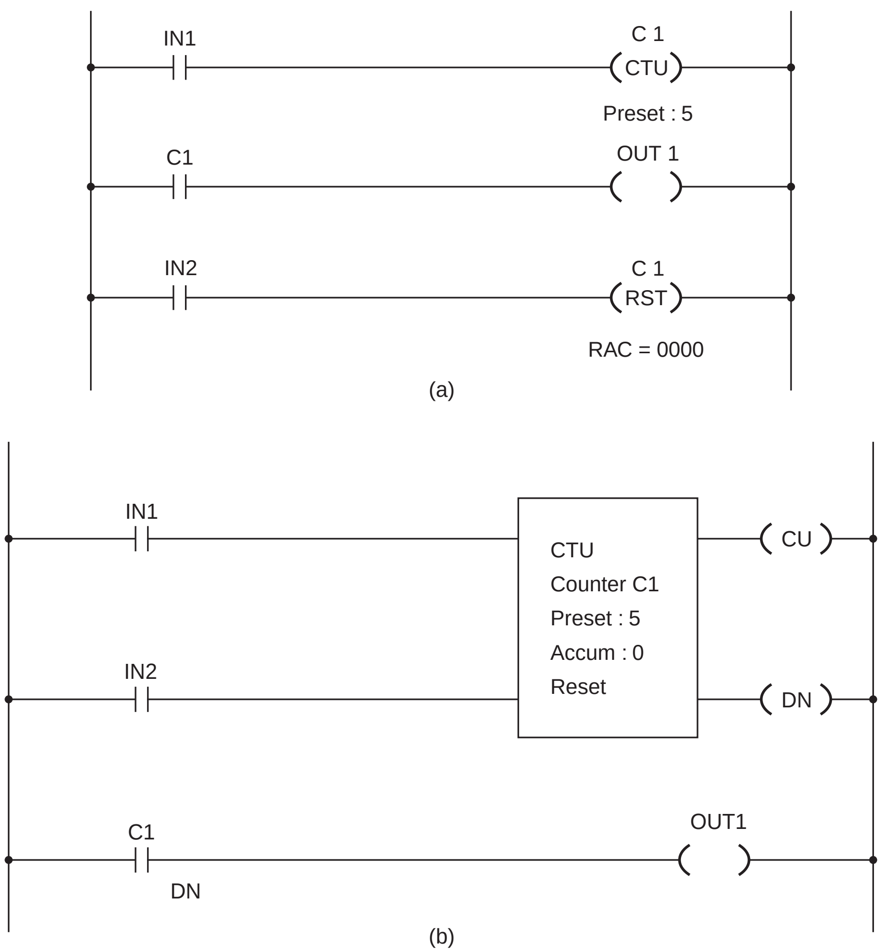


Fig. 12.36 (*a*) Counter representation in ladder logic diagram
(*b*) Counter representation in functional block diagram

In down counter, the counter instruction will be represented by CTD. In case of down counter the Reset accumulated value will be programmed equal to the preset value (counts required) and the preset value will be programmed to zero. When the IN1 instruction will go true, the accumulated value will decrement by one. When the accumulated value becomes equal to the preset value the down counter contact will changeover.

In some cases, it is convenient to have a counter that can count in either of the two directions, called a bi-directional counter or UP-Down counter. One example of UP-Down counter can be to keep a tally of number of vehicles in the parking lot and to give indication when the parking is full. In this situation, entry of a car into the parking lot will be sensed and will be used to increase the count of bi-directional counter and when a vehicle exits from the exit gate, a sensor will provide pulse to decrement the count in the bi-directional counter. The accumulated value of the counter at any time can be displayed to know the number of vehicles parked at any time in the parking lot. Program using a Up-Down counter is shown in Fig. 12.37. Note that in this program the counter up instruction -(CTU)- and the Down-counter instruction -(CTD)- have been given the same address as C1. This indicates that both the instructions constitute the Up-Down counter. When the accumulated value is equal to the Preset value of the Counter Up instruction, the contact C1 will close and light the indication lamp connected to OUT1 of the output module to indicate that the vehicle in the parking lot are equal to 100.

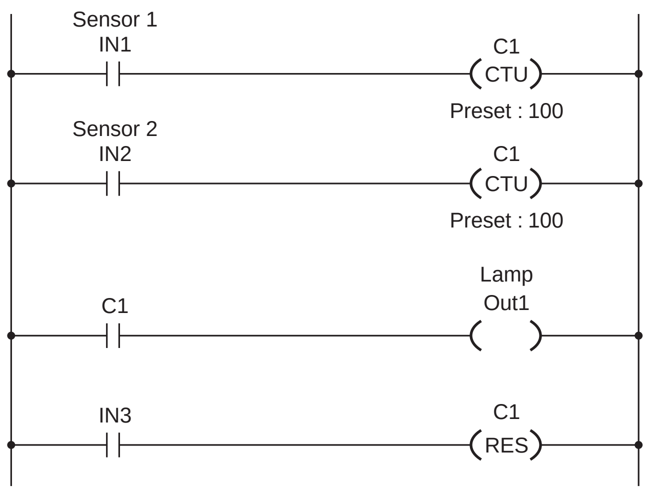


Fig. 12.37. Program using a up-down counter for counting the number of vehicles parked

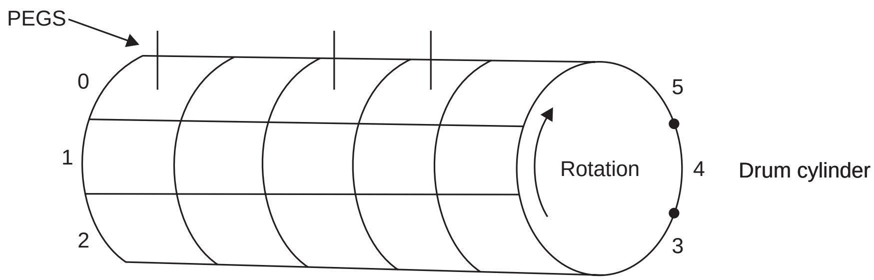
12.9.15 Sequencer Instruction

In some control applications, it is required that a particular sequence of events occur. Mechanical sequencers have been used for such applications. In automatic washing machines, a timer motor rotates one or more cams mounted on its shaft, which in turn causes switches to open or close to activate the next process in the wash cycles e.g., the machine advance from the main wash to the rinse cycle involving switching OFF of heaters, switching on pumps etc. A cam can consist of an eccentric circle of metal or plastic that rotates on a shaft. As it rotates, it pushes a switch or switches are closed to produce a sequence of steps. Sequencer is also referred to as cam timer. This has already been discussed on the chapter of control components and its application for conveyor system has been discussed in the chapter on industrial control circuits.

The speed of the sequencer motor and the shape of the cams determine the time allowed for each operation. The relation of the cams to each other determine the sequences of steps. These electro-mechanical sequential controllers are called Drum sequencers.

The main disadvantage of these sequencers is that they were time driven only i.e., each sequence was allowed a certain amount of time depending upon the speed of the motor. In modern control systems it is necessary for the sequencer to be advanced in response to an event. For example, consider the control of a small oven. If the oven is not up to the desired temperature, despite the heater being on for the allowed amount of time, then the processor should not advance the sequencer to the next step. The sequencer should only be advanced in response to an event, in this case a thermal switch closing of which indicates that the oven is up to temperature. PLCs also have sequencers but they are not physical device but exist only as software instructions. They can be visualized as a drum that rotates in steps. At each step a series of pegs along the drum can activate switches which then initiates a control action. This electro-mechanical drum switch is shown in Fig. 12.38 (*a*).

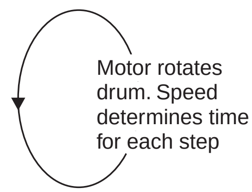
The presence of Peg indicate a logic 1 and the absence as logic 0. If the drum were unwound and laid flat then it would appear as shown in Fig. 12.38(*b*).



(a)

Switches

Steps	S_5	S_4	S_3	S_2	S_1
0	ON	OFF	ON	ON	OFF
1	OFF	OFF	ON	ON	ON
2	ON	OFF	ON	OFF	ON
3	ON	ON	OFF	ON	OFF
4	ON	OFF	ON	ON	ON
5	ON	ON	ON	OFF	OFF



(b)

Fig. 12.38 (*a*) A electro-mechanical drum sequencer (*b*) Alternate representation of drum sequencer in the chart form

OFF may be represented by logic 0

ON may be represented by logic 1

after step 5, the cycle repeats with step 0.

Unlike the mechanical Sequencer, the PLC Sequencer can be either EVENT or TIME driven. Also PLC Sequencer can be a output sequencer or a input sequencer. A output Sequencer sets up the outputs ON or OFF for each step while input Sequencer examines inputs to determine their ON and OFF status for each step.

12.9.16 Basic Operation of Time Driven Output Sequencer Instruction

The operation of a time driven Sequencer can be explained with the help of the program and table shown in Fig. 12.39.

Step	Output addresses				Time per step
	OUT1	OUT2	OUT3	OUT4	
0	0	0	0	0	5 sec.
1	0	1	0	1	20 sec.
2	1	0	1	0	60 sec.
3	1	1	1	1	25 sec.

Fig. 12.39 Operation of a time driven output sequencer

The data shown in the table has to be programmed for the Sequencer instruction S1 shown in the program. When the PLC will be put in the run mode after entering the program and data. The Sequencer rung goes true when the examine ON instruction IN1 becomes true. This starts the Sequencer action and the step 0 occurs for 5 secs, and all output from OUT1 to OUT4 will be off. After 5 secs the Sequencer will advance to step 1 and the status of OUT1 to OUT 4 will be as shown in the table and it will remain in step 1 for 20 secs. After 20 secs, Sequencer will go to step 2 and then to step 3, remain there for the programmed time and change the status of outputs as programmed which is shown in the table. After the step 3, Sequencer will again come back to step 0. The same operation is repeated as long as the IN1 instruction remains true. If IN1 goes false anytime during the Sequencer operation or the supply fails, the Sequencer operation will stop but the changes already made are retained and the Sequencer operation will resume from the same point when the instruction IN1 goes true or supply is restored. Similarly we have a **Event Driven Output Sequencer** in which the Sequencer shifts to the next step when an external pulse is given to the Sequencer instead of a preset time for each step.

In **Time Driven Input Sequencers,** the Sequencer stays at the predefined steps for the programmed times and monitor the status of specified inputs. If during its stay on a particular step for particular time the input status match the programmed status for the specified inputs, a sequencer contact is made true. This action is repeated at each step.

Similarly we have a **Event Driven Input Sequencer,** in which the Sequencer shifts to the next step in response to an external pulse given to the Sequencer.

There are many more instructions available in PLCs like Math functions, Data manipulation functions, Word and File move functions. For example in the Allen Bradleys 'SLC 500' PLC having 5/02 processor the number of functions available are seventy one (71).

12.10 A SIMPLE PROGRAMMING EXAMPLE

12.10.1 Sand Mixing Machine

A simple machine for preparation of a resin bonded sand is shown in Fig.12.40. Resin bonded sand is required in foundries for making cores which are used in the sand moulds for the making of metal castings. The sand and resin are mixed at a particular temperature to prepare the sand. Sand and resin are added in a predetermined proportion by adjusting the time of opening of ON-OFF type resin solenoid valve and the sand hopper gate. Sand hopper gate is operated by a pneumatic operated cylinder piston as shown in the diagram. Another Pneumatic operated gate is the mixer gate to throw out the mixed sand. Mixing is done by blades which rotate inside the mixer through the gear box connected to the shaft of a three phase squirrel cage induction motor. A limit switch is actuated when the mixer gate opens to throw out the sand. Sand is automatically thrown out due to the rotating mixer blades. This application requires the use of retentive timers as fixed quantities of resin and sand are to be mixed. The operation required from the machine is explained in steps given below:

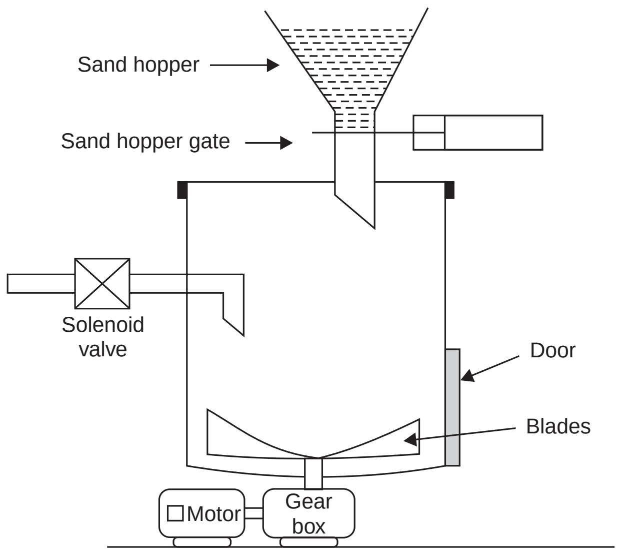


Fig. 12.40 Diagram of a sand mixing machine

1. On pressing the Start push-button, the heaters installed inside the mixer should get ON.
2. When the required temperature of 100 centigrade is achieved, the mixer motor should start, and the resin solenoid valve should get energised to add resin into the mixer for 20 secs.
3. After the resin addition, the sand hopper gate should open for 30 secs to add the required quantity of sand into the mixer.
4. The mixing of the sand and resin should continue for 300 secs.
5. The mixer gate should now open for 60 secs to throw the mixed sand out of the mixer.
6. When the mixer gate closes, all the timers should be reset and the heaters should be switched off.

12.10.2 Relay Ladder Logic Diagram

The Relay ladder diagram for the sand mixer machine will be as shown in Fig.12.41. It is left as an exercise for you to study this diagram thoroughly before you go to the next section to see how the same machine can be controlled by a PLC.

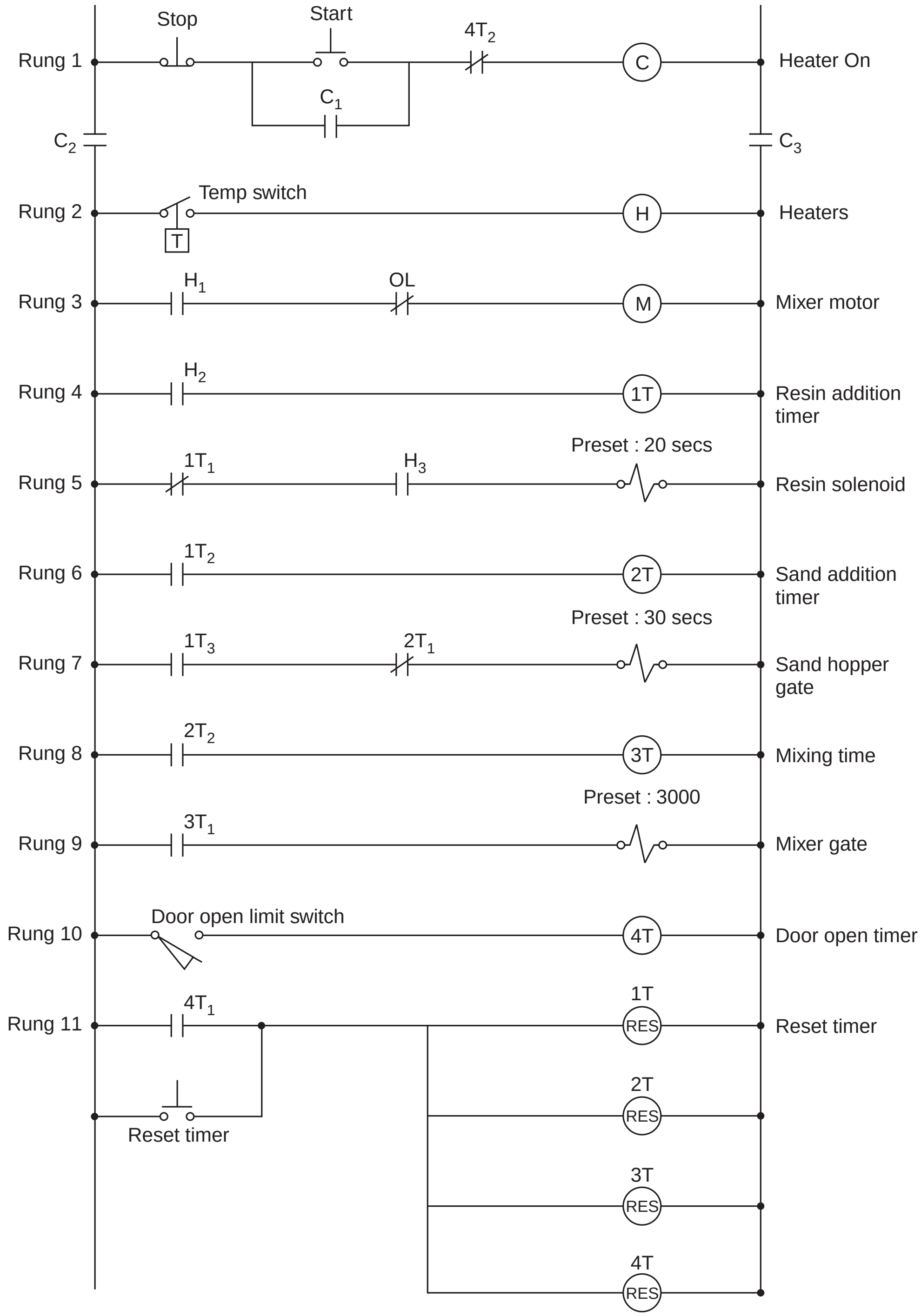


Fig. 12.41 Relay schematic ladder diagram for a sand mixer

12.10.3 Ladder Logic Program on PLC for Sand Mixing Machine

If the same machine, you studied in the previous section is to be controlled using the PLC, then the various input and output devices will be connected to the input and output module of the PLC as shown in the Fig. 12.42. Here we assume that a 8 input and 8 output module is used for this application.

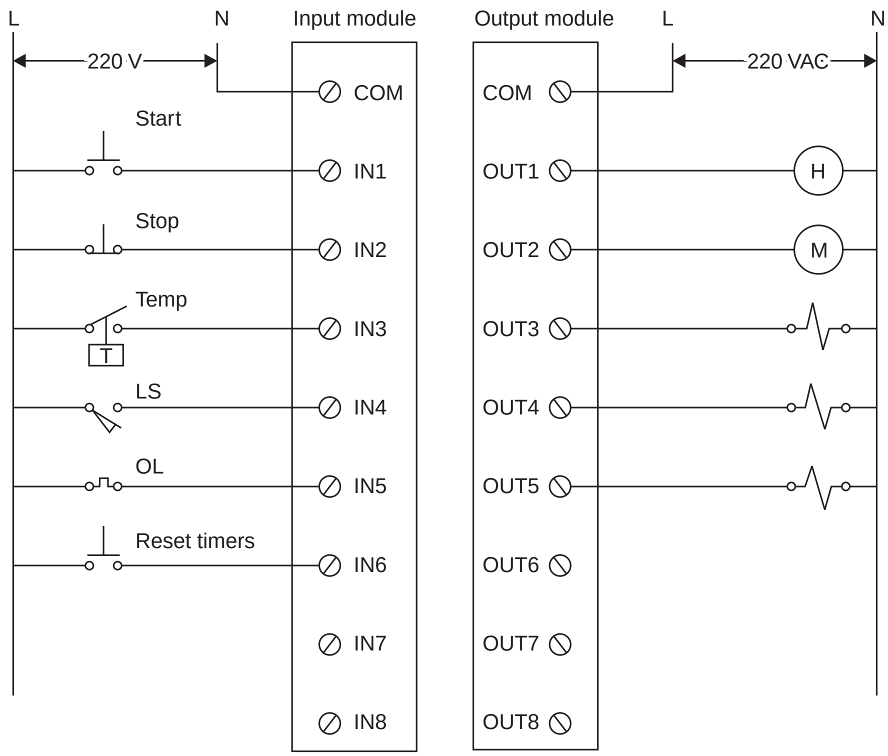


Fig. 12.42 Connection of input and output devices to PLC Input and output module

The first step in the development of program is to thoroughly note down the input and output addresses at which various input and output devices are connected. The program is first developed on paper on the similar lines as the relay ladder diagram is developed. At this point you have to be thoroughly familiar with the addresses which have to be alloted to the internal relays and timers which will be used in the program. A typical PLC program for the Sand mixer machine is shown in Fig. 12.43.

12.10.4 Explanation for the Ladder Program

Before the program execution is explained, recollect how the processor executes the program. When the PLC is put in run mode, it will start its scan cycle. First the inputs are read and their status is stored in a memory locations allotted for each input device. When input scan is complete, program is scanned starting from the left side of rung 1. If all the instruction in the rung are found true then the output instruction connected in extreme right of the rung is made true and the status in the memory location allotted this particular output instruction is changed. Then the processor similarly scans the second rung and it continues till the last rung. Now all the output connected to the output module are energized or de-energised according to latest status of output instructions in their respective memory locations. After this, again the inputs are read and program is scanned as described above.

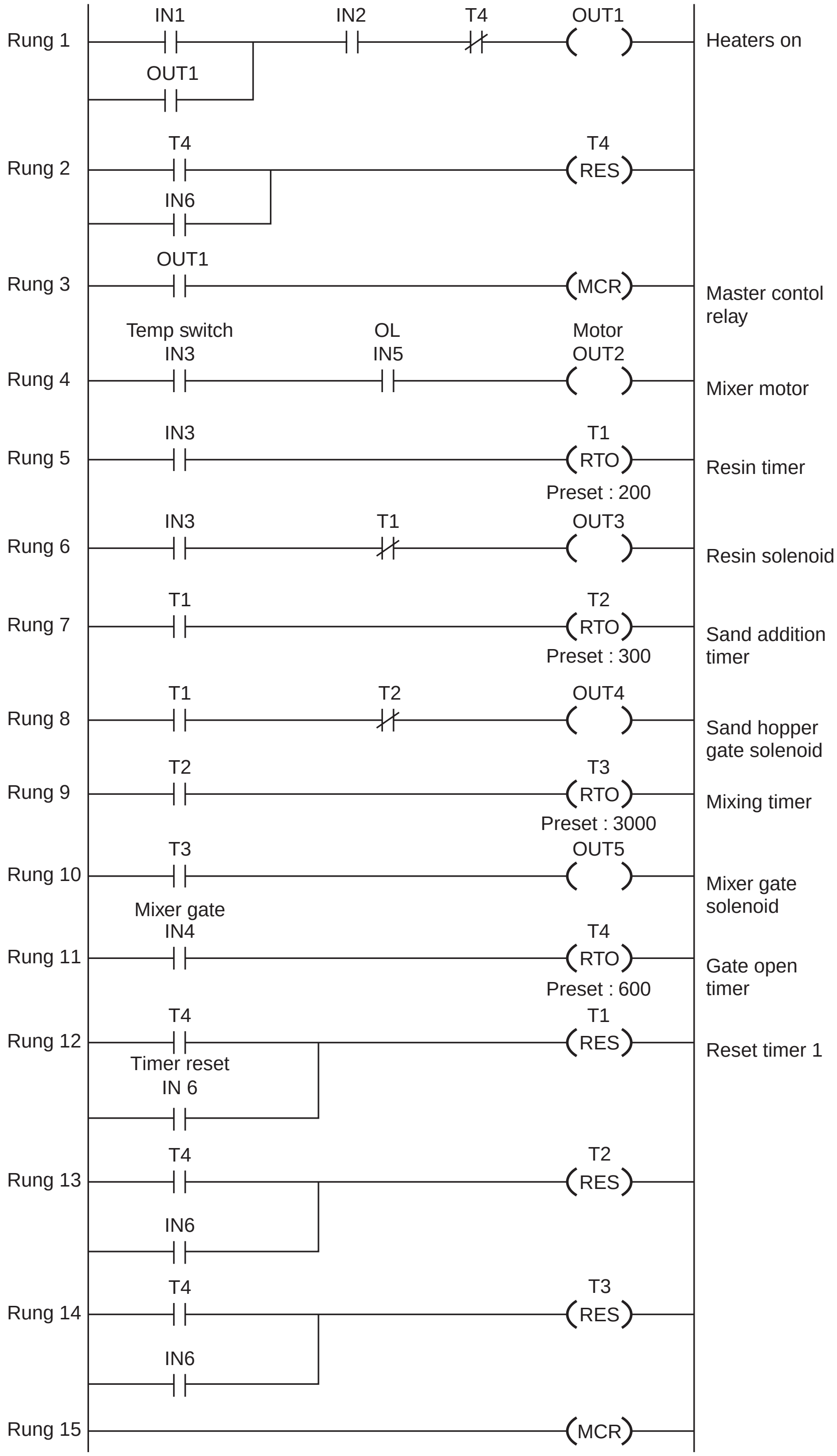


Fig. 12.43 PLC program for sand mixing machine

1. When the Start push-button is pressed, the Examine ON instruction IN1 in Rung 1 goes true. As normally closed contact of Stop push-button has been used, the Examine ON instruction IN2 is already true, and Normally closed contact of Timer T4 is also found closed. Thus the OUT1 output instruction will become true and will remain true even when Start pushbutton is released due to the programming of normally open contact of OUT1 in parallel with instruction IN1. This program is analogous to the use of holding contact in relay circuits. Output OUT1 becoming true will energise the contactor H which will switch ON the heaters.
2. Master control relay (MCR) becomes true due to the closing of normally open contact of OUT1 in Rung 3. This enables the rest of the program. Remember MCR relay has a function similar to control ON in relay circuits.
3. When the temperature in the mixer is more than 100 degrees centigrade, temperature switch will close and Examine ON instruction IN3 will become true as temperature switch is connected to input terminal IN3. Due to this instruction getting true, the mixer motor will be switched ON due to OUT2 getting true in Rung 4. IN3 instruction used in Rung 5 will start the Resin timer T1. Also the resin addition solenoid is energized as OUT3 instruction becomes true in Rung 6. Thus resin is added into the mixer.
4. When the Timer T1 times out after 20 secs, its normally closed contact in Rung 6 will open and thus Resin solenoid will be de-energised due to Output instruction OUT3 getting false.
5. The closing of normally open contacts of Timer T1 in Rung 7 and 8 will start the Sand addition Timer T2 and energise the Sand gate solenoid for the sand hopper. Thus sand gate opens to add sand into the mixer.
6. When the Timer T2 times out after 30 secs, its normally closed contact in Rung 8 will open to de-energise the sand gate solenoid, thus closing the sand gate. Timing out of Timer T2 will also start Mixing timer T3 in Rung 9 through its normally open contact., to allow a time of 300 secs for mixing the sand and resin properly.
7. When the mixing timer T3 times out, its contact in Rung 10 will close to energise the mixer gate solenoid valve for opening the mixer gate by making the OUT5 true. When the gate opens the mixed sand is thrown out as the mixer motor is running.
8. Due to opening of mixer gate, a door limit switch is actuated and thus the Examine ON instruction IN 4 will become true in the Rung 11 and will start the gate open timer T4.
9. After 60 secs the timer T4 times out and it will close its normally open contact T4 in Rung 12,13 and 14 to reset timers T1, T2 and T3.
10. In the next program scan the OUT1 in Rung 1 will become false as the Timer contact T4 will be found open. Thus heater contactor H will drop to de-energise the heaters.
11. When the Rung 2 is scanned, T4 contact will be found closed which will reset the timer T4.
12. When the Rung 3 is scanned, OUT1 contact will be found open and thus MCR instruction will become false. This will disable the whole of the program upto rung, 14, and thus the program is restored to its initial condition. If second batch of resin bonded sand is required, Start push-button is required to be pressed.

13. There is a provision in the program for resetting all the timers manually by pressing the Manual Reset push-button, which is connected to input terminal IN6. Thus the Examine ON instruction IN6 has been used in parallel with the timer T4 contact in Rungs no. 2,12,13 and 14.

REVIEW QUESTIONS

1. Mention the limitations of relay and static control circuits which have led to the use of programmable controllers.

2. How is PLC different from a ordinary personal computer.

3. Discuss the working of a PLC by drawing its block diagram.

4. Explain the Scan cycle for PLC.

5. What is watchdog timer.

6. What is the directions of information flow between the following pairs of locations.

(*a*) Input image table and input module

(*b*) Output image table and output module

(*c*) Input image table and CPU

(*d*) Output image table and CPU

(*e*) CPU and user-program memory

(*f*) CPU and variable data memory.

7. What type of variable data is stored in the variable data memory ?

8. Briefly describe why a hardwired emergency stop circuit is recommended for PLC installations.

9. Explain how a stop push-button must always be wired to PLC and why ?

10. Explain one advantage of wiring the overload contacts to an input module and then programming the overload address into the PLC program instead of wiring it in series within the motor contactor coil.

11. Explain why a master control relay will be necessary if there are OFF delay timers in the program.

12. What different types of programming languages are used to program a PLC ?

13. Define the terms, interface, real word, discrete and peripherals.

14. Briefly describe volatile and non-volatile memory.

15. Briefly describe the action of a Examine ON and Examine OFF instruction.

16. Briefly discribe the operation of Time driven Output sequencer.

17. Why the counter instruction should always be retentive. Explain how a Up-Down counter can be used to monitor number of vehicles in a parking lot.

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