HIGH VOLTAGE CIRCUIT BREAKERS

Design and Applications

Second Edition, Revised and Expanded

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To my grandson
Erik B. Dommers

PREFACE TO THE SECOND EDITION

The need for a second edition arises from the fact that, although it is generally recognized that circuit breakers represent a relatively mature technology there are some areas of this technology where changes are inevitable and where some of these changes take place continuously. The area of circuit breaker standards is one in which substantial changes have taken place. These changes have been driven primarily by the need and the desire to achieve a high level of harmonization between the International (IEC) and the American (ANSI) Circuit Breaker Standards.

New standards have recently been published and revisions to some others are in the process of being approved by both organizations. However, as new requirements are being established for the new generations of equipment, it must be recognized that a significant number of circuit breakers had been designed to meet what are now obsolete standards. These circuit breakers are still in service and consequently there is a need for preserving this type of information. It is the hope that the readers will find this second edition to be useful in providing a link between the old and the new requirements and furthermore that it can be considered to be a valuable source of information and guidance for the application of the older equipment.

Experience with the first edition has suggested the addition of some topics, which would serve to strengthen the reader's knowledge, related to the practical design and application of high voltage circuit breakers. More specifically, topics dealing with dielectric design considerations are covered in a new chapter where the basic concepts of dielectric strength field strength and types of insulation are presented. The presentation of this material has maintained the original philosophy of treating the subject based on a practical approach rather than a detailed mathematical one.

Also added are sections dealing with the application of circuit breakers that are connected to systems that have a large reactance to resistance (X/R) ratio and applications where the circuit breaker is connected directly to power generators.

The application section on capacitance switching has been revised, expanded, and updated to include recent work-related changes in the standards. The coverage of switching series and shunt reactors and of temporary voltages has been expanded in the switching overvoltages chapter, and a method for evaluating the benefits of condition monitoring is included in the final chapter.

A number of other minor corrections and additions have been made throughout the text in an attempt to provide the reader with an enhanced version of this book.

Again I am grateful to all who encouraged me to work on the second edition and who offered their comments and suggestions to make this possible.

Ruben D. Garzon

PREFACE TO THE FIRST EDITION

Ever since the time when electrical energy was beginning to be utilized, a need existed for a suitable switching device that was able to initiate and to interrupt the flow of the electric current. The early designs of such switching devices were relatively crude and the principles of their operation relied only on empirical knowledge. Circuit breakers were developed on the basis of a "cut and try" approach, but as the electrical system capacity continued to develop and grow, a more scientific approach was needed to achieve optimized designs of circuit breakers that would offer higher performance capabilities and greater reliability.

The transition of current interruption from being an empirical art to an applied science began in the 1920s. It was only then that worldwide research started to unravel the subtleties of the electric arc and its significance to the current interruption process. Since those early research days a great deal of literature on the subject of current interruption has been published. There is also a significant number of technical articles on specific applications of circuit breakers that have been published, but most of these publications are highly theoretical. What is missing are publications geared specifically to the needs of the practicing engineer. There is a need for a simple source of reference that provides simple answers to their most often-asked questions: Where does this come from? What does it mean? What can I do with it? How can I use it? How can I specify the right kind of equipment?

Circuit breakers are truly unique devices. They are a purely mechanical apparatus connected to the electrical system, where they must systematically interact with such a system providing a suitable path for the flow of the electric current; furthermore, they must provide protection and control of the electric circuit by either initiating or stopping the current flow. Combining these tasks into one device requires a close interaction of two engineering disciplines and it suggests that a good understanding of mechanical and electrical engineering principles is paramount for the proper design and application of any circuit breaker.

It is the purpose of this book to bridge the gap between theory and practice, and to do so without losing sight of the physics of the interruption phenomena. This can be done by describing in a simple fashion the most common application and design requirements and their solutions based on experience and present established practices. The strictly mathematical approach will be avoided;

however, the fundamentals of the processes will be detailed and explained from a qualitative point of view.

Beginning with a simplified qualitative, rather than quantitative, description of the electric arc and its behavior during the time when current is being interrupted, we will then proceed to describe the response of the electric system and the inevitable interaction of current and voltage during the critical initial microseconds following the interruption of the current. We will show the specific behavior of different types of circuit breakers under different conditions.

Once the understanding of what a circuit breaker must do is gained we will proceed to describe the most significant design parameters of such device. Particular emphasis will be placed in describing the contacts, their limitations in terms of continuous current requirements and possible overload conditions, and their behavior as the result of the electromagnetic forces that are present during short circuit conditions and high inrush current periods. Typical operating mechanisms will be described and the terminology and requirements for these mechanisms will be presented.

Over the years performance standards have been developed not only in the U.S. but in other parts of the world. Today, with the world tending to become a single market, it is necessary to understand the basic differences between these standards. Such an understanding will benefit anyone who is involved in the evaluation of circuit breakers designed and tested according to those different standards.

The two most widely and commonly recognized standard documents today are the ones issued by the American National Standards Institute (ANSI) and by the International Electrotechnical Commission (IEC). The standards set forth by these two organizations will be examined, their differences will be explained and by realizing that the principles upon which they are based are mainly localized operating practices, it is hoped that the meaning of each of the required capabilities will be thoroughly understood. This understanding will give more flexibility to the application engineer for making the proper choices of equipment for any specific application and to the design engineer for selecting the appropriate parameters upon which to base the design of a circuit breaker that can be considered to be a world class design because it meets the requirements of all of the most significant applicable standards.

This type of book is long overdue. For those of us who are involved in the design of these devices it has been a long road of learning. Many times not having a concise, readily available collection of design tips and general design information, we learned most of the subtleties of these designs by experience. For those whose concern is the application and selection of the devices there is a need for some guidance that is independent of commercial interests. As was said before, there have been a number of publications on the subject, but most, if not all of them, devote the treatment of the subject to the strict mathematical derivation of formulae with a textbook approach. The material presented here is limited to what is believed to be the bare essentials, the fundamentals of the fundamentals, the basic answers to the most common questions on the subject.

The book titled *Circuit Interruption Theory and Techniques* edited by Thomas Browne, Jr., and published by Marcel Dekker Inc., in 1984 partially meets the aims of the new publication. A more recent book, *Vacuum Switchgear*, written by Allan Greenwood and published by The Institution of Electrical Engineers, London, 1994, as its title implies, is limited and covers only a particular interrupting medium, vacuum. Earlier works have now become obsolete since some of the new design concepts of interrupter designs and revisions to the governing standards were not thoroughly covered. But none of these previous publications covers specific design details, applications, interpretation of standards, and equipment selection and specification.

There are a great number of practicing electrical engineers in the electrical industry, whether in manufacturing, industrial plants, construction or public utilities, who will welcome this book as an invaluable tool to be used in their day-to-day activities.

The references at the end of each chapter are intended to provide the readers with a source of additional information on the subject. These lists are by no means exhaustive, but they were selected as being the most representative in relation to the subject at hand.

The most important contributors to this book are those pioneer researchers who laid the foundations for the development of the circuit breaker technology. I am specially indebted to Lorne McConnell from whom I learned the trade and who encouraged me in my early years. I am also indebted to all those who actively helped me with their timely comments and especially to the Square D Company for their support on this project. Most of all, I am especially grateful to my wife Maggi for her support and patience during the preparation of this book.

Ruben D. Garzon

CONTENTS

1

ELECTRIC ARC FUNDAMENTALS

1.0 INTRODUCTION

From the time when the existence of the electric current flow was first established and even before the basic thermal, mechanical, and chemical effects produced by such current were determined, it had become clear that there was a need for inventing a device capable of initiating and stopping the flow of the current.

Fundamentally, there are two ways by which the flow of current can be stopped; one is to reduce the driving potential to zero, and the other is to physically separate a pair of contacts to create an open gap between the conductor that is carrying the current. Historically, the later method has been the one most commonly used to achieve current interruption.

Hanz Christian Oersted, Andre-Marie Ampere, and Michael Faraday are among the first known users of circuit breakers, and according to recorded history those early circuit breakers are known to have been a mercury switch that simply consisted of a set of conducting rods that were immersed in a pool of mercury.

Later as the current switching technology evolved, the mercury switch was replaced by a knife blade switch design, which is still widely used for some basic low-voltage, low-power applications. Today, under the present state of the art in current interruption technology, the interruption process begins at the very instant when a pair of electric contacts separate. It continues as the contacts recede from each other and as a plasma bridges the newly created gap. The interruption process is completed when the conducting plasma is deprived of its conductivity.

By recognizing that the conducting plasma is nothing more than the core of an electric arc, it becomes quite evident that inherently the electric arc constitutes a basic, indispensable, and active element in the process of current interruption.

Based on this simple knowledge, it follows that the process of extinguishing the electric arc constitutes the foundation upon which current interruption is predicated. It is rather obvious then that a reasonable knowledge of the fundamentals of arc theory is essential to the proper understanding of the interrupting process. It is intended that the following basic review describing the phenomena of electric discharges will serve to establish the foundation of the work that will be presented later dealing with current interruption.

1.1 BASIC THEORY OF ELECTRICAL DISCHARGES

The principles that govern the conduction of electricity through either a gas or a metal vapor, are based on the fact that such vapors always contain positive and negative charge carriers and that all types of discharges always involve the very fundamental processes of production, movement and final absorption of the charge carriers as the means of conveying the electric current between the electrodes.

For the sake of convenience and in order to facilitate the review of the gas discharge phenomena, the subject will be divided into the following three very broad categories:

(a) The non-self-sustaining discharge
(b) The self-sustaining discharge and
(c) The electric arc.

1.1.1 Non-Self-Sustaining Discharges

When voltage is applied across two electrodes a force proportional to the electric field strength acts upon the charge carriers. This force establishes a motion of the ions toward the cathode and of the electrons toward the anode. When the moving charges strike the electrodes they give up their charges thus producing an electric current through the gaseous medium. A continuous flow of current can take place only if the carriers whose charges are absorbed by the electrodes are continuously replaced. The replacement of the charge carriers can be made by a number of ionizing processes such as photoelectric, or thermionic emissions.

Initially, the discharge current is very small; however, as the voltage is increased it is observed that the current increases in direct proportion to the voltage applied across the electrodes until a level is reached where the charge carriers are taken by the electrodes at the same rate as they are produced. Once this equilibrium state is attained the current reaches a first recognizable stable limit that is identified as the saturation current limit. The value of the saturation current is dependent upon the intensity of the ionization; it is also proportional to the volume of gas filling the space between the electrodes and to the gas pressure.

At the saturation limit the current remains constant despite increases of the supply voltage to levels that are several times the level originally required to reach the saturation current limit. Because the saturation current is entirely dependent on the presence of charge carriers that are supplied by external ionizing agents, this type of discharge is called a non-self-sustaining discharge.

Since the charge carriers are acted upon not only by the force exerted by the electric field but by electro-static forces that are due to the opposite polarity of the electrodes, the originally uniform distribution of the charge carriers can be altered by the application of a voltage across the electrodes. It can be observed that an increase in the electrode's potential produces an increased concentration of electrons near the anode and of positive molecular ions near the cathode; thus creating what is known as space charges at the electrode boundaries.

The space charges lead to an increase in the electric field at the electrodes, which will result in a decrease of the field in the space between the electrodes. The drop of potential at the electrode is known as the anode fall of potential, or anode drop, and at the cathode fall of potential, the cathode drop.

As was mentioned previously, whenever the current reaches its saturation value, the voltage applied across the electrodes (and hence the electric field) may be substantially increased without causing any noticeable increase in the discharge current. However, as the electric field strength increases, so does the velocity of the charge carrier. Since an increase in velocity represents an increase in kinetic energy, it is logical to expect that when these accelerated charges collide with neutral particles new electrons will be expelled from these particles and thus create the condition known as shock ionization.

In the event that the kinetic energy is not sufficient for fully ionizing a particle, it is possible that it will be sufficient to re-arrange the original grouping of the electrons by moving them from their normal orbits to orbits situated at a greater distance from the atom nucleus. This state is described as the excited condition of the atoms. Once this condition is reached a smaller amount of energy will be required to expel the shifted electron from this excited atom and to produce complete ionization. It is apparent then, that with a lesser energy level of the ionizing agent, successive impacts can initiate the process of shock ionization.

The current in the region of the non-self-sustaining discharge ceases as soon as the external source is removed. However, when the voltage reaches a certain critical level the current increases very rapidly and a spark results in a self-sustained discharge in the form of either a glow discharge or an electric arc.

In many cases (for example between parallel plane electrodes), the transition from a non-self sustaining to a self-sustaining discharge leads to an immediate complete puncture or flashover which, provided that the voltage source is sufficiently high, will result in a continuously burning arc being established. In the event that a capacitor is discharged across the electrodes, the resulting discharge takes the form of a momentary spark.

In other cases, where the electric field strength decreases rapidly as the distance between the electrodes increases, the discharge takes the form of a partial flashover. In this case the dielectric strength of the gas space is exceeded only near the electrodes and as a result a luminous discharge known as "corona" appears around the electrodes.

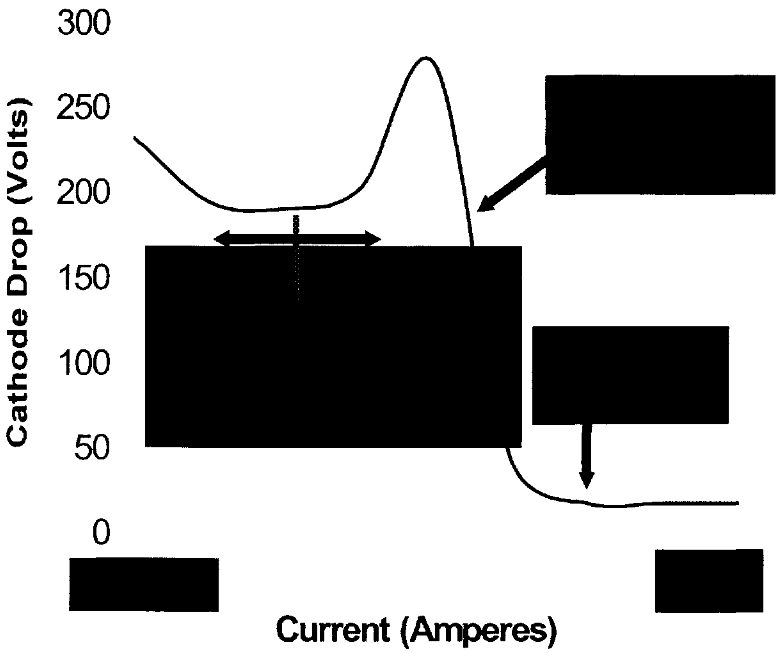

Figure 1.1 Schematic representation of the voltage-current relationship of a self-sustaining electrical discharge.

1.1.2 Self-Sustaining Discharges

The transition from a non-self-sustaining discharge to a self-sustained discharge is characterized by an increase in the current passing though the gas, whereas the voltage across the electrodes remains almost constant. When the electrode potential is increased to the point that ionization occurs freely, the positive ions produced in the gas may strike the cathode with a force that is sufficient to eject the number of electrons necessary for maintaining the discharge. Under these circumstances no external means of excitation are needed and the discharge is said to be self-sustaining.

During the initial stages of the self-sustaining discharge the current density is only in the order of a few micro-amperes per square centimeter, the discharge has not yet become luminous and consequently it is called a dark discharge. However as the current continues to increase, a luminous glow appears across the gas region between the electrodes (as illustrated in Figure 1.1), and the stage known as the "glow discharge" takes place and a luminous glow becomes visible. The colors of the glow differ between the various glowing regions and vary in accordance with the surrounding gas. In air, for example, the negative or cathode glow exhibits a very light bluish color and the positive column is salmon pink. The glow discharge characteristics have been very important for applications dealing with illumination.

The region called the normal glow region is that where the current is low and the cathode is not completely covered by the cathode glow. The cathode current density at this time is constant and is independent of the discharge current. While the region known as the abnormal glow region is observed when the cathode is completely covered by the negative glow as the result of an increase in current, it in turn produces an increase in the current density as well as a voltage drop at the anode.

As the current increases in the abnormal glow region, the cathode drop space decreases in thickness. This leads to a condition where the energy imparted to the positive ions is increased and the number of ionizing collisions encountered by an ion in the cathode drop space is decreased. The increased energy of the incoming positive ions increases the cathode temperature, which in turn leads to a condition of thermionic emission that subsequently results in an increase in current that is accompanied by a rapid collapse in the discharge voltage. During this transitional period, the physical characteristics of the discharge change from those of a glow discharge to those of a fully developed arc.

1.2 THE ELECTRIC ARC

The electric arc is a self-sustained electrical discharge that exhibits a low voltage drop, is capable of sustaining large currents, and behaves like a non-linear resistor. Though the most commonly observed arc discharge occurs across air at atmospheric conditions, the arc discharge is also observed at high and low pressures, in a vacuum environment, and in a variety of gases and metal vapors.

The gases and vapors that serve as conductors for the arc originate partly from the electrodes and partly from the surrounding environment and reaction products. The description of the electric arc will be arbitrarily divided into two separately identifiable types of arcs. This is done only as an attempt to provide a simpler way to relate future subjects dealing with specific interrupting technologies. The first arc type will be identified as the high-pressure arc and the second type, which is an electric arc burning in a vacuum environment, will be identified as a low pressure-arc.

1.2.1 High-Pressure Arcs

High-pressure arcs are considered to be those arcs that exist at, or above atmospheric pressure. The high-pressure arc appears as a bright column characterized by a small, highly visible, brightly burning core that consists of ionized gases that convey the electric current. The core of the arc is always at a very high temperature and therefore the gases are largely dissociated. The temperature of the arc core under conditions of natural air cooling reach temperatures of about 6000 Kelvin and when subjected to forced cooling, temperatures in excess of 20,000 Kelvin have been observed.

The higher temperatures recorded when the arc is being cooled at first appears to be a contradiction. One would think that under forced cooling conditions the temperature should be lower, however, the higher temperature is the result of a reduction in the arc diameter which produces an increase in the current density of the plasma and consequently leads to the observed temperature increase.

By comparing the cathode region of the arc with the cathode region of the glow discharge, the cathode of the glow discharge has a fall of potential in the range of 100 to 400 volts. It has a low current density, the thermal effects do not contribute to the characteristics of the cathode, and the light emitted from the region near the cathode has the spectrum of the gas surrounding the discharge. In contrast, the cathode of the arc has a fall of potential of only about 10 volts, a very high current density, and the light emitted by the arc has the spectrum of the vapor of the cathode material.

The fact that the arc can be easily influenced and diverted by the action of a magnetic field (or by the action of a high-pressure fluid flow), and that the arc behaves as a non-linear ohmic resistor, are among some of the most notable arc characteristics that have a favorable influence during the interrupting process. If the arc behaves like a resistor it follows that the energy absorbed in the arc is equal to the product of the arc voltage drop and the current flowing through the arc.

Under constant current conditions the steady state arc is in thermal equilibrium, which means that the power losses from the arc column are balanced by the power input into the arc. However, due to the energy storage capability of the arc, there is a time lag between the instantaneous power loss and the steady state losses. Therefore, at any given instant the power input to the arc plus the power stored in the arc is equal to the power loss from the arc. This time lag condition, as will be seen later in this chapter, is extremely significant during the time of interruption near current zero.

As a result of the local thermal equilibrium it is possible to treat the conducting column of the arc as a hot gas, which satisfies the equations of conservation of mass, momentum, and energy. To which, all of the thermodynamic laws and Maxwell's electromagnetic equations apply. This implies that the gas composition and its thermal and electrical conductivity are factors that are essentially temperature dependent.

The voltage drop across an arc can be divided into the three distinct regions, as illustrated in Figure 1.2. For short arcs, a voltage drop representing a large percentage of the total arc voltage appears in a relatively thin region located immediately in front of the cathode. This voltage drop across the region near the cathode is typically between 10 to 25 volts and is primarily a function of the cathode material. In the opposite electrode, the anode drop is generally between 5 to 10 volts.

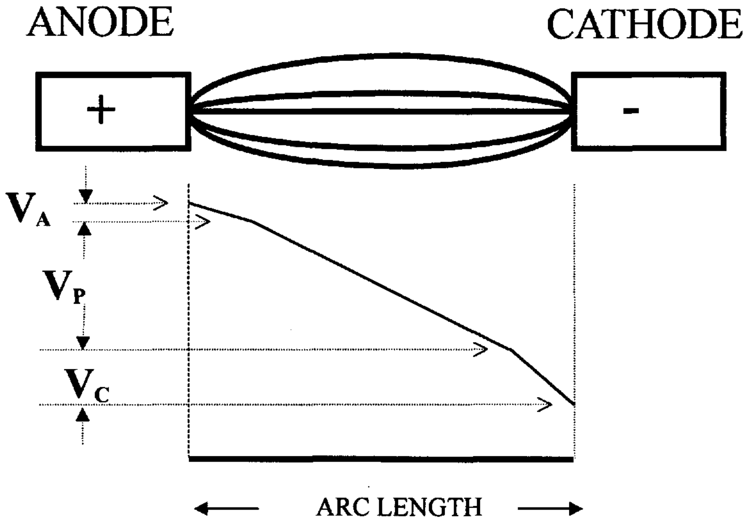

Figure 1.2 Voltage distribution of an arc column. V_A represents the anode voltage V_C represents the cathode voltage, and V_P represents the positive column voltage.

The voltage drop across the positive column of the arc is characterized by a uniform longitudinal voltage gradient. Its magnitude, in the case of an arc surrounded by a gaseous environment, depends primarily on the type of gas, the gas pressure, the magnitude of the arc current, and the length of the column itself. For the positive column gradient, voltage values ranging from only a few volts per centimeter to several hundred volts per centimeter have been observed.

The first extensive study of the electric arc voltage relationships, for moderate levels of current and voltage, was made by Hertha Ayrton [1], who developed a formula defining the arc voltage on the basis of empirical experimental results. The relationship is still considered to be valid and is still widely used, although within a limited range of current and voltage.

The classical Ayrton equation is given as:

$$e_0 = A + Bd + \frac{C + Dd}{i}$$

where:

e_0 = arc voltage
d = arc length
i = arc current
A=19, B=11.4, C=21.4 and D=3

The values of the constants *A, B, C,* and *D* are empirical values for copper electrodes in air.

The current density at the cathode is practically independent of the arc current, but it is strongly dependent upon the electrode material. In refractory materials that have a high boiling point, such as carbon, tungsten, or molybdenum the cathode spot is observed to be relatively fixed. The cathode operates by thermionic emission and its current density is in the order of 10^3 amps per cm^2. The "cold cathode arc" is characteristic of low boiling point materials such as copper and mercury. The cathode spot in these materials is highly mobile, it operates in some form of field emission, and its current density is in the order of 10^6 to 10^7 amps per cm^2. In those materials that have a low boiling point, a considerable amount of material is melted away from the electrodes. The material losses of refractory materials is only due to vaporization. Under identical arcing conditions the refractory material losses are considerably less than the losses of low boiling point materials, and consequently this constitutes an important factor that must be kept in mind when selecting materials for circuit breaker contacts.

1.2.2 Low-Pressure (Vacuum) Arcs

The low-pressure or vacuum arc, like those arcs that occur at or above atmospheric pressure, share most of the same basic characteristics just described for the electric arc. But the most significant differences are (a) an average arc voltage of only about 40 volts, which is significantly lower than the arc voltages observed in high pressure arcs; (b) the positive column of the vacuum arc is solely influenced by the electrode material because the positive column is composed of metal vapors that have been boiled off from the electrodes. The positive column of the high-pressure arc is made up of ionized gases from the arc's surrounding ambient, and perhaps the most significant and fundamental difference, (c) the unique characteristic of a vacuum arc that allows the arc to exist in either a diffuse mode or in a coalescent or constricted mode.

The diffuse mode is characterized by a multitude of fast-moving cathode spots, together with what looks like a multiple number of arcs in parallel. It should be pointed out that this is the only time when arcs in parallel can exist without the need of balancing, or stabilizing inductance. The magnitude of the current being carried by each of the cathode spots is a function of the contact material, and in most cases it is only approximately 100 amperes. Higher current densities are observed on refractory materials such as tungsten or graphite, while lower currents correspond to materials that have a low boiling point such as copper.

When the current is increased beyond a certain limit, which depends on the contact material, one of the roots of the arc gets concentrated into a single spot at the anode, while the cathode spots split to form a closely knit group of highly mobile spots as shown in Figure 1.3. If the cathode spots are not influenced by external magnetic fields, they move randomly around the entire contact surface at very high speeds.

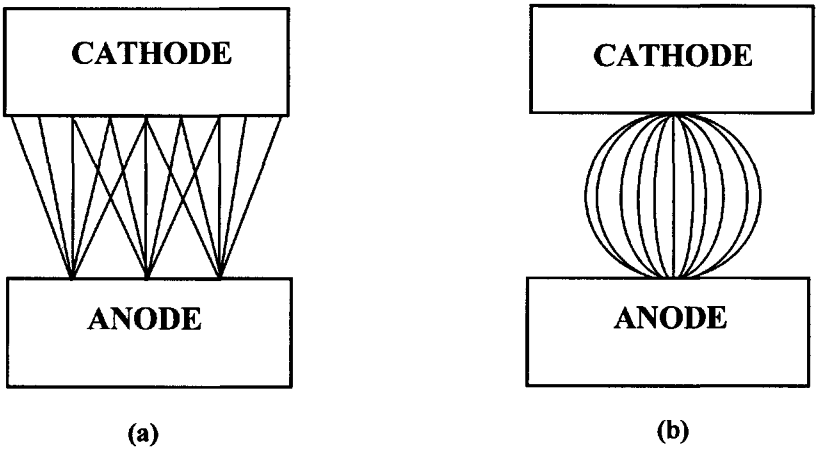

Figure 1.3 Outline of an arc in vacuum illustrating the characteristics of the arc (a) in a diffuse mode and (b) in a constricted mode.

When the current is increased even further, a single spot appears at the electrodes. The emergence of a single anode spot is attributed to the fact that large currents greatly increase the collision energy of the electrons and consequently when they collide with the anode, metal atoms are released thus producing a gross melting condition of the anode. There is a current threshold at which the transition from a diffuse arc to a constricted arc mode takes place. This threshold level is primarily dependent upon the electrode size and the electrode material. With today's typical, commercially available vacuum interrupters, diffused arcs generally occur at current values below 15 kilo-amperes and therefore in some ac circuit breaker applications it is possible for the arc to change from a diffuse mode to a constricted mode as the current approaches its peak and then returns to a diffuse mode as the current approaches its natural zero crossing. It follows then, that the longer the time prior to current zero that an interrupter is in the diffuse mode, the greater its interrupting capability is.

1.3 THE ALTERNATING CURRENT ARC

The choice of sinusoidal alternating currents as the standard for the power systems is convenient and fortuitous in more ways than one. As it was described earlier, in the case of an stable arc, as the arc current increases the arc resistance decreases due to the increase in temperature which enhances the ionizing process. When the current decreases, the ionization level also decreases while the arc resistance increases. Thus, there is a collapse of the arc shortly before the alternating current reaches its normal zero value at the end of each half cycle. The arc will re-ignite again when the current flows in the opposite direction, during the subsequent half cycle, provided that the conditions across the electrodes are still propitious for the existence of the arc. The transition time between the two half cycles is greatly influenced by the medium on which the arc is being produced and by the characteristics of the external circuit.

The arc current as it approaches zero is slightly distorted from a true sine wave form due to the influence of the arc voltage, and therefore the arc is extinguished just prior to the nominal current zero crossing. The current zero transition is accompanied by a sharp increase in the arc voltage, and the peak of this voltage is defined as the peak of extinction voltage. When the peak of the extinction voltage reaches a value equal to the instantaneous value of the voltage applied to the arc by the circuit, the arc current cannot be maintained and thereafter, the current in the opposite direction cannot be re-established immediately. Thus, at every current zero there is a finite time period when there cannot be any current flow. This is the time period generally referred as the "current zero pause." During the zero current period, the discharge path is partially de-ionized on account of the heat losses and, therefore, the electric field needed to re-establish the arc after the reversal of the current becomes greater than the field required to maintain the arc. This means that the required re-ignition voltage is higher than the voltage that is necessary to sustain the arc, and therefore the current will remain at its zero value until the re-ignition voltage level is reached. If the arc is re-established, the current increases and the voltage falls reaching its minimum value, which is practically constant during most of the half cycle, and in the region of maximum current.

Provided that the electrodes are symmetrical, the sequences that have just been described will continue to repeat during each of the subsequent half cycles. In most cases, however, there will be some deviations in the arc's behavior, which arise from differences in the electrode materials, cooling properties, gas ambient, etc. This asymmetric condition is specially accentuated when the electrodes are each made of different materials.

The time window that follows a current zero and during which arc re-ignition can occur depends upon the speed at which the driving voltage increases at the initiation of each half cycle and on the rate at which de-ionization takes place in the gap space. In other words, the re-ignition process represents the relationship between the rate of recovery of the supply voltage and the rate of de-ionization or dielectric recovery of the space across the electrode gap.

1.4 THE CURRENT INTERRUPTION PROCESS

In the preceding paragraphs the electric arcs were assumed to be either static, as in the case of direct current arcs, or quasi static, as in the case of alternating current arcs. What this means is that we had assumed that the arcs were a sustained discharge, and that they were burning continuously. However, what we are interested in is not the continuously burning arc but rather those electric arcs that are in the process of being extinguished. As we have learned, current interruption is synonymous with arc extinction, and since we further know that the interrupting process is influenced by the characteristics of the system and by the arc's capacity for heat storage, we can expect that the actual interruption process, from the time of the initial creation of the arc until its extinction, will depend primarily on whether the current changes in the circuit are forced by the arc discharge, or whether those changes are controlled by the properties of the power supply. The first alternative can be observed during direct current interruption when the current must be forced to zero. The second case is alternating current interruption, when a current zero naturally occurs twice during each cycle.

1.4.1 Interruption of Direct Current

Although the subject relating to direct current interruption does not enter into the later discussion, a brief explanation of the basics of direct current interruption is given for reference and general information purposes.

The interruption of direct current sources differs in several respects from the phenomena involving the interruption of alternating currents. The most significant difference is the obvious fact that in direct current circuits there are no natural current zeroes and consequently a current zero must be forced in some fashion in order to achieve a successful current interruption. The forcing of a current zero is done either by increasing the arc voltage to a level that is equal to, or higher than the system voltage, or by injecting into the circuit a voltage that has an opposite polarity to that of the driving voltage which, in reality, is the equivalent of forcing a reverse current flow into the source.

Generally the methods used for increasing the arc voltage consist of (a) simply elongating the arc column, (b) constricting the arc by increasing the pressure of the arc's surroundings to decrease the arc diameter and increase the arc voltage, or (c) introducing a number of metallic plates along the axis of the arc in such a way that a series of short arcs are developed.

With the last approach it is easy to see that as a minimum, the sum of the cathode and anode drops (which total at least 30 volts), can be expected for each arc. Since the arcs are in series, their voltage drop is additive and the final value of the arc voltage is simply a function of the number of pairs of interposing plates. The second method, that is driving a reversed current, is usually accomplished by discharging a capacitor across the arc. The former method is commonly used on low voltage applications, while the later method is used for high voltage systems.

For a better understanding of the role played by the arc voltage during the interruption of a direct current, let us consider a direct current circuit that has a voltage E, a resistance R, and an electric arc, all in series with each other. The current in the circuit and therefore the current in the arc will adjust itself in accordance with the values of the source voltage E, the series resistance R, and the arc characteristics.

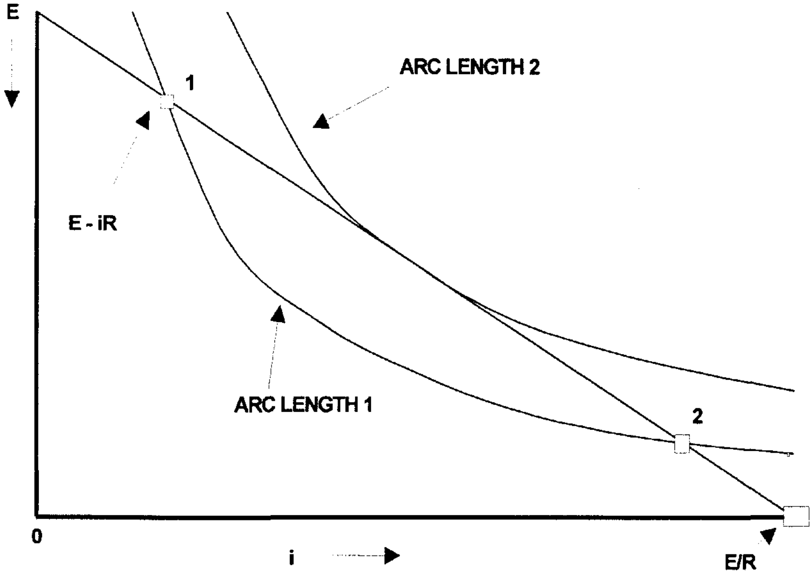

Figure 1.4 Relationships of arc and system voltages during the interruption of direct current.

By referring to Figure 1.4, where the characteristics of the arc voltage are shown as a function of the current for two different arc lengths, it is seen that the arc voltage e_0 is smaller than the supply voltage E by an amount equal to iR, so that $e_0 = E - iR$. If the straight line that represents this voltage is plotted as shown in the figure, it is seen that this line intercepts the curve representing the arc characteristics for length 1 at the points indicated as 1 and 2. Only at the intersection of these points, as dictated by their respective currents, is it possible to have a stable arc. If, for example, the current corresponding to point 2 increases, it can be seen that the arc voltage is too low, and if the current decreases the corresponding arc voltage is too high. Therefore the current will always try to revert to its stable point. In order to obtain a stable condition at point 1 it will be necessary for the circuit to have a very high series resistance and a high supply voltage. We already know that the net result of lengthening the arc is an increase in the arc resistance and a reduction in current, provided that the supply voltage remains constant. However, and as is generally the case in practical applications, some resistance is always included in the circuit and the reduction of the current will produce a corresponding reduction in the voltage across the series resistance. The electrode voltage is thus increased until eventually, when the arc is extinguished, it becomes equal to the system voltage. These conditions are shown graphically in Figure 1.4 for the limiting case where the arc characteristics of the longer arc represented by the curve labeled length 2 have reached a position where it no longer intercepts the circuit characteristics that are represented by the line $E - iR$, and therefore the condition where the arc can no longer exist has been reached.

When inductance is added to the circuit we find that the fundamental equation for this inductive circuit can we represented as follows:

$$L\frac{di}{dt} = (E - iR) - e_a = \Delta e$$

This equation indicates that the inductive voltage produced during interruption is equal to the source voltage E reduced by the voltage drop across the inherent resistance of the circuit, and by the arc voltage. For the arc to be extinguished the current i must continually decrease, which in turn suggests that the derivative of the current (di/dt) must be negative.

As seen in the equation, the arcing conditions at the time of interruption are significantly changed in relation to the magnitude of the inductance L. Since the inductance opposes the current changes, the falling current results in an induced electro-motive force (e.m.f.), which is additive to the source voltage. The relationship between the source voltage and the arc voltage still holds for the inductive circuit, therefore, it is necessary to develop higher arc voltages, which require that the rupturing arc length be increased to provide the additional voltage. It is also important to remember that when interrupting a direct current circuit, the interrupting device must be able to dissipate the total energy that is stored in the circuit inductance.

1.4.2 Interruption of Alternating Currents

As described in the previous section, in order to extinguish a direct current arc it is required to create, or in some way force a current zero. In an alternating current circuit the instantaneous value of the current passes through zero twice during each cycle and therefore the zero current condition is already self-fulfilled consequently, to interrupt an alternating current it is only necessary to prevent the re-ignition of the arc after the current has passed through zero. It is for this reason that de-ionization of the arc gap close to the time of a natural current zero is of utmost importance. While any reduction of the ionization of the arc gap close to the point of a current peak is somewhat beneficial, this action does not significantly aid in the interrupting process. However, because of thermodynamic constrains that exist in some types of interrupting devices, it is advisable that all appropriate measures to enhance interruption be taken well in advance of the next natural current zero, at which time interruption is expected to take place. Successful current interruption depends on whether the dielectric withstand capability of the arc gap is greater than the increasing voltage that is being impressed across the gap by the circuit in an attempt to re-establish the flow of current. The dielectric strength of the arc gap is primarily a function of the interrupting device. While the voltage appearing across the gap is a function of the circuit constants.

At very low frequencies, in the range of a few cycles but well below the value commonly used in general for power frequencies, the rate of change of the current passing through zero is very small. In spite of the heat capacity of the arc column, the temperature and the diameter of the arc have sufficient time to adjust to the instantaneous values of the current. Therefore, when the current drops to a sufficiently small value, (less than a few amperes depending upon the contact gap), the alternating current arc will self-extinguish unless the voltage at the gap contacts, at the time of interruption, is sufficiently high to produce a glow discharge.

Normal power application frequencies, which are generally in the range of 16 2/3 to 60 Hertz, are not sufficiently low to ensure that the arc will go out on its own. Experience has shown that an alternating current arc, supported by a 50 Hz system of 30 kilovolts that is burning across a pair of contacts in open air and up to 1 meter in length, cannot be extinguished. Special measures need to be taken if the effective current exceeds about 10 amperes. This is due to the fact that at these frequencies when the current reaches its peak value the electric conductivity of the arc is relatively high and since the current zero period is very short the conductivity of the arc, if the current is relatively large, can not be reduced enough to prevent re-ignition. However, since the current oscillates between a maximum positive and a maximum negative value there is a tendency to extinguish the arc at the current zero crossing due to the thermal lag previously mentioned. The time lag between temperature and current is commonly referred to as the "arc hysteresis".

When the alternating current passes through its zero, the arc voltage takes a sudden jump to a value equal to the sum of the instantaneous peak value of the extinguishing voltage from the previous current loop, plus the peak value of the re-ignition voltage of the next current loop, which is associated with the reversal of the current.

In the event that the arc is re-ignited, immediately after the re-ignition has taken place the arc voltage becomes relatively constant and of a significantly lower magnitude, as illustrated in Figure 1.5. In order for a re-ignition to occur, the applied voltage must exceed the value of the total re-ignition voltage (e_t).

One practical application, derived from observing the characteristics of the extinction voltage, is that during testing of an interrupting device, it provides a good indication of the behavior of the device under test. A good, large and sharp peak of voltage indicates that the interrupter is performing adequately, but if the peak of the voltage begins to show a smooth round top and the voltage magnitude begins to drop, it is a good indication that the interrupter is approaching its maximum interrupting limit.

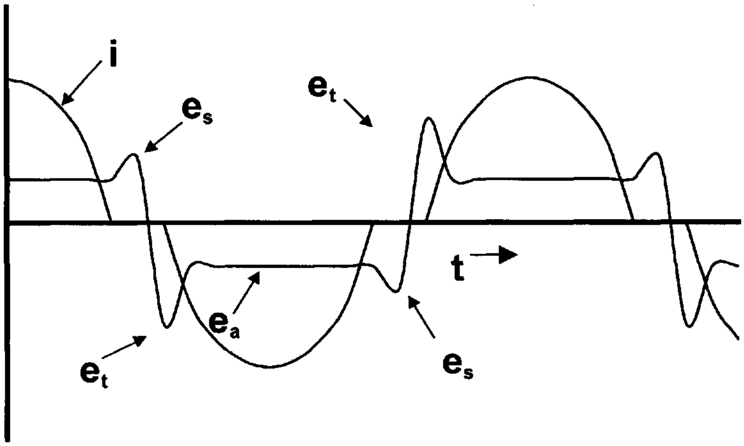

Figure 1.5 Typical variations of current and voltage showing the peak of extinction voltage e_s and peak of re-ignition voltage e_t.

If re-ignition does not happen, the flow of the current will cease and therefore interruption will be accomplished. From what has been described, it is rather obvious that the most favorable conditions for interruption are those in which the applied voltage is at its lowest when the current reaches the zero value, however this ideal condition can be realized only with a purely resistive circuit.

1.4.2.1 Interruption of Resistive Circuits

In an alternating current circuit containing only resistance, or having a negligible amount of inductance, the current is practically in phase with the voltage, and during steady state operating conditions, both the current and the voltage reach their zero value simultaneously. But when a pair of contacts separate and an arc is developed between the contacts, the phase relationship still exists in theory, but in practice the current will reach the zero value slightly ahead of the voltage. As the current (I) passes through zero, the instantaneous value of the peak of extinction voltage, shown as e_s in Figure 1.6, is equal to the instantaneous value of the applied voltage (E). From this point, no new charges are produced in the gas space between the contacts and those charges still present in the gas space are being neutralized by the de-ionized processes that are taking place. The gas space and the electrodes continue to increasingly cool down and therefore the minimum voltage required for the arc to re-ignite is increasing with time. The general idea of this increase is shown in the curve marked (1) in Figure 1.6. If the applied voltage E, shown as curve 2, rises at a higher rate than the re-ignition voltage e_t so that the corresponding curves intersect, then the arc will be re-established and will continue to burn for an additional half cycle, at the end of which the process will be repeated. It will be assumed that during this time the gap length had increased and

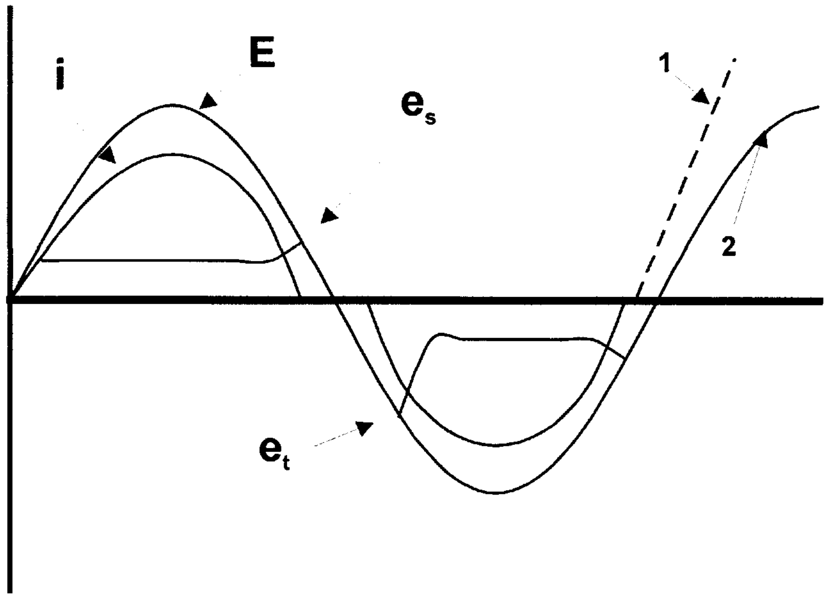

Figure 1.6 Interruption of a purely resistive circuit showing the current, voltages, and recovery characteristics for the electrode space (1) and for the system voltage (2).

therefore the arc voltage and the peak of the extinction voltage can be assumed to be larger than before. The increase in the gap length will also provide an additional withstand capability and if the supply voltage is less than the re-ignition voltage, then a successful interruption of the current in the circuit will be achieved.

1.4.2.2 Interruption of Inductive Circuits

Generally, in an inductive circuit the resistance is rather small in relation to the inductance and therefore there is a large phase angle difference between the voltage and the current. The current zero no longer occurs at the point where the voltage is approaching zero but instead when it is close to its maximum value. This implies that the conditions favor the re-striking of the arc immediately after the current reversal point.

It is important to note that in actual practice, all inductive circuits have a certain small amount of self capacitance such as that found between turns and coils in transformers and in the self-effective capacitance of the device itself in relation to the ground.

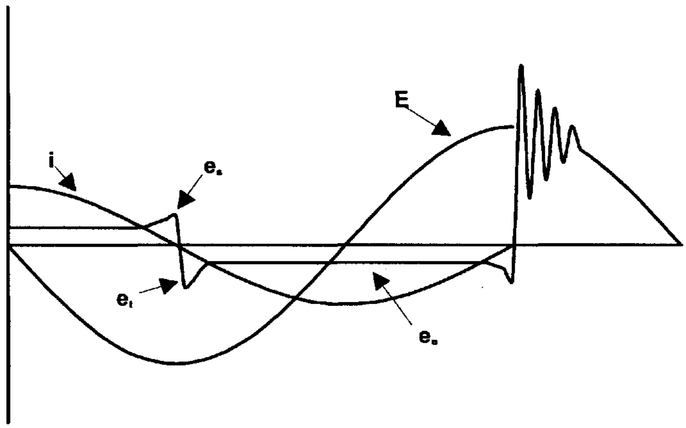

Figure 1.7 Current and voltage characteristics during interruption of an inductive circuit.

Although the effective capacitance, under normal conditions, can be assumed to be very small, it plays an important role during the interrupting process. The capacitance to ground appears as a parallel element to the arc, and therefore at the instant of current zero the capacitance is charged to a voltage equal to the maximum value of the supply voltage plus the value of the peak of the extinction voltage.

When the arc is extinguished, the electromagnetic energy stored in the inductance is converted into electrostatic energy in the capacitance and vice versa. The natural oscillations produced by the circuit are damped gradually by the effects of any resistance that may be present in the circuit and since the oscillatory frequency of the inductance and the capacitance is much greater than the frequency of the source, the supply voltage may be regarded as being constant during the time duration of the oscillatory response.

These voltage conditions are represented in Figure 1.7. During the interruption of inductive alternating circuits, the recovery voltage can be expected to reach its maximum value at the same time the current is interrupted. However, due to the inherent capacitance to ground, the recovery voltage does not reach its peak at the same instant the current is interrupted and, therefore, during this brief period a transient response is observed in the circuit.

1.4.2.3 Interruption of Capacitive Circuits

The behavior of a purely capacitive circuit during the interruption process is illustrated in Figure 1.8. It should be noted that in contrast with the high degree of difficulty that is encountered during the interruption of an inductive circuit, when interrupting a capacitive circuit the system conditions are definitely quite favorable for effective interruption at the instant of current zero because the supply voltage that appears across the electrodes is increased at a very slow rate.

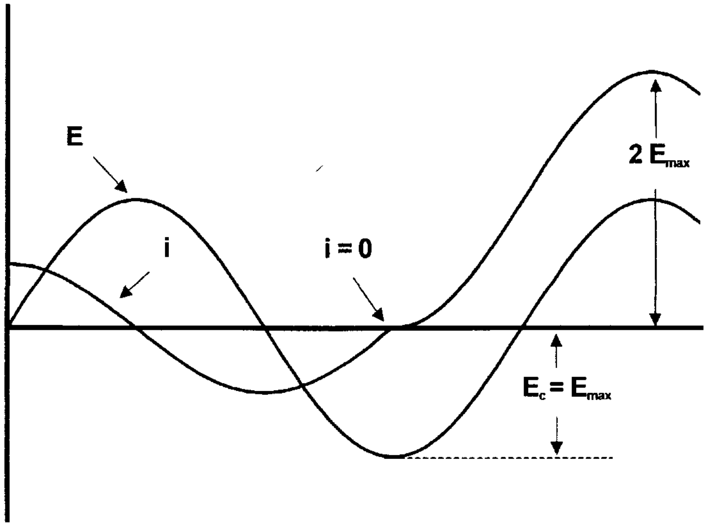

Figure 1.8 Voltage and current characteristics during the interruption of a capacitive circuit.

At the normal current zero, when the arc interruption has taken place, the capacitor is charged to, approximately, the maximum value of the system voltage. The small difference that may be observed is due to the arc voltage, however, the magnitude of the arc voltage is small in comparison to the supply voltage and generally it can safely be neglected.

At interruption, and in the absence of the current, the capacitor will retain its charge, and the voltage across the gap will be equal to the algebraic sum of the applied voltage and the voltage trapped in the capacitor. The total voltage increases slowly from an initial value equal to zero, until one half of a cycle later the voltage across the gap reaches twice the magnitude of the supply voltage. There is a relative long recovery period, however, that may enable the gap to recover its dielectric strength without re-igniting. Under certain circumstances there may be re-strikes that could lead to a voltage escalation condition. This particular condition will be discussed later in Chapter 4 dealing with high voltage transients.

1.5 REVIEW OF MAIN THEORIES OF AC INTERRUPTION

The physical complexity in the behavior of an electric arc during the interrupting process has always provided the incentive for researchers to develop suitable models to describe this process. Over the years many researchers have advanced a variety of theories. In the early treatments of the interruption theory, investigative efforts were concentrated at the current zero region, which most obviously is the region when the alternating current arc either re-ignites or is extinguished.

Recently, models of the arc near the current maximum have been devised for calculating the diameter of the arc. These models are needed since the arc diameter constitutes one of the critical dimensions needed for optimizing the geometry of the nozzles that are used in gas blasted interrupters. It should be recognized that all of these models provide only an approximate representation of the interrupting phenomena. But, as the research continues and with the aid of the digital computer, more advanced and more accurate models that include partial differential equations describing complex gas flow and thermodynamic relationships are being developed.

In the section that follows, a summary of qualitative descriptions of some of the early classical theories and of some of the most notable recent ones is presented. The chosen theories are those that have proved to closely represent the physical phenomena, or have been used as the basis for the development of more complex, combined modern day theories.

One of the early theories, which is usually referred to as the wedge theory, is now largely ignored. However, it is briefly mentioned here because of the strong influence it had among researchers during the early days in the area of arc interruption and of its application to the emerging circuit breaker technology.

1.5.1 Slepian's Theory

Joseph Slepian introduced the first known formal theory of arc interruption in 1928 [2]. The Slepian theory, also known as the "race theory", simply states that successful interruption is achieved whenever the rate at which the dielectric strength of the gap increases faster than the rate at which the reapplied system voltage grows.

Slepian visualized the process of interruption as beginning immediately after a current zero when electrons are forced away from the cathode and when a zone, or thin sheath composed of positive ions, is created in the space immediately near the cathode region.

He believed that the dielectric withstand of this sheath had to be greater than the critical breakdown value of the medium where interruption had taken place. The interrupting performance depended on whether the rate of ion recombination, which results in an increase in the sheath thickness, is greater than the rate of rise of the recovery voltage which increases the electric field across the sheath. The validity of this theory is still accepted, but within certain limitations. The idea of the sheath effects is still important for predicting a dielectric breakdown failure, which is the type of breakdown that occurs within several hundredths of microseconds after current zero, when the ion densities are low. However this mechanism of failure is not quite as accurate for the case of thermal failures, which generally occur at less than ten microseconds after current zero, when the ions densities are still significant and when the sheath regions are so thin that they can usually be neglected. The concept of the race theory is graphically illustrated in Figure 1.9.

1.5.2 Prince's Theory

This theory, which is known as the displacement or wedge theory, was advocated by D. C. Prince [3] in the U.S. and by F. Kesselring [4] in Germany. According to this theory, the circuit is interrupted if the length of the gas discharge path introduced into the arc increases during the interrupting period to such an extent that the recovery voltage is not sufficiently high to produce a breakdown in this path. This theory also claims that as soon as the current zero period sets in, the arc is cut in two by a blast of cooling gases and the partly conductive arc halves of the arc column are connected in series with the column of cool gas, which is practically non-conductive. If it is assumed that the conductivity of the arc stubs is high in comparison to that of the gas, then it can be assumed that the stubs can be taken as

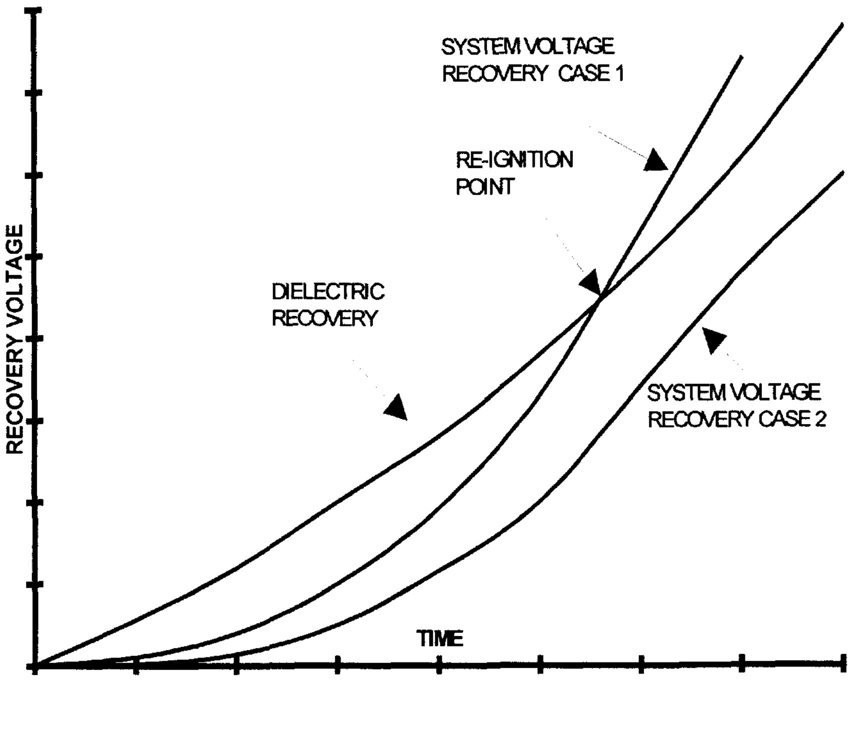

Figure 1.9 Graphical representation of the "race theory".

an extension of the electrodes. In that case the dielectric strength of the path between the electrodes is approximately equal to the sparking voltage of a needle point gap in which breakdown is preceded by a glow discharge. At the end of this current zero period, which corresponds to the instant t_l, the two halves of the arc are separated by a distance

$$D = 2vt$$

where v is the flow velocity of the cooling medium and t is the time duration of the current period. Assuming, for example, the interruption of an air blast circuit breaker where it is given that the current zero time $t = 100$ microseconds and the air flow velocity $v = 0.3$ millimeters per microsecond (which corresponds to the velocity of sound in air), then using the previously given equation for the space of cool air, the distance between the electrodes is $D = 60$ millimeters. Now referring to Figure 1.10 we find that for a 60 mm distance, the withstand capability should be approximately 50 kV.

1.5.3 Cassie's Theory

Among the first useful differential equations describing the dynamic behavior of an arc was the one presented by A. M. Cassie in 1939 [5]. Cassie developed his equation for the conductivity of the arc based on the assumption that a high current arc is governed mainly by convection losses during the high current time interval.

Under this assumption a more or less constant temperature across the arc diameter was maintained. However, as the current changes so does the arc cross section, but not the temperature inside the arc column. These assumptions were verified experimentally by measurements taken upstream of the vena contracta of nozzles commonly used in gas blast circuit breakers. Under the given assumptions, the steady state conductance G of the model is simply proportional to the current, so that the steady state voltage gradient E_o is fixed. To account for the time lag that is due to the energy storage capacity Q, and the finite rate of energy losses N, the concept of the arc time constant θ was introduced.

This "time constant" is given by:

$$\theta = \frac{Q}{N}$$

The following expression is a simplified form of the Cassie equation. This equation is given in terms of instantaneous current.

$$\frac{d}{dt}(G^2) = \frac{2}{\theta}(\frac{I}{E_0})^2$$

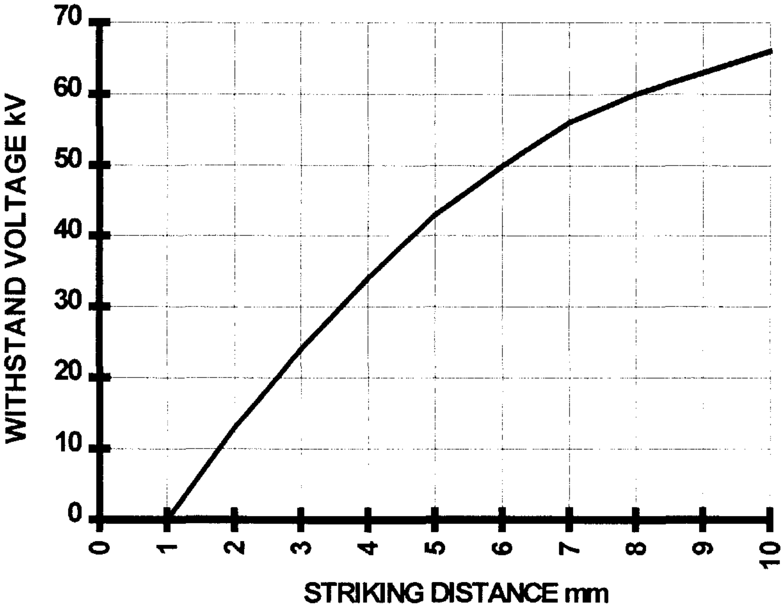

Figure 1.10 Withstand capability of a pair of plane electrodes in air at atmospheric pressure.

For the high current region, data collected from experimental results is in good agreement with the model. However, around the current zero region, agreement is good only for high rates of current decay. Theoretically and practically, at current zero the arc diameter never decays to zero to result in arc interruption. At current zero there is a small filament of an arc remaining with a diameter of only a fraction of a millimeter. This filament is still a high temperature plasma that can be easily transformed into an arc by the reappearance of a sufficiently high supply voltage. The Cassie model, in many cases, is referred to as the high current region model of an arc. This model has proved to be a valuable tool for describing the current interruption phenomena, especially when it is used in conjunction with the Mayr model.

1.5.4 Mayr's Theory

O. Mayr took a radically different approach than Cassie and in 1943 he published his theory [6]. He considered an arc column where the arc diameter is constant and where the arc temperature varies as a function of time and radial dimension. He further assumed that the decay of the temperature of the arc was due to thermal conduction and that the electrical conductivity of the arc was dependent on temperature.

From an analysis of the thermal conduction in Nitrogen at 6000 Kelvin and below, Mayr found only a slow increase of heat loss rate in relation to the axial temperature, therefore he assumed a constant power loss N_0, which was independent of temperature or current. The resulting differential equation is:

$$\frac{1}{G}\frac{dG}{dt} = \frac{1}{\theta}\left(\frac{EI}{N_0} - 1\right)$$

where:

$$\theta = \frac{Q_0}{N_0}$$

The validity of this theory during the current zero period is generally acknowledged and most investigators have successfully used the Mayr model near current zero primarily because the radial losses in this region are the most dominant and controlling factor.

1.5.5 Browne's Combined Theory

It has been observed that in reality, the arc temperature is generally well above the 6000 K assumed by Mayr and it is more likely to be in excess of 20,000 K. These temperatures are so high that they lead to a linear increase of the gas conductivity, instead of the assumed exponential relationship. To take into consideration these temperatures and in order to have a proper dynamic response representation, it is necessary that, in a model like Mayr's, the model must closely follow an equation of Cassie's type during the current controlled regime.

T. E. Browne recognized this need and in 1948 [7] he developed a composite model using an equation similar to Cassie's to define the current controlled arc regime, and then converting it to a Mayr-like equation for the temperature controlled regime, and in the event that interruption did not occur at the intended current zero, he reverted again to the Cassie model. The transition point where each of these equations was considered to be applicable was assumed to be at an instant just a few microseconds around the point where the current reached its normal zero crossing.

In 1958 Browne extended the application of his combined model [8] to cover the analysis of thermal re-ignitions that occur during the first few microseconds following the critical, post current zero energy balance period.

Starting with the Cassie and the Mayr equations, and assuming that before current zero the current is defined by the driving circuit, and that after current zero, the voltage applied across the gap is determined strictly by the arc circuit, Browne assumed that the Cassie equation was applicable to the high current region prior to current zero and also shortly after current zero following a thermal re-ignition. The Mayr equation was used as a bridge between the regions where the Cassie concept was applied. Browne reduced the Cassie and the Mayr equations to the following two expressions:

a) For the Cassie's period prior to current zero

$$\frac{d}{dt}\left(\frac{1}{R^2}\right)+\frac{2}{\theta}\left(\frac{1}{R^2}\right)=\frac{2}{\theta}\left(\frac{1}{E_0}\right)^2$$

b) For the Mayr's period around current zero

$$\frac{dR}{dt}-\frac{R}{\theta}=-\frac{e^2}{\theta N_0}$$

Experimental evidence [9] demonstrated that this model was a valuable tool that has practical applications. It has been used extensively in the design and evaluation of circuit breakers. Its usefulness, however, depends on the knowledge of the constant θ, which can only be deduced from experimental results. Browne calculated this constant from tests of gas blast interrupters and found it to be in the order of one microsecond, which is in reasonable agreement with the commonly accepted range found by other investigators [10].

1.5.6 Modern Theories

In recent years there has been a proliferation of mathematical models; however these models are mainly developments on more advanced methodologies for performing numerical analysis, using concepts established by the classic theories just described. But there have also been a number of new, more complex theories proposed by several groups of investigators. Significant contributions have been made by Lowke and Ludwig [11], Swanson [12], Frind [13], Tuma [14, 15], and Hermann et al. [16,17,18]. Among these works, probably the most significant technical contribution can be found in the investigations of Hermann and Ragaller [18]. They developed a model that accurately describes the performance of air and SF_6 interrupters. What is different in this model is that the effects of turbulence downstream from the throat of the nozzle are taken into consideration.

In this model the following assumptions are made:

a) There is a temperature profile that encompasses three regions; the first one embodies the arc core, the second covers the arc's surrounding thermal layer, and the third consists of the external cold gas.
b) The arc column around current zero is cylindrical and the temperature distribution is independent of its axial position.
c) The average gas flow velocities are proportional to the axial position.

The relatively consistent and close agreement that has been obtained, between the experimental results and the theory suggests that, although some refinements may still be added, this model has given the best description and the most accurate representation of the interruption process in a circuit breaker.

The models listed in this section have as a common denominator in the recognition of the important role-played by turbulence in the interrupting process. B. W. Swanson [19], for example, has shown that at 2000 Amps turbulence has a negligible effect on the arc temperature, while at 100 Amps turbulence makes a difference of 4000 Kelvin and at current zero the difference made by turbulence reaches values of over 6000 Kelvin. In a way these new models serve to probe or reinforce the validity of the Mayr equation because the magnitudes of temperature reductions produced by the turbulent flow makes the arc column cool down to a range of values that are nearing those assumed by the Mayr equation, where the electrical conductivity varies exponentially with respect to temperature.

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2

SHORT CIRCUIT CURRENTS

2.0 INTRODUCTION

Under normal operating conditions an electrical system is in a balanced, or steady-state condition. This steady-state condition persists as long as no sudden changes take place in either the connected supply or the load of the circuit. Whenever a change to the normal conditions takes place in the electric system, there is a resultant temporary unbalance, and due to the inherent inertia of the system there is a required finite period of time needed by the system to re-establish its previously balanced or steady-state condition.

When a fault, in the form of a short circuit current, occurs in an electrical system, and if as a result of such fault it becomes necessary to operate an interrupting device then the occurrence of both events, the fault and the current interruption, constitute destabilizing changes to the system that result in periods of transient behavior for the associated currents and voltages.

Interruption of the current in a circuit generally takes place during a transient condition that has been brought about by the occurrence of a short circuit. The interruption itself produces an additional transient that is superimposed upon the instantaneous conditions of the system, and thus it can be recognized that interrupting devices must cope with transients in the currents generated elsewhere in the system, plus voltage transients that have been initiated by the interrupting device itself.

2.1 CHARACTERISTICS OF THE SHORT CIRCUIT CURRENT

Because of its magnitude and the severity of its effects, a short circuit current, undoubtedly, represent the most important type of current transient that can appear in any electrical system.

The main factors that determine the magnitude, and other important characteristics of a short circuit current are the energy capacity of the source of current, the impedance of the power source, the characteristics of the portion of the circuit that is located between the source and the point of the fault, and the characteristics of the rotating machines that are connected to the system at the time of the short circuit. It must be remembered that connected rotating machines, whether synchronous generators, induction or synchronous motors, all become sources of power during a short circuit condition and consequently at the time of the short circuit, motors will act as generators feeding energy into the short circuit due to the inherent inertia of their moving parts.

The combination of these factors and the instantaneous current conditions, prevailing at the time of initiation of the fault will determine the asymmetry of the fault current as well as the duration of the transient condition for this current. As will be discussed later, these two characteristics are quite important for the application of an interrupting device.

2.1.1 Transient Direct Current Component

Short-circuit current transients produced by a direct current (dc) source are less complex than those produced by an alternating current (ac) source. The transients occurring in the dc circuit, while either energizing or discharging a magnetic field, or a capacitor through a resistor, are fully defined by a simple exponential function.

In ac circuits, the most common short-circuit current transient is equal to the algebraic sum of a transient direct current component, which, as stated before, can be expressed in terms of a simple exponential function and of a steady-state alternating current component that is equal to the final steady-state value of the alternating current, which can be described by a trigonometric function.

The alternating current component is created by the external ac source that sustains the short circuit current. The dc component, on the other hand, does not need an external source and is produced by the electromagnetic energy stored in the circuit inductance.

A typical short circuit current waveform showing the above-mentioned components is illustrated in Figure 2.1. In this figure the direct current component is shown as I_{dc}, the final ac steady-state component is shown as I_{sym}, and the resulting transient asymmetrical current as I_{Total}.

It should be noted that in order to satisfy the initial conditions required for the solution of the differential equation that defines the current in an inductive circuit, the value of the direct current component is always equal and opposite to the instantaneous value of the alternating current at the moment of fault initiation. Furthermore it should be noted that it is this dc transient current that is directly responsible for and determines the degree of asymmetry of the fault current.

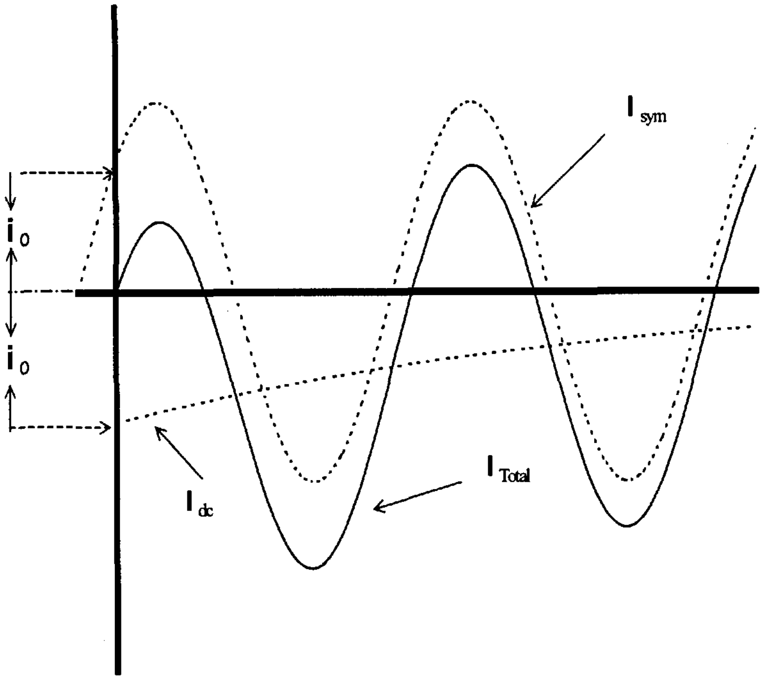


Figure 2.1 Transient components and response of an ac short circuit current.

A short circuit current will be considered to be symmetrical when the peak values of each half cycle are equal to each other when measured in reference to its normal axis.

An asymmetrical current is one that is displaced in either direction from its normal axis and in which the peak value will be different for each half cycle with respect to the normal axis.

The total current is mathematically described by the following:

$$I_{Total} = I_m[(e^{-\alpha t}) \times Sin(\phi) + Sin(\omega t + \phi)]$$

where:

I_m = peak value of the steady-state ac current
α = system time constant = R/L
ϕ = fault's initiation angle
R = system resistance
L = system inductance

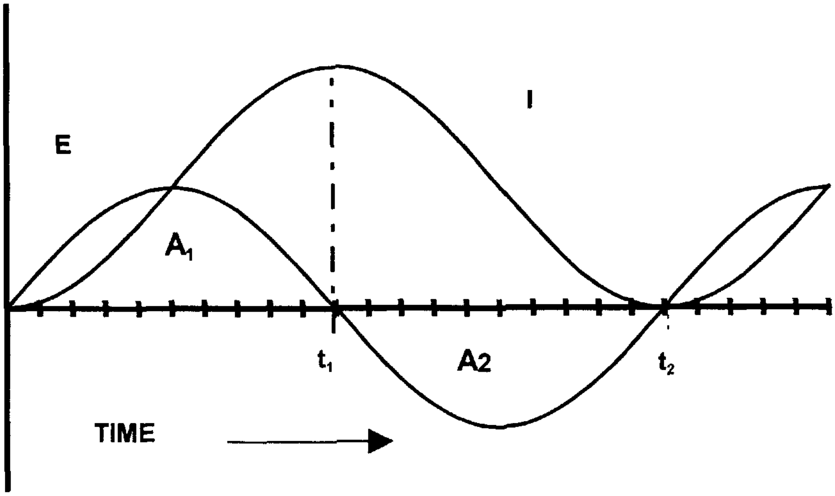


Figure 2.2 Volt–time and current relationships for a short circuit initiated at the instant of voltage zero.

2.1.2 The Volt–Time Area Concept

To better understand the physics of the phenomena involving the circuit response to a change of current flow conditions, it is extremely helpful to remember that in a purely inductive circuit, the current will always be proportional to the volt–time area impressed upon the inductance of the affected circuit. This statement implies that the current is not instantaneously proportional to the applied voltage but that it is dependent upon the history of the voltage application.

The visualization of this concept, in terms of what we are calling the volt–time area, is important because it shows the inter-dependency between the variations of voltage and current at its simplest level. This concept is demonstrated by simply observing the dimensional relationship that exists in the basic formula, which describes the voltage appearing across an inductance:

$$e = L\, di/dt$$

Dimensionally this expression can be written as follows:

$$Volts = \frac{Inductance \times Current}{Time}$$

Solving (dimensionally) for the current,

$$Current = \frac{Volts \times Time}{\text{Inductance}}$$

To illustrate the concept, let us consider some specific examples of a fault. In these examples it will be assumed that the circuit is purely inductive, and that there is no current flow prior to the moment of the insertion of the fault.

First, let us consider the case illustrated in Figure 2.2 when the fault is initiated at the precise instant when the voltage is zero. In the figure it can be seen that the current is totally shifted above the axis and that the current peak is twice the magnitude of the steady-state current. The reason for this is that, in the purely inductive circuit, there is an electrical 90 degrees phase difference between the current and the voltage. Therefore, the instantaneous current should have its peak when the voltage is zero. Furthermore, as stated earlier, the value of the direct current component is equal and opposite to the alternating current at the same instant of time.

It can also be seen that at time t_1 the current reaches its peak at the same moment as the voltage reaches a zero value. This instant corresponds with the point where the area under the voltage curve reverses.

At time t_2, it is noted that both the current and the voltage reach an instantaneous value of zero. This instant corresponds with the time when the area A_2 under the voltage curve begins its phase reversal. The two areas, A_1 and A_2, being equal and opposite, yield a net area value equal to zero, which in turn is also the current value at that instant.

The second example, shown in Figure 2.3 illustrates the condition when the short circuit current is initiated at the instant when the voltage is at its peak value. At time t_2 it is observed that the area under the voltage curve becomes negative and therefore the current is seen to reverse until time t_3, when the current becomes zero since the areas A_1 and A_2 are equal and opposite, as seen in the corresponding figure.

The first example describes the worst fault condition, when the short circuit current is fully displaced from its axis and the maximum current magnitude is attained.

The second example represents the opposite, that is, the most benign of the short circuit conditions. The current is symmetrical about its axis since there is no direct current contribution and the magnitude of the short circuit is the lowest obtainable for all other faults when the voltage and the circuit impedance are the same.

The last example shown, Figure 2.4, is given as an illustration of a short circuit that is initiated somewhere between the voltage zero and the voltage maximum.

One significant characteristic that takes place, as shown in the figure, is the existence of a major and a minor loop of current about the axis. In this figure we can observe the proportionality of the current and the volt–time curve. It should be noted that the major current loop is the result of the summation of areas A_1 and A_2, and the minor loop corresponds to the summation of A_3 and A_4.

From the above examples, and by examining the corresponding figures, the following facts become evident:

1. Peak current always occurs at voltage zero.
2. Current zero always occurs when the net of the volt–time areas are zero.
3. The current magnitude is always proportional to the volt–time area.
4. At all points on the current wave, the slope of the current is proportional to the voltage at that time.

In all of the above examples it was assumed that the circuit was purely inductive. This was done only to simplify the explanation of how the short circuit current wave is formed.

In real applications, however, this condition is not always attainable since all reactors have an inherent resistance and therefore the dc component of the current will decay exponentially as a result of the electromagnetic energy being dissipated through this resistance. This condition was illustrated in Figure 2.1 when the general form of the short circuit current was introduced.

2.1.3 Transient Alternating Current Components

In the preceding discussion, the source of current was assumed to be far removed from the location of the short circuit and therefore the ac current was simply defined by a sinusoidal function. Under certain conditions, however, the transient ac current may have an additional ac transient component which is the result of changes produced by the short circuit current in the inductance of the circuit.

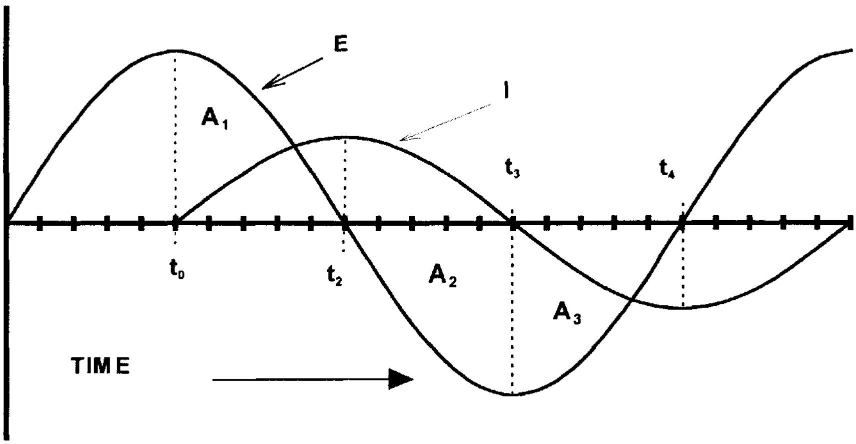


Figure 2.3 Volt–time and current relationships for a short circuit current initiated at maximum voltage.

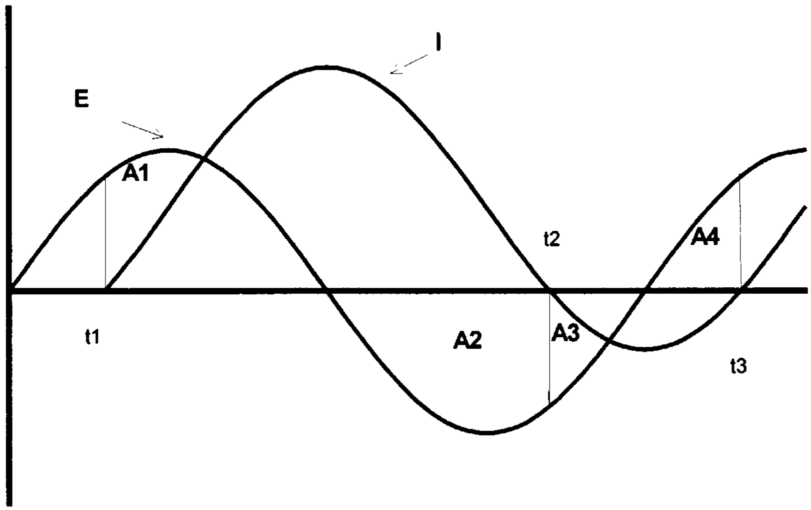


Figure 2.4 Volt–time and current relationships illustrating major and minor loops of short circuit current.

This condition generally happens when a rotating machine is one of the circuit components that is involved with the short circuit. More specifically it refers to the condition where the short circuit, at the terminals of the generator, is initiated at the time when the generated voltage passes through its peak. Whenever this happens, the short circuit current rises very rapidly. Its rise is limited only by the leakage reactance of the generator stator, or by its sub-transient reactance. This current creates a magnetic field that tends to cancel the flux at the air gap, but to oppose these changes an electromotive force (emf) is induced in the generator winding and eddy currents are induced in the pole faces. The net result is that the ac component is not constant in relation to time, but instead it decreases from an initial high value to a constant or steady-state value. The particular form of the rate of decrease precludes the use of a single exponential function, and instead it makes it necessary to divide the curve into segments and to use a different exponential expression to define each segment. This results in the use of very distinctive concepts of reactance for each exponential function. The "subtransient" reactance is associated with the first, very rapid decrease period; the "transient" reactance, with the second, less rapid decrease period; and the "synchronous" reactance which is associated with the steady-state condition, after all the transients have subsided. In Figure 2.5 the transient components as well as the resulting total short circuit current are shown.

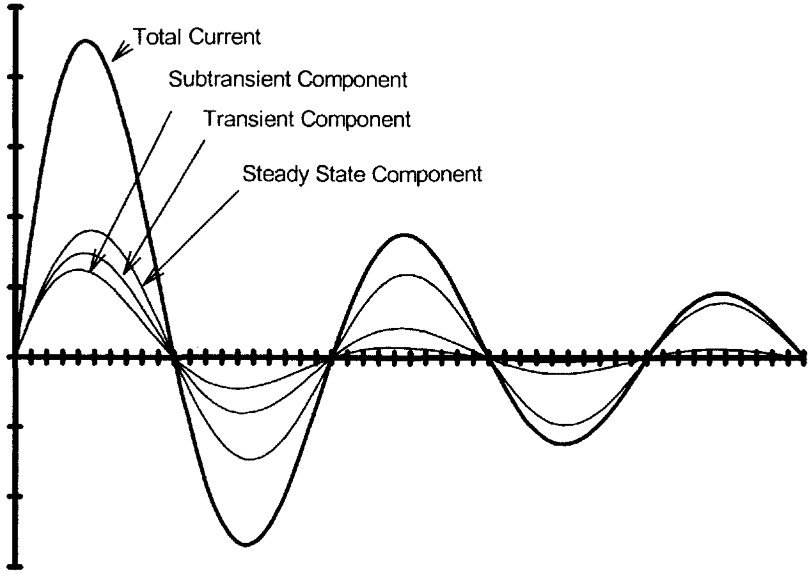


Figure 2.5 The composition of a short circuit current including the ac transient components.

2.1.4 Asymmetry of Three Phase Short Circuit Currents

In our discussion of short circuit currents, only single phase system currents have been described. The reason is that in a simultaneous fault of a three phase balanced system, or for that matter in any balanced multi-phase system, only one maximum dc component can exist because only one phase can satisfy the required conditions for developing maximum asymmetry at the instant when the fault occurs. Furthermore a symmetrical short circuit current can not happen in all three phases of a three phase generator simply because of the current phase displacement inherent to a multi-phase system. If a symmetrical fault occurs in one phase, the other two phases will have equal and opposite direct current components, since in all cases the algebraic sum of all of the dc components must be equal to zero.

The preceding statement is demonstrated in Figure 2.6, where three phase steady-state currents are shown. It can be readily seen that if the peak value of the alternating current is assumed to be equal to 1 in all the phases, and as established before, then the initial value of the dc component in a series LR circuit is equal and opposite to the instantaneous value of the ac current that would exist immediately after switching if the steady-state could be obtained instantaneously.

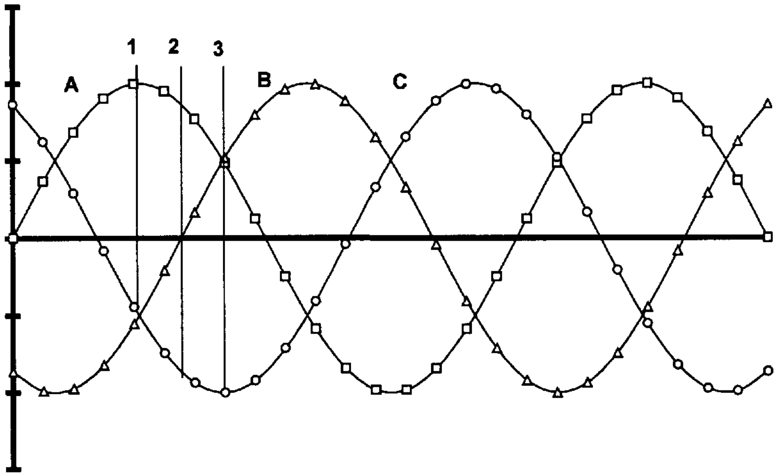


Figure 2.6 Three phase short circuit current characteristics.

Examining Figure 2.6 we can see that for a fault initiated at point 1, the instantaneous value for the current in phase A is at its peak and therefore the dc offset current will also be at its maximum. The steady-state value for the currents in phases B and C at that same instant are one-half that of the peak value of A and their dc offset is also one-half of A. For a fault that starts at instant 2, there is no offset on phase B since current B is zero at that instant. The offset on phase A at that instant is equal to $-\sqrt{3/2}$, while the offset on phase C is equal to $+\sqrt{3/2}$. When the short circuit is initiated at time 3, we get a condition that is similar to that obtained when the starting point for the fault was at instant 1, except that the maximum offset is now observed on phase C instead of phase A.

Having shown the conditions where the maximum dc component is produced, we now look at what happens to the currents some time later. Any combination of dc components that produces a maximum average offset at t = 0 will also produce the maximum offset at any instant thereafter, compared to any other possible combinations of dc components. This follows from the fact that the decay factor of the dc component is identical for the three currents, since it is determined by the physical components of the system, which is assumed to be balanced under steady-state conditions. If the dc current decays at the same rate in all three phases, then all of the dc components will decay in the same proportion from whatever initial value they had. Therefore it follows that the maximum asymmetry of a fault that started with the maximum offset on one phase will occur one-half cycle later in the same phase that had the maximum offset.

When considering a fault that has the maximum offset on phase A, we see that the first peak occurs in phase C approximately 60° or $(t = \pi/3\omega)$ after the inception of the short circuit. The second peak occurs on phase B at approximately 120° or $(t = 2\pi/3\omega)$. The third occurs on phase A at approximately 180° or at $(t = -\pi/\omega)$. Since the ac components are identical we can easily see which peak is larger by comparing the dc components. Starting with phases B and C, we can see that they start at the same value $(I_m /2)$. We also know, without looking at the absolute quantitative values, that since the decay at 60° is less than at 120°, the peak of the current on phase C is larger. Next comparing the peaks of phases A and C, we can see that the dc component on A starts with twice the value of the component of C, but by the time A reaches its peak it has decayed more than the C component.

These relative values can be compared by establishing their ratio.

$$\frac{A}{B} = \frac{I_m e^{-(\pi/\omega T)}}{\frac{I_m}{2} e^{-(\pi/3\omega T)}} = 2e^{-(\pi/\omega T)+(\pi/3\omega T)} = 2e^{-(2\pi R/3X)}$$

From this result we can conclude that the dc components, and therefore the current peaks, would be equal if X/R had a value such that:

$$2e^{-(2\pi R/3X)} = 1$$

When this expression is solved for X/R , which is normally the way in which the time constant of a power system is expressed, we obtain a value of 3.02. Which means that for values of $X/R > 3.02$, the value of the exponential is greater than 1 and therefore the peak on phase A at 180° will be greater than the peak on phase C at 60°. Conversely for values of X/R smaller than 3.02, the peak on phase A will be smaller than the earlier peak on phase C.

Practical systems, in general, can be expected to have X/R ratios significantly greater than 3, and this will cause the peak on phase A at the end of a half cycle to be the greatest of the three peaks. Because this is the most severe peak, it is the one of most interest for circuit breaker applications as will be discussed later.

2.1.5 Measuring Asymmetrical Currents

The effective, or root mean squared value (rms), of a wave form is defined as the square root of the arithmetic mean of the square of the ordinates of a given curve between two zero points. Mathematically, for an instantaneous current, which is a function of time, the effective value may be expressed as follows:

$$I_{eff} = \sqrt{\frac{1}{t_2 - t_1} \times \int_{t_1}^{t_2} i^2 dt}$$

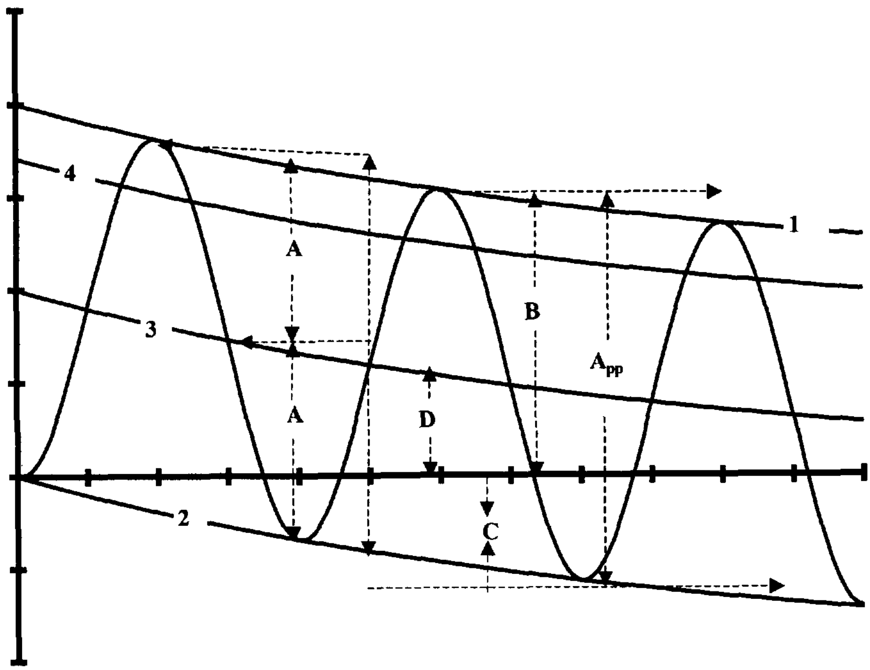


Figure 2.7 Typical asymmetric short circuit current as observed from an oscillogram. The figure illustrates the parameters used for calculating the instantaneous values of current.

In Figure 2.7 a typical asymmetric short circuit current during its transient period is shown (as may be seen in an oscillographic record). In this figure, during the transient period, the axis of the steady-state sinusoidal wave is offset by an amount equal to the dc component of the short circuit current. It has been plotted as curve 3. Lines 1 and 2 define the envelope of the total current, and line 4 represents the rms value of the asymmetrical current. The dimension A_{pp} represents the peak to peak value of the sinusoidal wave. A is the maximum value of the current referred to its own axis of symmetry, or in other words, is the maximum of the ac component (I_M). B and C represent the peak value of the major and minor loop of current, respectively.

In its simplest form, the general equation for the current wave shown in Figure 2.7 represents a short circuit current where, for the sake of simplicity, the ac transient decrement has been omitted. It can be written as:

$$i = I_M Sin\phi + D$$

where the term D represents the dc component as previously defined in terms of an exponential function.

As given before, the basic definition of a rms function is:

$$I_{rms}^2 = \frac{1}{2\pi}\int_0^{2\pi} i^2 d\theta$$

Now, to obtain an expression that will represent the rms value of the total current we can substitute the first equation, which defines the value of the current as a function of time, into the second expression, which as indicated represents the definition of the rms value. After simplifying (and some manipulation of the trigonometric functions), we arrive at the following expression:

$$I_{eff} = \sqrt{(\frac{I_M}{2})^2 + D^2}$$

In this equation the term I_{eff} is used to represent the rms value of the total current. The term effective is synonymous with rms, however, in the context of this derivation, (and only for the purpose of clarity), this term is used to differentiate between the rms value of the ac component of the current and the rms value of the total current, which contains the ac component plus the dc component.

By recognizing that the first term under the radical is the rms value of the ac component itself, and that D represents the dc component of the wave, it can be realized then that the effective, or total rms asymmetrical current, is equal to the square root of the sum of the squares of the rms values of the alternating current component and the direct current component.

If the dc term is expressed as a percentage of the dc component with respect to the ac component, it becomes $\% dc * I_M / 100$. When substituted into the equation for I_{eff}, the following expression results:

$$I_{eff} = \sqrt{(\frac{I_M}{2})^2 + (\frac{\%dc}{100})^2 \times I_M^2}$$

Furthermore, if the peak value of the ac component is substituted by the rms value of the same ac component, then the equation can be simplified and it becomes:

$$I_{eff} = I_{rms}\sqrt{1 + 2(\frac{\%dc}{100})^2}$$

This equation is the basis of circuit breaker standards [1] [2].

When the graphical depiction of the waveform of the transient current is available (see Figure 2.7), the instantaneous values, at a time t, for the dc component, and for the rms of the total current, can be calculated as follows.

The rms value for the ac component is:

$$I_{rms} = \frac{A}{\sqrt{2}}$$

Furthermore it is seen that:

$$A_{pp} = B + C = 2A$$

It then follows that:

$$A = \frac{A_{pp}}{2}$$

In terms of the rms value of the ac component, it becomes:

$$\frac{A}{\sqrt{2}} = \frac{A_{pp}}{2\sqrt{2}} = \frac{A_{pp}}{2.828}$$

Also from Figure 2.7, we find that:

$$A = C + D = \frac{B + C}{2}$$

Solving for the dc component D we have:

$$D = \frac{B - C}{2}$$

And finally, the rms value for the asymmetric current can be written (in terms of quantities that are directly measurable from the recorded data) as:

$$I_{rms} = \sqrt{\frac{A_{pp}}{2.828} + D^2}$$

2.2 CALCULATION OF SHORT CIRCUIT CURRENTS

Short circuit currents are usually determined by calculations from data about the sources of power and the impedance of all interconnected lines and equipment up to the point of the fault. The precise determination of short circuit currents, especially in large interconnected systems, generally requires complicated and laborious calculations. However in most cases there is no need for those complicated calculations and within a reasonable degree of accuracy the approximated magnitude of the short circuit current can be easily determined (within acceptable limits) for the application of circuit breakers and the settings of protective relays. Since the resistance in a typical electrical system is generally low in comparison to the reactance, it is safe to ignore the resistance and to use only the reactance for the calculations. Furthermore, for the calculation of the short circuit current in a system, all generators and both synchronous and induction motors are considered sources of power. The load currents are neglected, and when several sources of current are in parallel, it is assumed that all the generated voltages are in phase and that they are equal in magnitude at the time of the short circuit.

While computations of fault currents may be made with each reactance expressed in ohms, a number of rules must be observed for machine ratings and changes in the system voltages due to transformers. The calculation will usually be much easier if the reactance is expressed in terms of percentage or per unit reactance. Another simple method of calculation is using the system's rated mega-volt-ampere (MVA) for the calculations. This method is generally known as the MVA method.

2.2.1 The Per Unit Method

The per unit method consists of using the ratings of the equipment as the units for measuring the quantities appearing in problems that involve the same equipment. It is equivalent to adopting a set of units that are tailored to the system under consideration. If, for example, we consider the load on a transformer expressed in amperes, it will not tell us how much we are loading the transformer in relation to what could be considered sound practice. Before we are justified in saying that the load is too much, or too little, we compare it with the normal or rated load for that transformer. Suppose that the transformer in our example is a three phase, 2300-460 volts, 500 KVA transformer that delivers 200 amperes to the load on the low voltage side. The 200-ampere value standing alone does not tell the full story, but when compared to the full load current (627 amperes in this case), it does have some significance. In order to compare these two values we divide one by the other, obtaining a value equal to 0.318. This result has more significance than the plain statement of the amperes value of the actual load, because it is a relative measure. It tells us that the current delivered by the transformer is 0.318 times the normal current. We will call it 0.318 per unit, or 31.8 percent.

Extending this concept to the other parameters of the circuit, namely volts, currents, KVAs, and reactances, we can develop the whole theory for the per unit method.

Let V = actual or rated volts and V_b = base or normal volts. Then, the per unit volts (expressed as V_{pu}) is defined by:

$$V_{pu} = \frac{V}{V_b}$$

Using similar notation, we define per unit KVA as:

$$(KVA)_{pu} = \frac{(KVA)}{(KVA)_b}$$

Per unit amperes:

$$I_{pu} = \frac{I}{I_b}$$

And per unit reactance:

$$X_{pu} = \frac{X}{X_b}$$

The normal values for all of the above quantities can be defined with only one basic restriction: The normal values of voltage, current, and KVA must satisfy the following relationship:

$$1000(KVA)_b = V_b \times I_b$$

which, when solved for I_b, gives:

$$I_b = \frac{1000(KVA)_b}{V_b}$$

The base or normal values for reactance, voltage, and current are related by Ohm's law as follows:

$$X_b = \frac{V_b}{I_b}$$

When substituting the value of I_b we obtain:

$$X_b = \frac{V_b^2}{1000(KVA)_b}$$

which, when solving for the per unit value, becomes:

$$X_{pu} = \frac{1000 \times (KVA)_b}{V^2}$$

From the above it follows that a device is said to have a certain percentage reactance when the reactance drop of the device, operating at its rated KVA, is that percentage of the rated voltage. To describe a reactance, for example 5%, is to say that at rated KVA, or when full load rated current is flowing, the reactive voltage drop is equal to 5% of the rated voltage. Expressing the reactance as a percentage is to say that for a rated load, the voltage drop due to the reactance is that number (of volts) per hundred volts of rated voltage.

When the reactance is expressed in per unit (pu), this number represents the reactive voltage drop at rated current load per unit of rated voltage.

The percentage and the per unit values, when referred to the same base KVA, are related by the following simple expression:

$$X\% = X_{pu} * 100$$

When the reactances are given in ohms they can be converted to per unit using the following relationship:

$$X_{pu} = \frac{1000 \times (KVA)_b}{V^2} \times X_{\Omega}$$

In order for the percentage or per unit values to be used for the calculations of a given circuit, it is necessary that all such values be referred to the same KVA base. The choice for this base KVA can be absolutely arbitrary; it does not need to be tied to anything in the system. However it will be advantageous to choose as the KVA base a particular piece of equipment in which we are interested.

When the given percentage, or per unit values represent the ratings of a piece of equipment that have a different base than the one that we have chosen as the base KVA for our calculations, it will be necessary to translate this information to the same basis. This is readily accomplished by obtaining the proper ratios between the values in question, as shown below.

$$\frac{X_{pu}(Base2)}{X_{pu}(Base1)} = \frac{(KVA)_{b2}}{(KVA)_{b1}}$$

2.2.1.1 General Rules for Use of Per Unit Values

The following rules, tabulated below, are given to provide a quick source of reference for calculations that involve the per unit method.

When all reactance values are expressed in per unit to the same base KVA, the total equivalent reactance is:

a) For reactances in series:

$$X_{total} = X_1 + X_2 \ldots + X_i$$

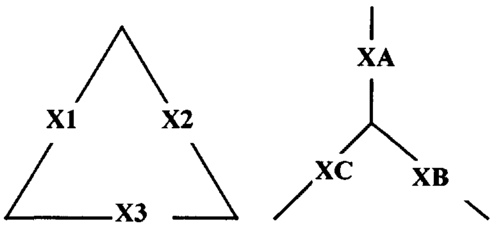
b) For reactances in parallel:

$$X_{Total} = \frac{1}{\frac{1}{X_1} + \frac{1}{X_2} + \ldots\ldots + \frac{1}{X_i}}$$

c) To convert reactances from delta to wye or vice versa:

Delta to wye

$$X_A = \frac{(X_1)(X_2)}{X_1 + X_2 + X_3}$$



$$X_B = \frac{(X_2)(X_3)}{X_1 + X_2 + X_3}$$

$$X_C = \frac{(X_3)(X_1)}{X_1 + X_2 + X_3}$$

Wye to delta

$$X_1 = \frac{(X_A X_B) + (X_B X_C) + (X_C X_A)}{X_A}$$

$$X_2 = \frac{(X_A X_B) + (X_B X_C) + (X_C X_A)}{X_B}$$

$$X_3 = \frac{(X_A X_B) + (X_B X_C) + (X_C X_A)}{X_C}$$

2.2.1.2 Procedure Using the Per Unit Method

The complete procedure used to calculate a short circuit current using the per unit method can be summarized in the following six basic steps:

1. Choose a base KVA.
2. Express all reactances in per unit values, referring to the chosen base KVA.
3. Simplify the circuit by appropriately combining all of the involved reactances. The objective is to reduce the circuit to a single reactance.
4. Calculate the normal or rated current at the rated voltage, at the point of the fault corresponding to the chosen base KVA.

$$I_n = \frac{(KVA)_b \times 1000}{\sqrt{3} \times V}$$

5. Calculate the per unit short circuit current corresponding to the per unit system voltage divided by the per unit total reactance.

$$I_{pu} = \frac{E}{X_{pu}(total)} = \frac{1}{X_{pu}(total)}$$

6. Calculate the fault current magnitude by multiplying the per unit current (I_{pu}) by the rated current (I_n).

The following example is given to illustrate the application of the per unit method to the solution of a short circuit problem. The circuit to be solved is shown as a single line diagram in Figure 2.8.

1. Choose the value given by the utility as the base MVA. This value is 800 MVA.

2. Calculation of the reactance for the different portions of the system yields the following values:

For the 69 kV line, $X_{base} = \dfrac{69^2 \times 1000}{80{,}0000} = 5.95$

For the 13.8 kV line, $X_{base} = \dfrac{13.8^2 \times 1000}{80{,}0000} = 0.24$

3. Simplifying the circuit (see Figure 2.9), obtain the per unit reactance of each component (shown in a) by the following:

For the 4.16 kV, line $X_{base} = \dfrac{4.16^2 \times 1000}{800{,}000} = 0.022$

System (1) $= X1 = 1.0$

Line (2) $= X2 = \dfrac{X}{X_{base}} = \dfrac{3.85}{5.95} = 0.65$

Transformer T1(3) $= X3$

$$X3 = X_{rated} \times \frac{(KVA)_{base}}{(KVA)_{rated}} = 0.08 \times \frac{800{,}000}{30{,}000} = 2.13$$

Generator G1 (4) $= X4 = \dfrac{0.1 \times 800{,}000}{25{,}000} = 3.2$

Transformers T2, T3, and T4 (5,6,8) $= X5,\ X6,\ X8$

$$X5, X6, X8 = \frac{0.06 \times 800{,}000}{7{,}500} = 6.4$$

Motors M1, and M2 (7,9) $= X7, X9 = \dfrac{0.15 \times 800{,}000}{5{,}000} = 24$

Continuing the process of reducing the circuit, and referring to Figure 2.9 (b), the series combination of 1,2,3 is added arithmetically to give:

$X\,1{,}2{,}3\ (1.1) = 1.0 + 0.65 + 2.13 = 3.78$

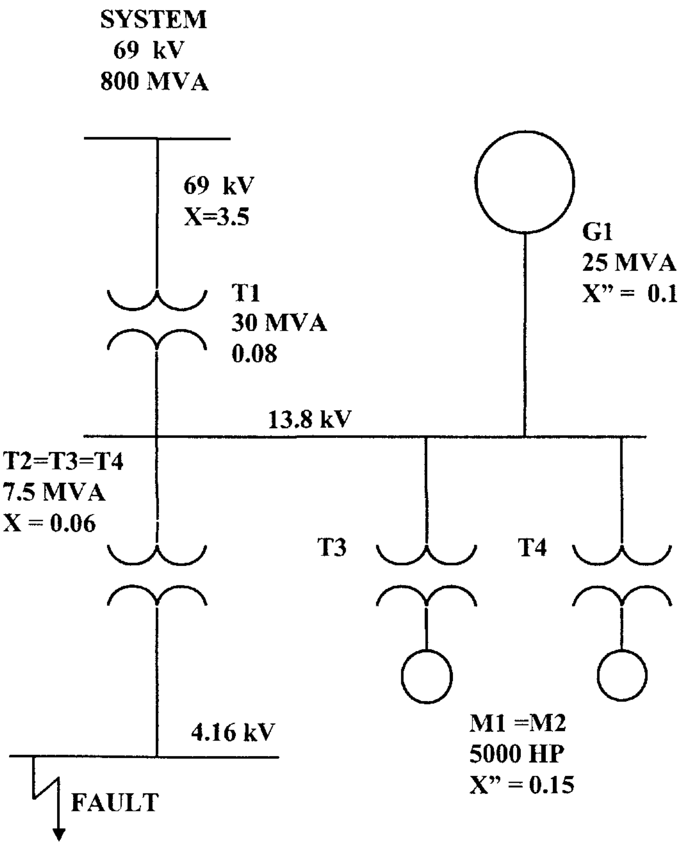


Figure 2.8 Single line diagram of the distribution system solved in the example problem.

The two branches containing the components 6, 7 and 8, 9 are also combined independently to obtain 6.1 and 8.1.

$$X\,6{,}7{,}8{,}9\ (6.1),\ (8.1) = 6.4 + 24 = 30.4$$

Next, the reduced series elements are combined with the parallel components, obtaining the new components, which are represented by 1.2 and 6.2 in Figure 2.9 (c).

$$(1.2) = \frac{X1{,}2{,}3 \times X4}{X1{,}2{,}3 + X4} = \frac{3.78 \times 3.2}{3.78 + 3.2} = 1.73 \quad \text{and,}$$

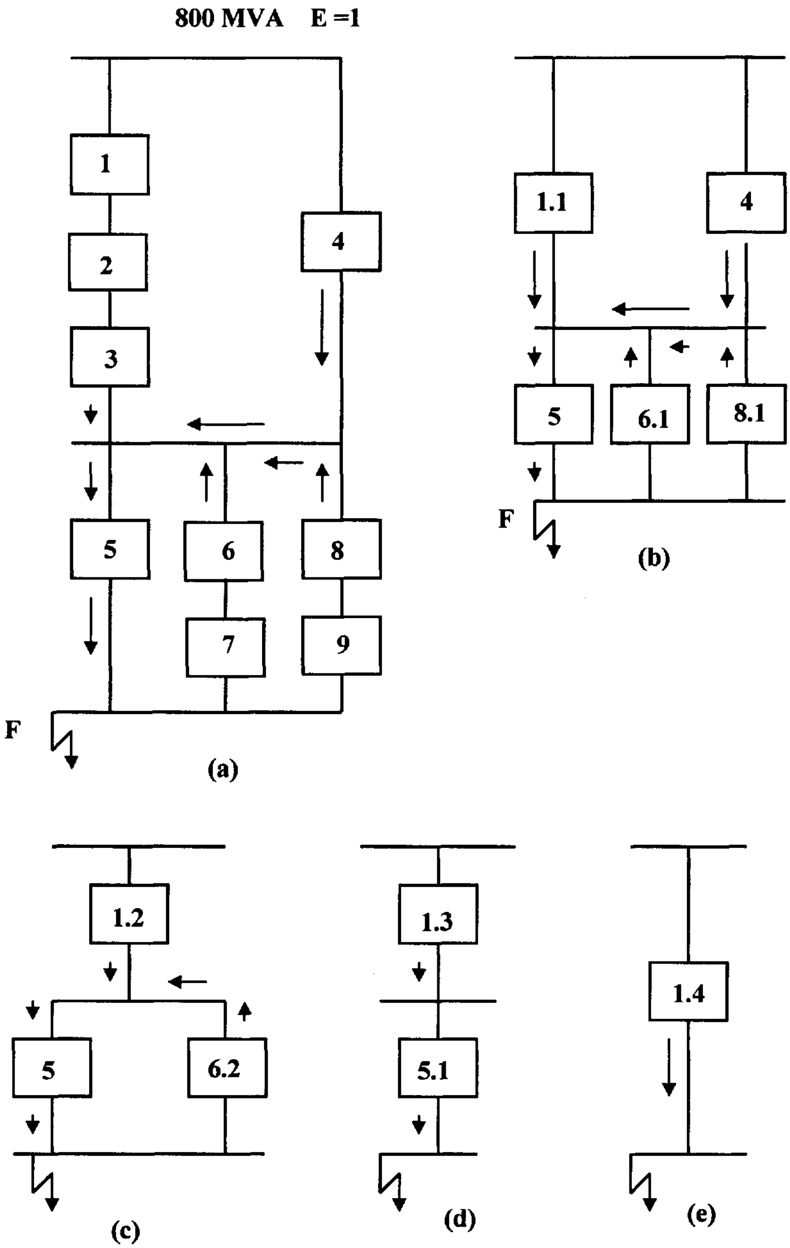


Figure 2.9 Block diagram showing the reducing process of the circuit in Figure 2.8.

$$(6.2) = \frac{X6{,}7 \times X8{,}9}{X6{,}7 + X8{,}9} = \frac{30.4 \times 30.4}{30.4 + 30.4} = 15.2$$

Continuing with the process in Figure 2.9 (d) we have:

$$(1.3) = \frac{(1.2) \times (6.2)}{(1.2) + (6.2)} = \frac{1.73 \times 15.2}{1.73 + 15.2} = 1.55$$

Finally we add (1.3) + (5) to obtain the total short circuit reactance:

(1.4) =X_{sc} =7.95

We then calculate the value of I_{pu}, which is equal to:

$$I_{pu} = \frac{E}{X_{sc}} = \frac{1.0}{7.95} = 0.126$$

I_{rated} is calculated as:

$$I_{base(4.16)} = \frac{800{,}000}{\sqrt{3} \times 4.16} = 111{,}029$$

Now we can proceed with the calculation of the short circuit current at the specified fault location (F).

$$I_{sc} = I_{pu} \text{ x } I_{base} = 0.126 \text{ x } 111{,}029 = 13{,}966 \text{ amperes}$$

Alternatively the short circuit current can also be calculated by figuring the equivalent short circuit MVA and then dividing it by the square root times the rated voltage at the point of the short circuit.

$$MVA_{sc} = \frac{MVA_{base}}{X_{pu}} = \frac{800{,}000}{7.95} = 100.63$$

$$I_{sc} = \frac{MVA_{sc}}{\sqrt{3} \times V_{rated}} = \frac{100.63}{\sqrt{3} \times 4.16} = 13966 \text{ amperes}$$

2.2.2 The MVA Method

The MVA method is a variation of the per unit method. It generally requires a lesser number of calculations, which makes it somewhat simpler than the per unit method. The MVA method is based on the asumption that a short circuit current is being supplied from an infinite capacity source. The admittance, which is the reciprocal of the impedance, represents the maximum current, or amperes/volts at unit voltage, which can flow through a circuit or an individual component during a short circuit condition.

With the MVA method, the procedure is similar to that of the per unit method. The circuit is separated into components, which are further reduced to a single component, which is expressed in terms of its MVA. The short circuit MVA for each component is calculated in terms of its own infinite bus capacity. The value for the system MVA is generally specified by the value given by the utility system. For a generator or transformer, a line or cable, the MVA is equal to the equipment-rated MVA divided by its own impedance and by the square of the line-to-line voltage divided by the impedance per phase, respectively. The MVA values of the components are combined according to the following conventions:

1. For components connected in series:

$$MVA_{Total} = \frac{1}{\dfrac{1}{(MVA)1} + \dfrac{1}{(MVA)2} + \ldots\ldots \dfrac{1}{(MVA)i}}$$

2. For components connected in parallel:

$$MVA_{Total} = (MVA)1 + (MVA)2 + \ldots\ldots\ldots (MVA)i$$

To convert from a delta to a wye connection or vice versa, the same rules that were previously stated in Section 2.2.1.1 for the per unit method are applicable.

The same example, shown in Figure 2.8 (that was solved before using the per unit method), will now be solved using the MVA method. Referring to Figure 2.9, we can use the same schematics used with the per unit method.

The MVA values for each component are calculated as follows:

For system (1), the $MVA = \dfrac{800{,}000}{1}$

For line (2), the $MVA = \dfrac{69^2}{3.5} = 1{,}360$

For transformer T1 (3), the $MVA = \dfrac{30}{0.08} = 375$

For generator G1 (4), the $MVA = \dfrac{25}{0.1} = 250$

For transformers T2,T3, and T4 (5,6,8) the $MVA = \dfrac{7.5}{0.06} = 125$

For the motors M1,M2 (1,2) the $MVA = \dfrac{5}{0.15} = 33.3$

The MVA value for the combined group 1,2,3 is:

$$MVA(1.1) = \frac{1}{\frac{1}{800} + \frac{1}{1360} + \frac{1}{375}} = 465$$

In Figure 2.9 (b), the MVA for (6.1) and (8.1) is:

$$MVA\ (6.1), (8.1) = \frac{125 \times 33.3}{125 + 33.3} = 26.3$$

In 2.9 (c) the reduced circuit is obtained by combining (6.1) + (8.1) to give (6.2) whose MVA value is:

$$(6.2)\ MVA = 26.3 + 26.3 = 52.6$$

Next, as shown in (d), the MVA for (1.3) is equal to the parallel combination of (1.2) and (6.2) which numerically is equal to:

$$(1.3)\ MVA = 465 + 52.6 = 518$$

Finally, combining the $MVAs$ of (1.3) and (5) we obtain:

$$(1.4) = MVA_{sc} = \frac{518 \times 125}{518 + 125} = 100.69$$

Now the value of the short circuit current can be calculated as follows:

$$I_{sc} = \frac{100.69}{\sqrt{3} \times 4.16} = 13{,}975 \text{ amperes}$$

It is now left up to the reader to chose whichever method is preferred.

2.3 UNBALANCED FAULTS

The discussion so far has been based on the premise that the short circuit involved all three phases symmetrically and, therefore, that this fault had set up a new three phase balanced system where only the magnitude of the currents had changed. However, it is recognized that fault conditions other than three phase balanced faults can happen in a system (for example, there may be a line-to-ground or a line-to-line fault).

Generally it is the balanced three phase fault where the maximum short circuit current can be observed. In a line-to-line fault the fault currents would very seldom, if ever, be greater than those occurring in the three phase balanced situation. A one-line-to-ground fault obviously is of no importance if the system is ungrounded. Nevertheless, in such cases, because of the nature of the fault, a new three phase system where the phase currents and phase voltages are unbalanced is created.

Analytical solution of the unbalanced system is feasible but it is usually highly involved and often very difficult. The solution of a balanced three phase circuit, as has been shown, is relatively simple because all phases being alike, one can be singled out and studied individually as if it was a single phase. It follows then, that if an unbalanced three phase circuit could somehow be resolved into a number of balanced circuits then each circuit might be evaluated based on its typical single phase behavior. The result of each single phase circuit evaluation could then be interpreted with respect to the original circuit using the principle of superposition. This tool for the solution of unbalanced faults is afforded by the technique known as the symmetrical components method.

2.3.1 Introduction to Symmetrical Components

The method of symmetrical components is applied to three phase circuits and is based on Fortesque's [3] theorem, which deals in general with the resolution of a group of three related vectors of any unbalanced system into a new set of three vectors. The three vectors of each set are of equal magnitude and spaced at either zero or 120 degrees. Each set of these newly created vectors represents a symmetrical component of the original set.

Using this method, an unbalanced three phase circuit may be resolved into a circuit containing three balanced components. Each component is symmetrical in itself and therefore can be evaluated on the basis of single phase analysis. The three components are the positive-phase-sequence component, the negative-phase-sequence component, and the zero-phase-sequence component.

The positive-phase-sequence component consists of three currents (or voltages) all of equal magnitude spaced 120 degrees apart and in a phase sequence that is the same as the original circuit. If the original phase sequence is, for example A, B, C, then the positive-phase-sequence component is also A, B, C. Refer to Figure 2.10 (a).

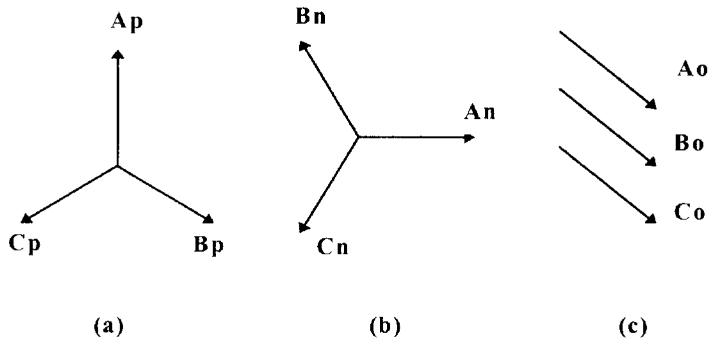


Figure 2.10 Symmetrical vector system. (a) Positive-phase sequence vector; (b) negative-phase sequence vector; (c) zero-phase sequence vector.

The negative-phase-sequence component also consists of three currents (or voltages) all of equal magnitude spaced 120 degrees apart, and in a phase-sequence opposite to the phase sequence of the original vector, that is C, B, A, see Figure 2.10 (b).

The zero-phase-sequence component is constituted by three currents (or voltages) all of equal magnitude, but spaced 0° apart see Figure 2.10 (c). In this zero-sequence, the currents or voltages, as can be observed, are in phase with each other and in reality they constitute a single phase system.

With this method of symmetrical components, currents and voltages in each phase-sequence interact uniquely. These phase-sequence currents or voltages do not have mutual effects with the currents or voltages of a different phase-sequence and, consequently, the systems defined by each phase-sequence may be handled quite independently and their results can then be superimposed to establish the conditions of the circuit as a whole.

The solution of the short circuit using the method of symmetrical components is carried out in much of the same manner as the per unit or MVA method. The main difference is that the negative and zero reactance's are included in the solution.

In a balanced circuit, the negative-phase-sequence, and the zero-phase-sequence components are absent, and only the positive-phase-sequence is present. Therefore the solution is reduced to the simplified method described earlier. In the unbalanced circuit, the positive-and the negative-phase-sequence components are both present, and in some cases the zero-phase-sequence component may also be present. The zero-phase-sequence component will generally be present when there is a neutral or a ground connection. The zero-sequence components, however, are nonexistent in any system of currents or voltages if the vector sum of the original vectors is equal to zero. This also implies that the current of a poly-phase circuit feeding into a delta connection is always zero.

2.3.1.1 Impedance For Computing Fault Currents

Defining impedance as the ratio of the voltage to its respective current makes it possible to define an impedance that can be identified with each of the phase sequence components. Therefore, there is a positive-phase-sequence impedance, a negative-phase-sequence impedance and a zero-phase-sequence impedance. Each of these impedances may also be resolved into their resistance and reactance components.

The effect of resistance on the fault currently is generally very small and in most cases considered negligible. Positive and negative sequence resistances are very small in comparison to positive and negative reactances. Arc resistance is very seldom an important factor except in low voltage systems, and in most cases the arc elongation is not sufficient to create a high enough arc voltage as to be able to produce a measurable effect on the fault current. In addition, the arc resistance is at a 90 degrees phase relationship with the reactance and, therefore, it does not greatly influence the total impedance.

In the case of the zero sequence the resistance may be significant depending on the method of neutral grounding being used.

As was stated earlier, there is a reactance, which is identifiable with each phase-sequence vector, just as any other related parameter, such as the current, the voltage, or the impedance. The reactance can be expressed under the same set of rules described and, consequently, the reactance can be identified as follows.

The positive-phase-sequence reactance, Xp, is the reactance commonly associated and dealt with in all circuits. It is the familiar reactance from application of the simplified per unit method. In rotating machinery, positive-phase-sequence reactance may have three values: sub-transient, transient, and synchronous.

The negative-phase-sequence reactance, Xn, is present in all unbalanced circuits. In all lines and static devices, such as transformers, the reactance to positive-and negative-phase-sequence currents is equal, that is, $Xp = Xn$ for such types of apparatus. For synchronous machines and rotating apparatus in general, it is reasonable to expect that due to the rotating characteristics, the reactance of the positive-and the negative-phase-sequence currents will not be equal. In contrast, with the possibility of three values for the positive-phase-sequence, the negative-phase-sequence has but one for rotating machinery and its magnitude is very nearly the same as that of the sub-transient reactance for that machine.

The zero-phase-sequence reactance, X_0, depends not only upon the particular characteristic of the individual device, which must be ascertained for each device separately, but it also depends upon the way the device is connected. For transformers, for example, the value of the zero-phase-sequence reactance is given not only by the characteristics of its windings but also by the way they are connected.

To take into account the issue of resistances, two sets of formulas are given below. They represent both conditions of

a) when no resistance has been considered and, in such case, the value of the reactance is used, and

b) when the fault resistances are being taken into account.

The formulas are given using the impedance format and, in addition, an impedance *Zf*, which represents the fault impedance, has been added.

It should be noted that these formulas could be used when the fault resistance is ignored simply by replacing *Zf* by zero.

2.3.1.2 Balanced Three Phase Faults

For balanced three phase faults the value for the total reactance *Xt* is given by the value of the positive-sequence reactance *Xp* alone. In terms of impedance, the total value is $Zt + Zf$.

2.3.1.3 Unbalanced Three Phase Faults

For unbalanced three phase faults, the same equations may be used with the special understanding as to the values of *Xt* or *Zt* for each case.

Line-to-Line Fault.

$$Xt = \frac{Xp + Xn}{\sqrt{3}} \quad \text{or}$$

$$Zt = \frac{Zp + Zn}{\sqrt{3}}$$

This kind of fault seldom causes a fault current greater than that for a balanced three phase fault because of the usual relationship of *Xp* and *Xn* (*Zp, Zn*). It is probable then, that investigation of the balanced fault will be sufficient to establish the maximum magnitude of the fault current.

Line-to-Ground Fault. Obviously this type of fault is of no importance for an ungrounded system, however, if the system is grounded we have the following:

$$Xt = \frac{Xp + Xn + X_0}{3}$$

This equation, may be simplified to:

$$Xt = \frac{2Xp + X_0}{3}$$

In terms of impedances, the equation is as follows:

$$Zt = \frac{Zp + Zn + Z_0 + Zf}{3}$$

Two-Line-to-Ground-Fault. The impedance/reactance expressions corresponding to a double-line-to-ground fault are:

$$Xt = \frac{XpXn + X_0(Xp + Xn)}{\sqrt{3(X_0{}^2 + XnX_0 + Xn^2)}}$$

$$Zt = \frac{ZpZn + (Zp + Zn)(Z_0 + 3Zf)}{-j\sqrt{3}(Z_0 + 3Zf - aZn)}$$

where

a = vector operator = – 0.5+j0.866

2.4 FORCES PRODUCED BY THE SHORT CIRCUIT CURRENTS

The electromagnetic forces that are exerted between conductors, whenever there is a flow of current, is one of the most significant, well known, and fundamental phenomena produced by the electric current. Bent bus bars, broken support insulators, and in many instances totally destroyed switchgear equipment, are the catastrophic result of electrodynamic forces that are out of control. Since the electrodynamic forces are proportional to the square of the instantaneous magnitude of the current, it is to be expected that the effects of the forces produced by a short circuit current would be rather severe and oftentimes quite destructive.

The mechanical forces acting between the individual conductors, parts of bent conductors, or contact structures within switching devices, can attain magnitudes in excess of several thousand pounds (newtons), per unit length. Consequently the switching station and all of its associated equipment must be designed in either of two general ways to solve the problem.

One way would be to design all the system components so that they are fully capable of withstanding these abnormal forces. The second alternative would be to design the current path in such a way as to make the electromagnetic forces balance each other. In order to use either approach, and to provide the appropriate structures, it is necessary to have at least a basic understanding about the forces that are acting upon the conductors.

The review that follows is intended as a refresher of the fundamental concepts involved. It will also describe a practical method to aid in the calculation of the forces for some of the simplest and most common cases encountered during the design of switchgear equipment. Relatively accurate calculations for any type of conductor's geometric configurations are possible with a piece-by-piece approach using the methods to be described; however the process will be rather involved and tedious. For more complex arrangements, it is preferable to use one of the ever-increasing number of computer programs developed to accomplish the task.

2.4.1 Direction of the Forces Between Current-Carrying Conductors

This section will be restricted to establish, only in a qualitative form, the direction of the electromagnetic forces in relation to the instantaneous direction of the current. Furthermore, and for the sake of simplicity, only parallel or perpendicular pairs of conductors will be considered.

To begin with, it would be helpful to restate the following well-known elementary concepts:

1. A current-carrying conductor that is located within a magnetic field is subjected to a force that tends to move the conductor. If the field intensity is perpendicular to the current, the force is perpendicular to both the magnetic field and the current. The relative directions of the field, the current, and the force are described by Fleming's left-hand rule. This rule simply says that in a three-directional axis system, the index finger points in the direction of the field, the middle finger points in the direction of the current, and the thumb point in the direction of the force. In reality, this relation is all that is needed to determine the direction of the force on any portion of a conductor where the magnetic field intensity is perpendicular to the conductor.
2. The direction of the magnetic field around a conductor is described by the right-hand rule. This rule requires that the conductor be grasped with the right hand with the thumb extended in the direction of the current flow. The curved fingers around the conductor, will then establish the direction of the magnetic field.
3. Another useful concept to remember is that the field intensity at a point in space, due to an element of current, is considered as the vector product of the current and the distance to the point. This concept will be expanded in the discussions that are to follow.
4. For the purpose of the discussions that are to follow, the directions in space will be represented by a set of coordinates consisting of three mutually perpendicular axes. These will be labeled as the X, Y, and Z-axis.

2.4.1.1 Parallel Conductors

To begin this review section, the simplest, and most well known case, consists of two parallel conductors, where each conductor is carrying a current and both currents are flowing in the same direction. Assume, as shown in Figure 2.11, that two parallel conductors, Y and Y', carry the currents i_y and $i_{y'}$. Let us also assume that both currents are flowing in the same direction and let us take a small *dy'* portion of the conductor Y'.

The current in that small portion of the conductor produces a field everywhere in the space around it. The field intensity produced by that element of current on a point P located somewhere along the second conductor Y can be represented by a vector equal to **dB** (vector quantities will be represented by bold face characters). Since this vector is the result of the cross product of two other vectors then, remember that the result of a cross vector product is itself a vector, which is perpendicular to each of the multiplied vectors. Its direction, when the vectors are rotated in a direction that tends to make the first vector coincide with the second, will follow the direction of the advance of a right-handed screw. Applying these concepts it can be seen that the field intensity vector **dB** at point P must be along a line parallel to the Z axis, since that is the only way that it can be perpendicular to dy' and to **r**, both of which are contained in the X-Y plane. Rotating dy' in a counter-clockwise direction will make it coincide with the vector **r**. A right-handed screw with its axis parallel to Z would move in the upwards direction when so rotated; then the field intensity **dB** is directed upwards as shown in Figure 2.11. The direction that has just been determined for the field intensity can also be verified using the right-hand rule.

This determination for a particular element dy' is applicable to any other element along Y'. All of the small sections of the conductor Y', therefore, produce at point P field intensities that are all acted in the same direction. Furthermore, what has been said about point P on conductor Y is also applicable to any other point along Y and therefore it can be stated that the field along Y due to the current in Y' is parallel everywhere to the Z axis.

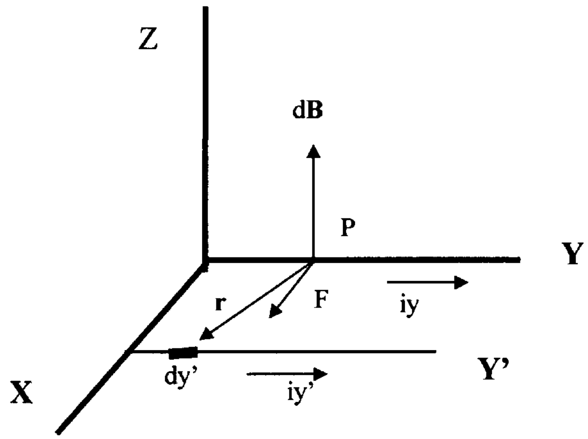


Figure 2.11 Graphical representation of the relationship between current, electromagnetic field, and electromagnetic force for a pair of parallel conductors (Biot–Savart Law).

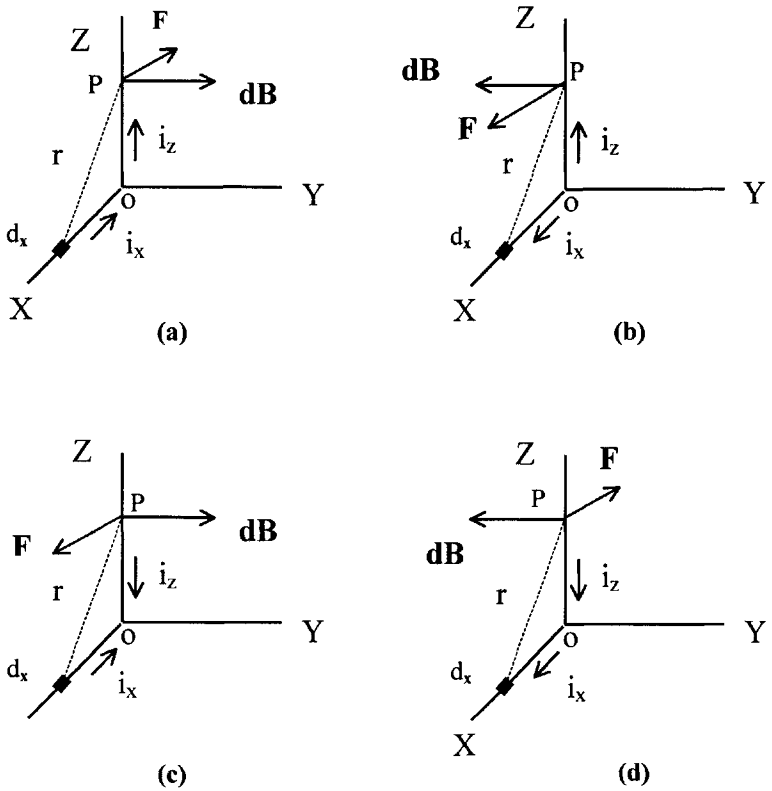


Figure 2.12 Electromagnetic field and force relationships for perpendicular conductors as a function of current direction.

To find the direction of the force that is acting upon the conductor Y, simply apply Fleming's left-hand rule. When this is done, it can be seen that the force is parallel to the X axis, as shown in the corresponding figure. This is not surprising and it only confirms a principle that is already well known, that is, that two parallel conductors, carrying currents in the same direction, attract each other.

If the direction of the current $i_{y'}$ is reversed, the vector product will yield a field intensity vector **dB** that is directed downward. Then, by Flemming's rule, the force is directed in such a way as to move Y away from Y'. Now, by leaving $i_{y'}$ flowing in its original direction, which will keep **dB** pointing upwards, and reversing the direction of i_y, Flemming's rule indicates that a force will move Y away from Y'. Therefore, once again it is verified that two parallel conductors carrying currents in opposite directions will repel each other.

2.4.1.2 Perpendicular Conductors in a Plane

For the arrangement where there are two perpendicular conductors, it is possible to have four basic cases. For all cases it will be assumed that the conductors coincide with the X and Z axis as shown in Figure 2.12.

Case 1. Observing Figure 2.12 (a), the field **dB** at point P, due to the current i_x in the segment **dx,** is parallel to the Y-axis. This is the result of the vector cross-product, since both **dx** and **r** are in the X-Z plane. If **dx** is rotated to make it coincide with vector **r**, the direction of the rotation will make a right-handed screw parallel to Y to move to the right. This determines the direction of the field, which is readily confirmed by the use of the right-hand rule.

The above applies to any **dx** element and therefore, the total field B at point P coincides with **dB**. Since this applies to any point P on the Y-axis, then the field at any point on Z, due to the current i_x has the direction as shown in Figure 2.12 (a). Again, Flemming's left-hand rule can be used to determine the direction of the force at any point along the conductor Z. The direction of the force for this particular case is shown in Figure 2.12 (a).

Case 2. If the direction of the current i_x is reversed, **dB** still remains parallel to Y but now it points to the left, as shown in Figure 2.12 (b). The force F is still parallel to the X-axis but it is reversed from the direction corresponding to case 1 shown in 2.12 (a).

Case 3. If i_z is reversed, leaving i_x with its original direction, **dB** is identical to the first case but F is reversed as shown in 2.12 (c).

Case 4. Finally if both i_x and i_z are reversed, the field **dB** is reversed in comparison to case 1 but the direction of the force remains unchanged as can be seen in Figure 2.12 (d).

The four cases described above have one common feature, which is related to the direction of the current flow. In every case the direction of the force on the Z conductor is such as to try to rotate it about the origin O to make its current, i_z coincide with current i_x.

The current in Z also produces a force on X. Its direction can be determined by applying the principle just described. A graphical summary showing the directions of the forces acting on two conductors at right angles and in the same plane is given in Figure 2.13 (a)-(d).

2.4.1.3 Perpendicular Conductors Not in the Same Plane

This particular case is represented in Figure 2.14 where it is shown that the field **dB** at point P due to the current i_x is in the Z-Y plane. Being the vector product of **dx** and **r, dB** must be perpendicular to **dx**. Because of the cross vector product relationship, it must also be perpendicular to **r**. A line through point P on the Z-Y plane, perpendicular to **r**, is also perpendicular to **r'**, which is the projection of **r** on the Z-Y plane. This can be demonstrated visually by lifting any of the acute angle corners of a drafting triangle.

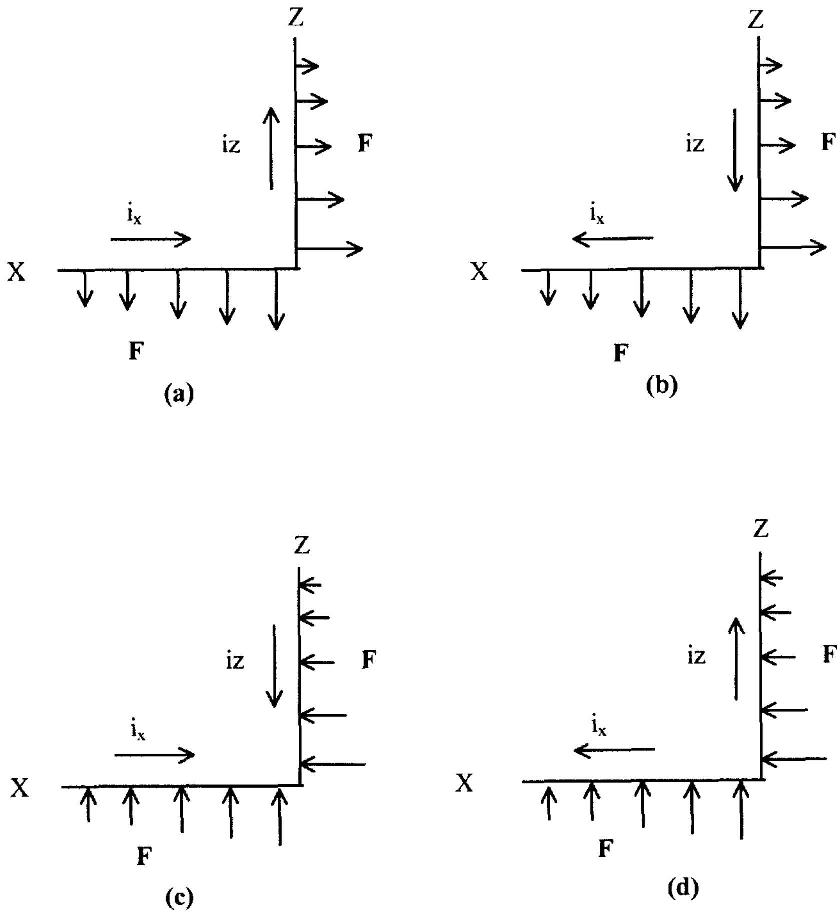


Figure 2.13 Graphical summary showing the direction of the electromagnetic force as a function of current direction.

The vectors like **r** joining P with all the elements d**x'** along the conductor X' have a common projection **r'** on the Y-Z plane. Therefore the components d**B** at P all coincide, and the total field intensity **B** has a direction as shown in the figure.

The directions of the field intensities at other points along Z, due to the current i_x in X', have directions tangential to circles drawn with their centers at O' as shown in Figure 2.15.

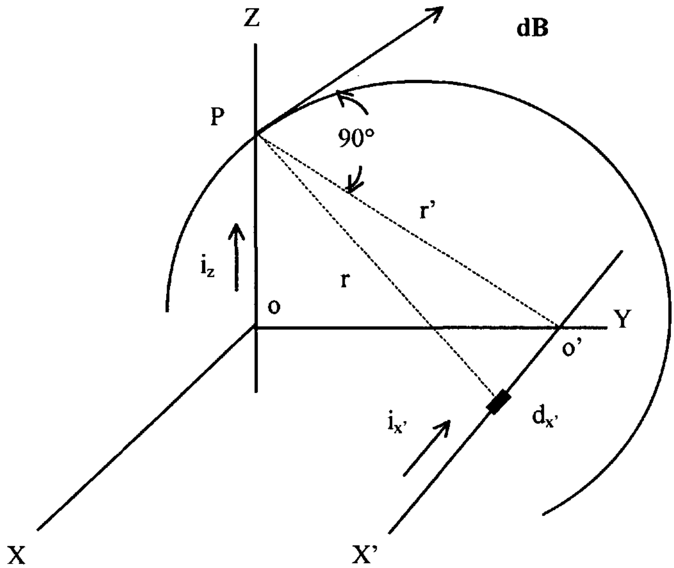


Figure 2.14 Electromagnetic field and forces for a pair of perpendicular conductors not in the same plane.

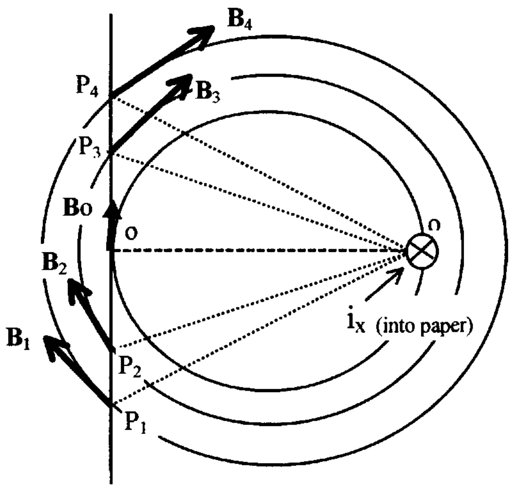


Figure 2.15 Field intensity along the Z axis due to current in the X' axis.

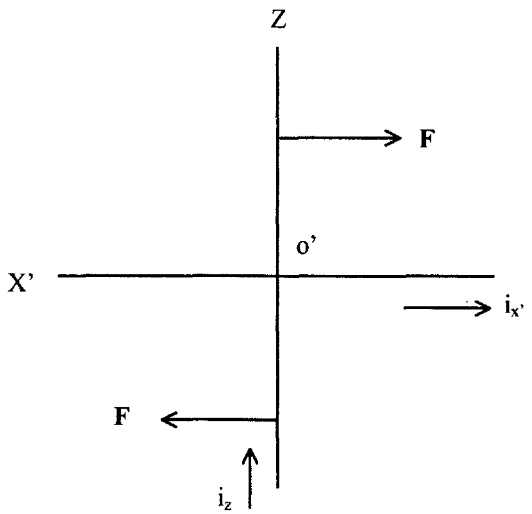


Figure 2.16 Two dimensional view diagram of the force direction. View looking into the end of the Y-axis.

The direction for **B** is established by applying the right-hand rule. At the point on Z nearest X', the field intensity $\mathbf{B_0}$ coincides in direction with Z. There is no force applied on the conductor at that point, since **B** does not have a component perpendicular to the conductor. At any other point along Z, field **B** has a component perpendicular to the conductor and is therefore capable of producing a force on the conductor. In Figure 2.15, it can be seen that above O, the nearest point to X' on Z, the perpendicular component of **B** is directed toward X, and below O, away from X.

Putting this information back into a three-dimensional diagram, the direction of the forces can be determined by applying the left-hand rule. Figure 2.16, which is drawn looking into the end of the Y-axis will serve to clarify the results.

The forces on the conductor Z are directed so that they tend to rotate the conductor about OO' so as to make i_x coincide in direction with i_z. If any of the currents are reversed this principle still applies.

2.4.1.4 Direction of Forces Summary

The following observations represent a simplified summary of the results obtained in the preceding section related to the determination of the force direction between conductors carrying current.

1. The preceding discussion covered parallel runs of conductors, as well as conductors that have rectangular corners, and conductor crossovers, which may be found in common switchgear construction.
2. In the case of parallel arrangements, conductors simply attract or repel each other.
3. In the case of perpendicular arrangements, the forces on the conductors simply tend to flip over the conductors to make their respective currents coincide in direction.

Once it is known how the first conductor acts on a second, the basic principle of action and reaction of forces will define how the second conductor acts on the first. It pushes back when being pushed and pulls when being pulled.

2.4.2 Calculation of Electrodynamic Forces Between Conductors

The mechanical forces acting on conductors are produced by the interaction between the currents and their magnetic fields. The attraction force between two parallel wires, where both are carrying a common current that is flowing in the same direction, is used to define the unit of current, the ampere. According to this definition, 1 ampere is equal to the current that will produce an attraction force equal to 2×10^{-7} newtons per meter between two wires placed 1 meter apart.

The calculation of the electrodynamic forces acting on the conductors is based on the Biot–Savart law. According to this law, the force can be calculated by solving the following equation:

$$\frac{F}{l} = \frac{\mu_0 i_1 \times i_2}{2\pi d} = \frac{\left(4\pi \times 10^{-7}\right) \times i_1 \times i_2}{2\pi \times d} = 2 \times 10^{-7} \frac{i_1 \times i_2}{d} \quad \text{newtons per meter}$$

where:

F = force in newtons
l = length in meters
d = distance between wires in meters
i_1 and i_2 = current in amperes
μ_0 = permeability constant = $4\pi \times 10^{-7}$ (weber / amp-m)

From the above equation and from the previous discussion describing the direction of the electromagnetic forces, the force between two conductors is proportional to: (a) the currents, i_1 and i_2, flowing through the conductors; (b) to the permeability constant μ_0, and (c) to a constant that is defined only by the geometrical arrangement of the conductors. As indicated before, calculations for complex geometric configurations should be made with the aid of any of the computer models that are available.

The total force acting on a conductor can be calculated as the summation of the component forces for each of the individual sections or members of the conductor. However these force components do not exist independently by themselves, since in order to have current flow a complete electric circuit is needed. The use of conductor members in pairs is a convenient way of calculation, but every conducting member in the circuit must be taken in combination with each other member in the circuit.

The force calculation for the bus arrangements that follow only represent some of the most typical and relatively simple cases that are found in the construction of switchgear equipment.

2.4.2.1 Parallel Conductors

The general equation given by the Biot–Savart law is directly applicable to the calculation of the electromagnetic forces acting between parallel conductors, if the conductors are round and they have an infinite length. The equation is applicable if the ratio between the length of the conductor and the distance separating the conductors is more than 10, in which case the resulting error in the calculated force is less than 10 percent, and therefore it is generally acceptable to use this approximate value to estimate the conductor strength requirements.

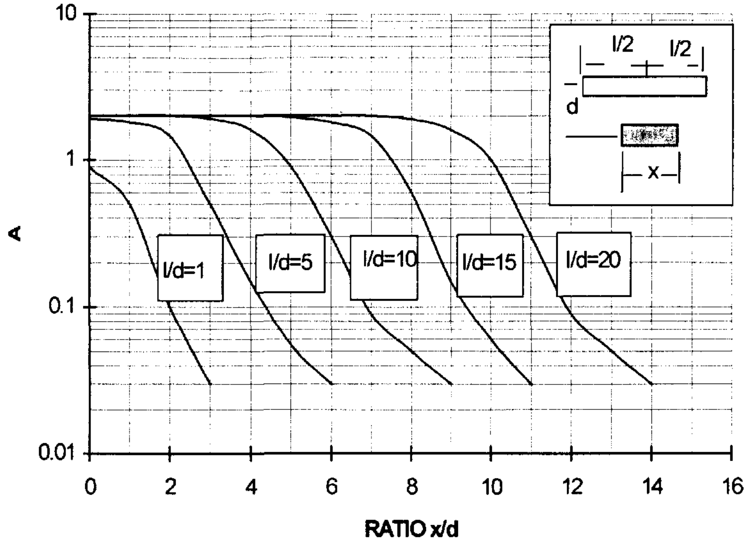


Figure 2.17 Multiplying factor A to calculate the distributed force along a pair of short conductors in parallel.

For conductors of a finite length, the following relationship given by C.W. Frick [4] should be used.

$$F = 2 \times 10^{-7} \times \frac{i_1 \times i_2}{d} \times A \times l \qquad \text{newtons}$$

where:

$$A = \frac{1}{2l}\left[\sqrt{4d^2 + (l+2x)^2} - \sqrt{4d^2 + (l-2x)^2}\right]$$

The numerical values for the factor A can be obtained from Figure 2.17. In the enclosed box in Figure 2.17 the relationships between the lengths, l and x, of the conductors, and their spacing d, is shown.

In the case of rectangular conductors, the force can be determined using the same formula that was used for round conductors except that a shape correction factor K is added to the original formula.

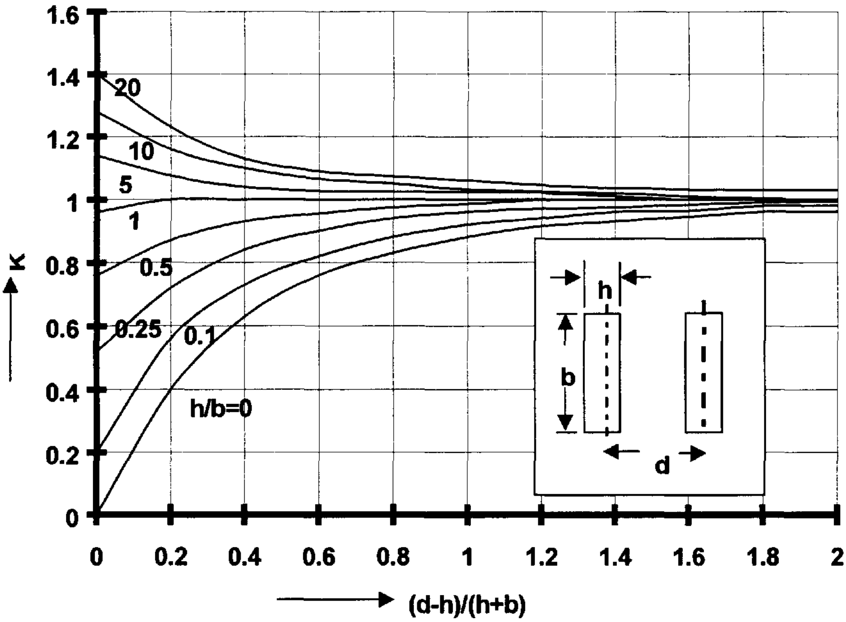


Figure 2.18 Correction factor K for flat parallel conductors.

The correction factor takes into account the width, thickness, and spacing of the conductors, and accounts for the fact that the electromagnetic forces between conductors are not always the same as those calculated under the assumption that the current is concentrated at the center of the conductor.

The values for K have been calculated by H.B. Dwight [5] and are given in Figure 2.18. For arrangements where the ratio $(d\text{-}h) / (h+b) > 2$ (refer to Figure 2.18), the error introduced is not significant and the correction factor may be omitted.

2.4.2.2 Conductors at Right Angles

In Figure 2.19 a multiplying factor A is plotted for different lengths l of one of the conductors. The distributed force, per unit length, for the second conductor at a distance y from the bend, is calculated using the following formula:

$$\frac{F}{l} = 1 \times 10^{-7} \times i_1 \times i_2 \times A \qquad \text{newtons per meter}$$

where: (as represented in Figure 2.19)

$$A = \frac{l}{\left(y\sqrt{l^2 + y^2}\right)}$$

and where y and l are as shown in Figure 2.19.

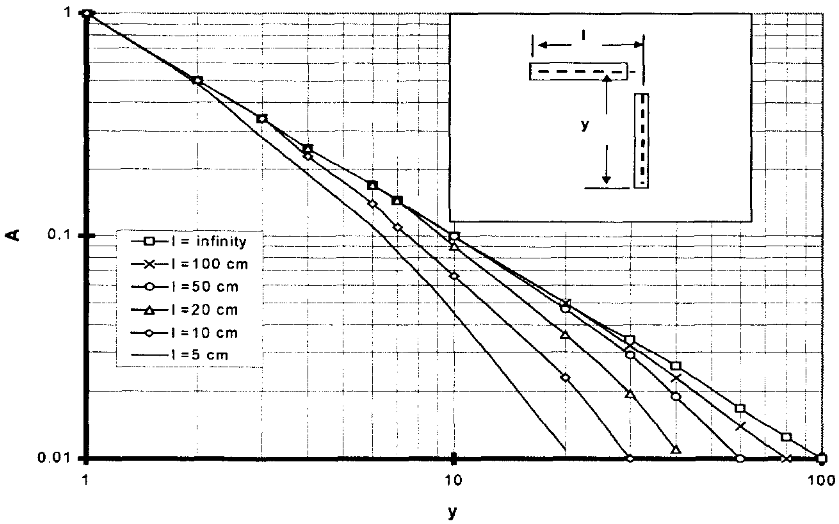


Figure 2.19 Multiplying factor A used to calculate the distributed force along different lengths of conductors at right angles to each other.

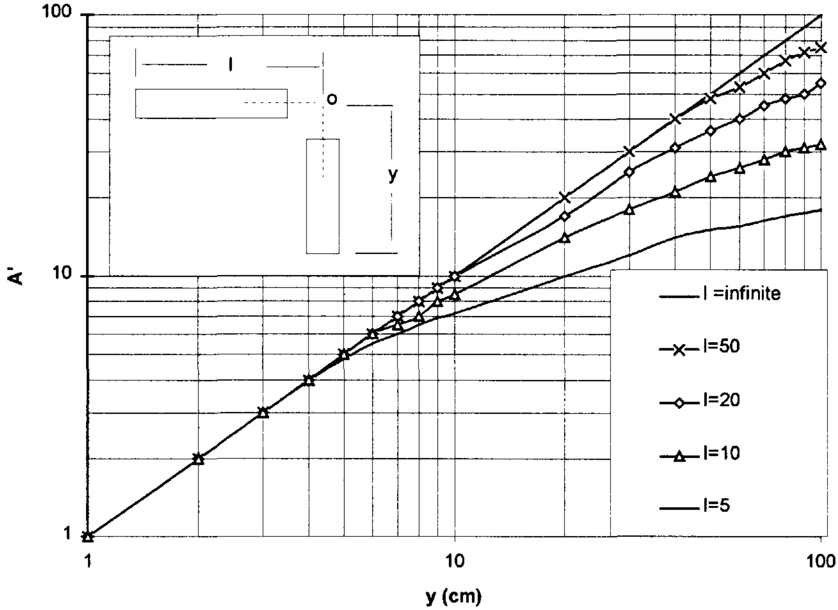


Figure 2.20 Values of A' for calculating the total force at a point on a conductor at a right angle.

The direction of the forces was previously determined in Section 2.4 of this chapter. But now, for convenience, the general rule will be restated here, as follows: When in a simple bend the current flows from one leg into the other leg of the bend, the force will act in a direction away from the bend. If the currents flow into the bend from both sides or flow away from the bend from both sides, the forces are directed toward the inside the bend, as if trying to make a straight line out of both conductors.

When one conductor joins another at a right angle, the force distribution in each conductor can be calculated using the method given above. To find the total effect of the electrodynamic forces, the force on each leg of the conductor is calculated and then the summation of these forces will yield the desired result.

To calculate the stresses on the individual parts, it is necessary to calculate the force acting on a certain section of the conductor, and in most cases it will also be required to find the moment produced by this force with respect to some given point. The total force acting on the conductor can be calculated using the same equation given for the distributed forces, however, the multiplying factor A will now become A'.

The new factor A' is then defined as:

$$A' = ln\frac{y}{y_0} \times \left(\frac{l + \sqrt{l^2 + y_0^2}}{l + \sqrt{l^2 + y^2}} \right)$$

where (see insert on Figure 2.20),

l = length of one of the conductor's leg
y = length of the other leg
y_0 = 0.779 multiplied by conductor radius (for round conductors) and 0.224 multiplied by $(a + b)$ for square bars

where

a and *b* are the cross section dimensions of the bar.

Typical values for the multiplying factor A' that have been calculated for different lengths of conductors are shown in Figure 2.20.

To calculate the moment of the total force with respect to the center of moments *o*, which in this case corresponds to the center point of the bend, the following equation is used:

$$M_o = 1 \times 10^{-7} \times i_1 \times i_2 \times D$$

where:

D = a multiplying factor whose value is given in Figure 2.21.

When the origin point of the desired moment is not at the center of the bend, then the moment with respect to a different point can be calculated by first calculating the moment M_o with respect to the point *o*, which can be regarded as the product of the force *F* and a certain perpendicular distance *p*, where *p* is related to *o*. Then the moment of the same force *F*, with respect to a point at a distance $p+n$ from *o*, will be

$$M_p = F(p + n)$$

where *n* is the distance from *o* to *p*, and therefore

$$M_p = M_o + F \times n$$

Distance *n* is considered to be either positive or negative, according to the position of *p* with respect to the force and to the point *o*. That is, *n* is positive when it is to be added to *p* and it is negative when it is to be subtracted from *p*.

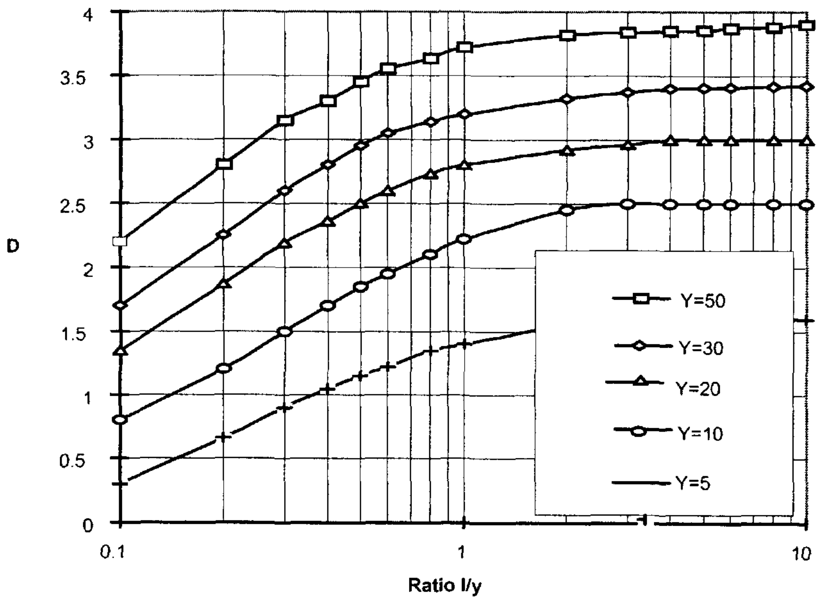


Figure 2.21 Multiplying factor *D* used to calculate the moment of the force acting on a conductor with respect to an origin point "*o*".

2.4.3 Forces on Conductors Produced by Three Phase Currents

As shown earlier, when a fault occurs on a three phase circuit, because of their difference in phase all three currents cannot be equally displaced. It is also known that at least two of the currents must be displaced in relation to their normal axis, and in many instances all three phases may be displaced from the normal axis.

Because of the interaction between all conductors, the forces acting on each of the conductors of a set of three parallel conductors, (which are located in the same plane and are equally spaced), can be defined as follows:

The force on conductor 1 is equal to the force due to conductor 2 plus the force due to conductor 3, ($F_1 = F_{1,2} + F_{1,3}$).

The force on conductor 2 is equal to the force due to conductor 3 minus the force due to conductor 1, ($F_2 = F_{2,3} + F_{2,1}$).

The force on conductor 3 is equal to the force due to conductor 1 plus the force due to conductor 2, ($F_3 = F_{3,1} + F_{3,2}$).

When these forces are calculated, their mathematical maximum is found. Assuming that the currents exhibit a phase sequence 1, 2, 3 (when looking at the conductors from left to right), and that the current in phase 1 leads the current in phase 2, while the current in phase 3 lags the current in phase 2, the following generalized results are obtained.

The maximum force on the outside conductors is equal to:

$$F_1 \,\&\, F_{3(max)} = 12.9 \times 10^{-7}\left(\frac{i_r^2}{d}\right) \quad \text{newtons per meter}$$

The maximum force on the center conductor is:

$$F_{2(max)} = 13.9 \times 10^{-7}\left(\frac{i_r^2}{d}\right) \quad \text{newtons per meter}$$

where:

i_r = rms value of the symmetrical current

d = center to center distance from the middle to the outside conductors

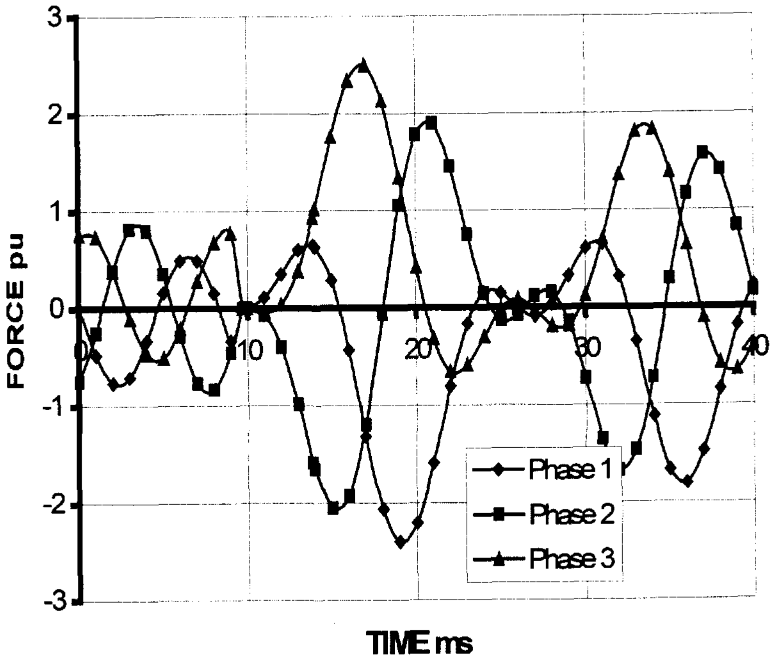


Figure 2.22 Diagram representing the forces on a three phase parallel conductor arrangement. Short circuit initiated at 75° after current zero on phase No.1.

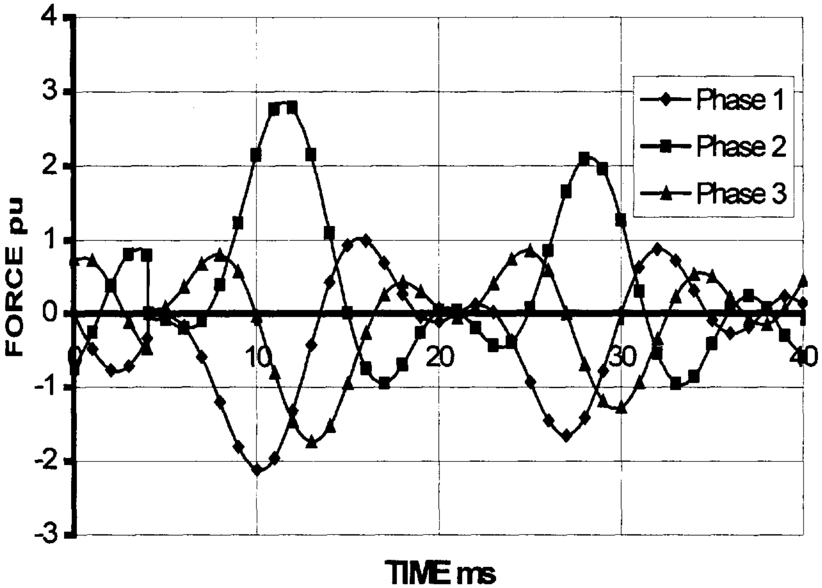


Figure 2.23 Diagram representing the forces on a three phase parallel conductor arrangement. Short circuit initiated 45° before current zero on center phase (phase No.2).

Figures 2.22 and 2.23 show a plot of the maximum forces for a fault initiated in the outside pole, and for one initiated in the center pole, respectively.

It is interesting to note that for any of the three conductors the force reaches its maximum at one-half of a cycle after the short circuit is initiated. It should also be noted that the value of the maximum force is the same for either of the outside conductors. However, for the force to reach that maximum, the short circuit must occur 75 electrical degrees *before* current zero in the conductor carrying a current that is *leading* the current in the middle conductor, or alternatively it must occur 75 electrical degrees *after* the current zero (corresponding to the phase that is *lagging* the current of the middle conductor).

The maximum force on the center phase (conductor 2) will reach a maximum if the short circuit is initiated 45 electrical degrees either *before* or *after* the occurrence of a current zero in the middle phase. The maximum force on the middle conductor represents the greatest force on the three conductors.

From all of this, another interesting fact develops. If the short circuit happens 75 degrees *after* the current zero for the current in the conductor that is *lagging* the current in the middle conductor, that instant is 45 degrees *before* the current zero in the middle conductor. Therefore, under these conditions the respective forces on both of the outside conductors will reach their maximum and it will be reached simultaneously on both phases one-half cycle after the initiation of the short circuit. Similarly, if the short circuit is initiated 75 degrees *before* current zero in phase 1, that instant corresponds to 45 degrees *after* current zero in phase 2 and therefore the respective forces on phases 1 and 2 will reach their maximum simultaneously one-half cycle after the start of the short circuit.

For a conductor arrangement where the spacing is symmetrical, such as in an equilateral triangular arrangement, the maximum value of the resultant force on any conductor will be:

$$F = 13.9 \times 10^{-7}\left(\frac{i_r^2}{d}\right) \quad \text{newtons per meter}$$

The force on any of the conductors in this geometry will reach its maximum if the instant when the short circuit begins is 90 electrical degrees either *before* or *after* the occurrence of the current zero in that conductor. The force will reach a maximum value, under those conditions, 180 electrical degrees, or one-half of a cycle after the initiation of the fault. The direction of the maximum force, in this case, is perpendicular to the plane determined by the other two conductors, and the maximum force is directed away from that plane.

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3

TRANSIENT RECOVERY VOLTAGE

3.0 INTRODUCTION

At the beginning of Chapter 2 it was stated that all current interrupting devices must deal with current and voltage transients. Among the current transients of special interest are those which are the direct result of sudden changes in the load impedance, such as in the case of a short circuit. Current transients produced by a short circuit are dependent upon events that are part of the system and therefore they are considered transients that are induced by the system. The voltage transients, on the other hand, are the result of either the initiation or the interruption of current flow. The switching device itself initiates these transients and, therefore, they can be considered as being transients that are equipment induced. However, the characteristics of these transients do not depend on the type of equipment, but rather, they depend upon the parameters and the specific location of each component of the circuit.

What follows is an introduction to this all-important subject dealing with voltage transients. Knowledge about the nature and characteristics of transient voltages is an essential necessity for all those involved in the design, the application, and the testing of interrupting devices. Transient voltage conditions, especially those occurring following current interruption, must be properly evaluated before selecting an interrupting device, whether it is a circuit breaker, an automatic recloser, a fuse, a load breaking switch, or any kind of fault interrupting or load breaking equipment in general.

Whenever any of these devices is applied, it is not sufficient to consider and to specify only the most common system parameters such as: available fault current, fault impedance ratio (X/R), load current level, system operating voltage, or dielectric withstand levels. It is also imperative that the requirements imposed by the transient voltage be truly understood and properly acknowledged to ensure the correct application of the selected switching device.

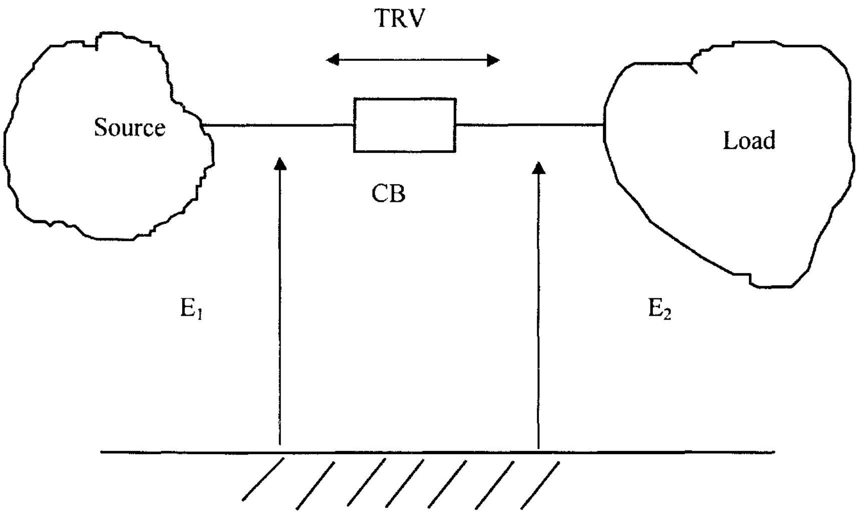


Figure 3.1 Graphical representation of an electrical network illustrating the sources of the transient recovery voltage.

Voltage transients, as stated earlier, generally occur whenever a circuit is being energized or de-energized. In either case these transients can be quite damaging, specially to transformers, reactors, and rotating machinery that may be connected to the circuit. The transients, occurring while clearing a faulted circuit and which are referred here as transient recovery voltages (TRV), will be discussed first. In a later chapter, other types of voltage transients such as those produced by switching surges, current chopping, restrikes and prestrikes, will be covered.

3.1 TRANSIENT RECOVERY VOLTAGE: GENERAL CONCEPTS

All types of circuit interrupting devices can be considered as a link that joins two electrical networks. As is illustrated in Figure 3.1, on one side of the device is the electrical network that delivers power and can be identified as the source-side network. On the other side is an electrical network that consumes power and consequently it can be identified as the load side network.

Whenever the interrupting device is opened, the two networks are disconnected and each of the networks redistribute its trapped energy. As a result of this energy redistribution, each network develops a voltage that appears simultaneously at the respective terminals of the interrupter, shown as E_1 and E_2 in Figure

3.1. The algebraic sum of these two voltages represents the transient recovery voltage, is which normally referred to as TRV.

A comprehensive evaluation of the recovery voltage phenomena that takes place in any electrical system should be based upon the conditions prevailing at the moment of the interruption of a short circuit current. The minimum requirements to be taken into consideration for this evaluation are the type of fault, the characteristics of the network connections, and the switching arrangement used.

Depending on the different combinations of these conditions, it is obvious that the transient recovery voltage can have many different characteristics. It can exhibit a single frequency or a multi-frequency response. It can be expressed in the form of a sinusoidal function, a hyperbolic function, a triangular function, an exponential function, or as a combination of these functions. It all depends on the particular combination of the many factors, which directly influence the characteristics of the TRV.

If all factors are taken into consideration, exact calculations of the TRV in complex systems is rather complicated and generally are best made with the aid of a digital computer program such as the widely used electromagnetic transients program (EMTP).

For those applications where a somewhat less accurate result will suffice, E. Boehne [1], A. Greenwood [2] and P. Hammarlund [3], among others, have shown that it is possible to simplify the calculations by reducing the original system circuits to an equivalent circuit that has a simple mathematical solution. Nevertheless, when these simplified calculation methods are employed, the problem of how to properly select the equivalent circuits and the values of the constants to be used in the calculations still remains.

The selections are only practical equivalents containing lumped components that approximately describe the way in which the actual distributed capacitances and inductances are interrelated in the particular system under consideration. Furthermore, the calculation procedures are still somewhat tedious, which again points out the fact that even for moderately complex systems, it is advantageous to use the modern computer-aided methods of calculation.

Nevertheless, there is something to be said about simple methods for approximated calculations of TRV, and at the risk of oversimplifying the problem, it is possible to say that in the majority of cases a first hand approximation of the TRV is generally all that is needed for the proper initial selection and for judging the adequacy of prospective applications of circuit breakers. For some particular cases it is possible to consider only the most basic conditions found in the most common applications. In most cases these are the conditions that have been used as the basis for establishing standards that define the minimum capability requirements of circuit breakers.

A simplified calculation approach can also be of help in determining if the rated TRV of a circuit breaker is sufficient for the application at hand. In many cases the results obtained, with such simplified calculations, can be used to determine if there is a need for further, more accurate calculations. Another possible application of the simplified calculation approach is that it can be used to evaluate possible corrective actions that may be taken to match the capability of the device with the characteristics of the circuit. One such possible corrective action is the addition of surge capacitors to modify the inherent TRV of a system.

3.1.1 Basic Assumptions for TRV Calculations

The following assumptions are generally made when calculating the transient recovery voltage of a transmission or a distribution high-voltage power system.

1. Only three phase, symmetrical, ungrounded terminal faults need to be considered. This is because the most severe TRV appears across the first pole that clears an ungrounded three phase fault occurring at the terminals of the circuit breaker.
2. It is assumed that the fault is fed through a transformer, which in turn is being fed by an infinite source. This implies that a fault at the load side terminals of a circuit breaker allow the full short circuit current to flow through the circuit breaker.
3. The current flowing in the circuit is a totally reactive symmetrical current. This means that at the instant when the current reaches zero, the system voltage will be at its peak.
4. As the current approaches zero, the voltage across the circuit breaker contacts is equal to the arc voltage of the device. This voltage is assumed to be negligible during the TRV calculation because when dealing with high voltage circuit breakers, the arc voltage represents only a small fraction of the system voltage. However, this may not be the case for low-voltage circuit breakers where the arc voltage, in many instances, represents a significant percentage of the system voltage.
5. The recovery voltage rate represents the inherent TRV of the circuit and it does not include any of the effects that the circuit breaker itself may have upon the recovery voltage.

3.1.2 Current Injection Technique

A convenient contrivance employed in the calculation of the TRV is the introduction of the current injection technique. What this encompasses is the assumption that a current equal and opposite to the short circuit current that would have continued to flow in the event that interruption had not occurred, is flowing at the precise instant of the current zero when the interruption of the short circuit current takes place. Since the currents at any time are equal and opposite, it is rather obvious that the resultant value of the sum of these two currents is zero. Consequently the most basic condition required for current interruption is not being violated.

Furthermore, it is possible to assume that the recovery voltage exists only as a consequence of this current, which is acting upon the impedance of the system when viewed from the terminals of the circuit breaker.

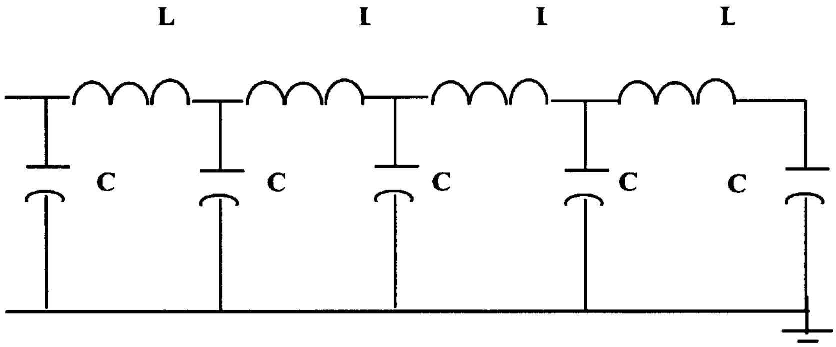


Figure 3.2 Schematic representation of the elements of a transmission line.

Additionally, since the frequency of the TRV wave is much higher than that of the power frequency, it is possible to assume that without introducing any significant error the injected current (i) can be represented by a linear current ramp that is defined by:

$$i = \sqrt{2} \times I_{rms} \times \omega \times t$$

where:

I_{rms} = rms value of the short circuit current
$\omega = 2\pi f = 377$
t = time in seconds

As will be seen later this concept will be used extensively for the calculation of transient recovery voltages.

3.1.3 Traveling Waves and the Lattice Diagram

To better understand some of the important characteristics related to the transient voltage phenomena taking place during the execution of switching operations involving high voltage equipment, it would be beneficial to have at least a basic knowledge about the physical nature and behavior of traveling waves that are present on the transmission lines during these circumstances.

One important characteristic of transmission lines is that since their resistance is generally neglected, they can be represented as a combination of distributed inductive and capacitive elements. The inductive elements are all connected in series, and the capacitive elements are distributed along the line in parallel as is shown in Figure 3.2. When an electrical system is visualized in this fashion it can be seen that, if a voltage is applied to the end of the line, the first capacitor will be charged immediately, and the charging of the capacitors located downstream from the point where the voltage was initially applied will be sequentially delayed as a consequence of the inductances that are connected in series between the capacitors. The observed delay will be proportionally longer at each point down the line.

If the applied voltage is in the form of a surge signal that starts at zero and returns to zero in a short time, then it is reasonable to expect that the voltage across the capacitors will reach a maximum value before returning to zero. As this pattern is repeated at each capacitor junction point along the line, it can easily be visualized that the process serves as a vehicle to propagate the applied surge in the form of a wave that moves along the line. During the propagation of the wave, the original characteristics of the surge signal remain basically unchanged in terms of their amplitude and waveform.

In order to charge the capacitors at each connection point along the line, a current must flow through the inductances that are connecting the capacitors. Then, at any point along the line, the instantaneous value of the voltage $e(t)$ will be related to the instantaneous value of the current $i(t)$ by the following relationship:

$$e(t) = Zi(t)$$

where the constant of proportionality Z represents the surge impedance of the line. This constant is represented as:

$$Z = \sqrt{\frac{L}{C}}$$

In the above relationship L and C are the inductance and the capacitance per unit length of the line. The numerical value of the surge impedance Z is a constant in the range of 300 to 500 ohms. A value of 450 ohms is usually assumed for single overhead transmission conductors and 360 ohms for bundled conductors.

Dimensionally, the surge impedance is given in ohms and is in the nature of a pure resistance, however, it is important to realize that the surge impedance, although resistive in nature, cannot dissipate energy as a normal resistive element can. It is also important to note that the surge impedance of a line is independent of the length of such line. This is because any point at any distant location in a circuit does not experience a voltage that has been applied somewhere in the line until a traveling wave reaches that point.

Traveling waves, as with any other electromagnetic disturbance in air, will propagate at the speed of light, which is 300 meters per microsecond or approximately 1000 feet per microsecond. As the wave passes from a line that has an impedance equal to Z_1 into another circuit element, possibly but not necessarily another line which has an impedance equal to Z_2, new waves will propagate from the junction point and travel back into Z_1, and through the junction into Z_2. The new waves are shaped identically to the incident wave but their amplitude and possibly their signs are changed. The coefficients used to obtain the new voltage waves are:

Reflection (from Z_2 back into Z_1):

$$K_R = \frac{(Z_2 - Z_1)}{(Z_2 + Z_1)}$$

Refraction (from Z_1 into Z_2):

$$K_T = \frac{2Z_2}{(Z_2 + Z_1)}$$

If the line termination is a short circuit, then $Z_2 = 0$ and the above equation becomes:

For a reflected wave: $K_{RS} = -1$

For a refracted wave: $K_{TS} = 0$

If the line end is an open circuit, then $Z_2 = \infty$ and the expressions are:

For a reflected wave: $K_{RO} = +1$

For a refracted wave: $K_{TO} = +2$

The back- and forward-moving waves will pass each other undisturbed along the line, and the potential at any point along such a line is obtained by adding the potentials of all the waves passing through the point in either direction.

With the aid of a lattice diagram (Figure 3.3), it is possible to keep track of all waves passing through a given point at a given moment. A lattice diagram can be constructed by drawing a horizontal line from "a" to "b" which represents, without any scale, the length of the transmission line. Elapsed time is represented in a vertical coordinate that is drawn downward from the abscissa. This time is given by the parameter T which symbolizes the time required by the wave to travel from one end of the line to the other end. The progress of the incident wave and of its multiple reflections is then tracked as shown with their corresponding labels by the zigzag lines in Figure 3.3.

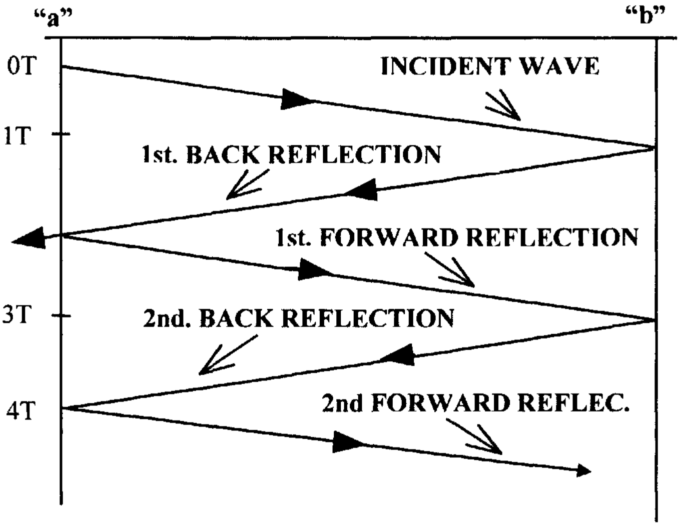


Figure 3.3 Typical construction of a lattice diagram.

The next step is to determine the relative amplitudes of successive reflections. It can be seen that an incident wave, whether it is a current or a voltage wave, which is entering point "a" from the left is a function of time *f*(*t*) and it progresses undisturbed to point "b" where the first back-reflection takes place. This first back-reflection is equal to $K_{Rb}f(t)$, where K_{Rb} is the same coefficient that was defined earlier using the values of *Z* on both sides of "b". When this wave reaches point "a", the reflection back toward point "b" is obtained by using the coefficient K_{Ra}, which was also defined earlier, but this time the values of *Z* on both sides of "a" are used. The refraction beyond point "a" is calculated by the coefficient K_{Ta} which is evaluated using the same relationship given earlier for the coefficient K_T. The process is repeated for successive reflections, and the amplitude of each successive wave is expressed in terms of these coefficients. These coefficients can be substituted by the corresponding numerical values defined below and the values can then be used to obtain the actual amplitude of the wave.

For a line terminating on a shorted end:

$K_{Rb} = -1$; $K_{Tb} = 0$

For a line terminating on an opened end:

$K_{Ra} = +1$; $K_{Ta} = +2$

3.2 CALCULATION OF TRANSIENT RECOVERY VOLTAGES

For any high voltage transmission or distribution network, it is customary and also rather convenient to identify and to group the type of short circuits or faults as either terminal, or bolted or short-line faults.

A terminal fault is defined as one where the short circuit takes place at, or very near, the terminals of the circuit breaker, while a short-line fault (SLF) is one where the short circuit occurs at a relatively short distance downstream from the circuit breaker on its load side. The short-line fault is also known as a kilometric fault since this is generally considered to be the critical distance for maximum severity of the recovery voltage.

Depending on the characteristics of the network and the type of the fault, the typical TRV can be represented by either single-frequency or double-frequency waveforms for the terminal faults, and by a multi-frequency that includes a saw-toothed waveform component for the short-line fault.

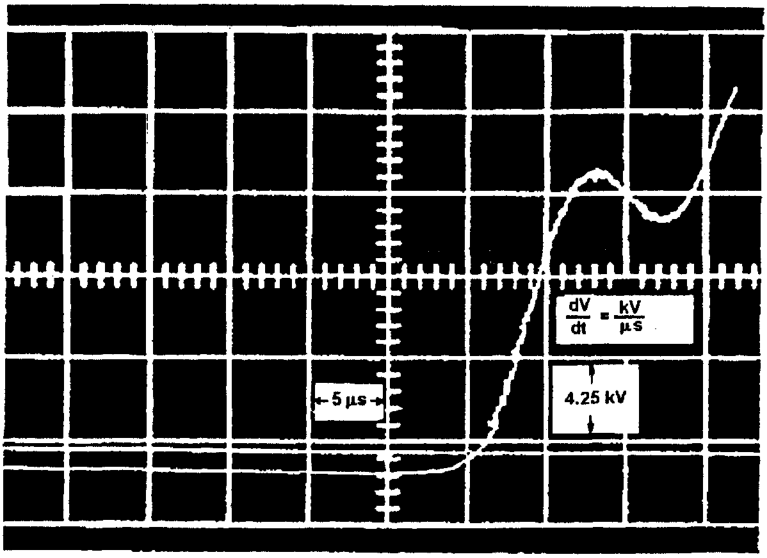
It is also important to recognize that the type of fault is important to the performance recovery of the circuit breaker. Following a short-line fault, the circuit breaker is more likely to fail in what is called the thermal recovery region. This is a region of approximately the first ten microseconds following the interruption of the current, when thermal equilibrium has not yet been re-established. In Figures 3.4 (a) and (b), the oscillograms of a successful and an unsuccessful interruption are shown.

For a terminal fault it is more likely that if any failures to interrupt do occur, they will be in the dielectric recovery region, which is the region located between approximately 20 microseconds up to about 1 millisecond, depending on the rating of the circuit breaker.

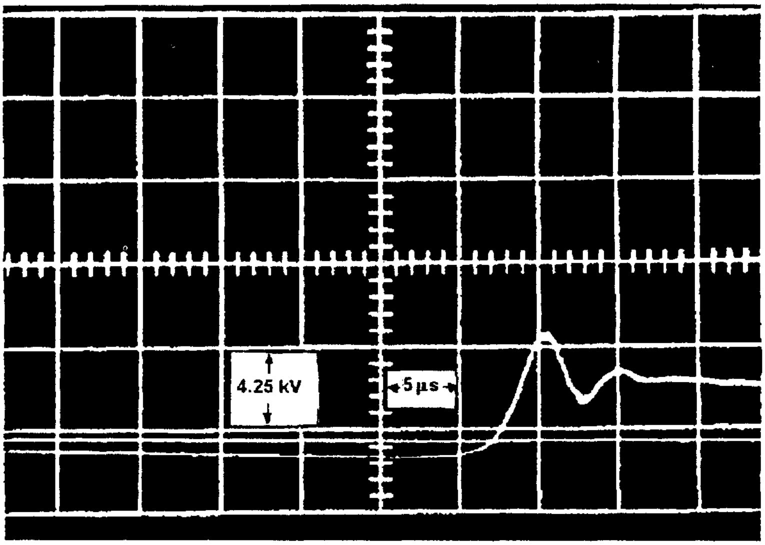
In Figure 3.5 (a), a dielectric region failure is shown while in Figure 3.5 (b) the recovery voltage corresponding to a successful interruption is shown.

3.2.1 Single Frequency Recovery Voltage

A single frequency TRV ensues when, during the transient period, the electric energy is redistributed among equivalent single capacitive and a single inductive elements. In general this condition is met when the short circuit is fed by a transformer and when no additional transmission lines remain connected at the bus following the interruption of the short circuit. This condition generally occurs only in distribution systems at voltages lower than 72.5 kV. In the majority of these cases the fault current is supplied by step-down transformers and, because the characteristics of the lines connected to the bus are such that (when considering the transient response of the circuit), they are better represented by their capacitance rather than by their surge impedance. As a consequence of this condition the circuit becomes underdamped and it produces a response, which exhibits a typical one minus cosine waveform.



(a)



(b)

Figure 3.4 Transient recovery voltage in the thermal recovery region. Oscillographic traces of a short-line fault. (a) Successful interruption and (b) dielectric failure after approximately 5 µs.

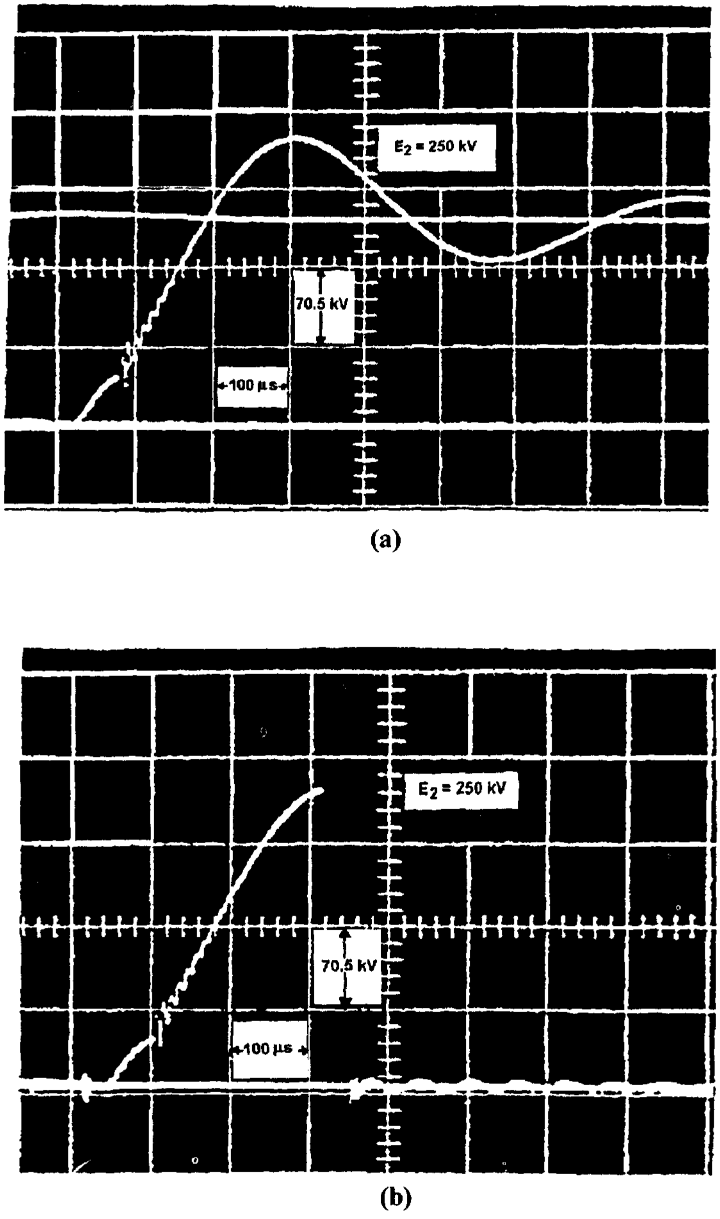


Figure 3.5 Transient recovery voltage in the dielectric recovery region. Oscillographic traces of a terminal fault. (a) Successful interruption and (b) dielectric failure after approximately 260 μs.

The simplest circuit that serves as an illustration for the single-frequency TRV response is shown in Figure 3.6 (a) and (b). After opening the switch, the following very basic equation can be written to describe the response of the circuit shown in Figure 3.6:

$$V \times \cos\omega t = L\frac{di}{dt} + \frac{1}{C}\int idt$$

where the initial values are:

$I_0 = 0$ since this is a basic requirement for interrupting the current,

and

$V_{C0} = 0$ since the value of the arc voltage was disregard.

Using the Laplace transform and rewriting the equation we obtain:

$$V\left(\frac{S}{S^2+\omega^2}\right) = SLI_{(s)} + \frac{I_{(s)}}{SC}$$

where S represents the Laplace transform operator.

Solving for the current $I_{(S)}$.

$$I_{(s)} = V\left[\frac{S}{S^2+\omega^2}\right]\left[\frac{SC}{S^2LC+1}\right]$$

Since the TRV is equal to the voltage across the capacitor, then this voltage (when shown in the Laplace notation) is equal to:

$$\text{TRV} = I_{(s)}\left(\frac{1}{SC}\right)$$

Substituting the value of $I_{(S)}$ in the above equation and collecting terms:

$$\text{TRV} = \frac{V}{LC}\left(\frac{S}{S^2+\omega^2}\right)\left(\frac{1}{S^2+\dfrac{1}{LC}}\right)$$

Letting $\sqrt{\dfrac{1}{LC}} = \omega_0$

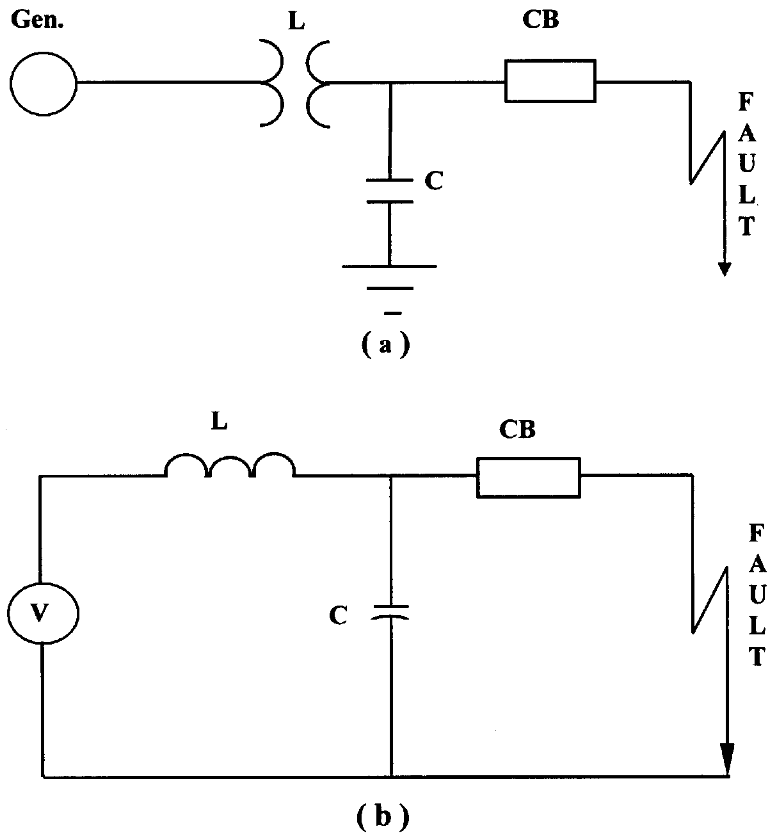


Figure 3.6 A typical simple circuit that produces a single-frequency response.

The inverse transform yields the following equation:

$$\text{TRV} = \frac{V}{LC}\left[\frac{\text{Cos}\ \omega t - \text{Cos}\ \omega_0 t}{\omega_0^2 - \omega^2}\right]$$

And if $\omega_0 >> \omega$ then

$$\text{TRV} = V(1 - \text{Cos}\ \omega_0 t)$$

where:

$$V = E_{TRV} = 1.88E_{rated}$$

The value 1.88 is used as a constant following the recommendations made by the Association of Edison Illuminating Companies [4]. This recommendation is based on the fact that at the time of current zero, on an ungrounded three phase terminal fault, the voltage at the source terminal of the breaker is equal to 1.0 per unit while the voltage on the load side terminal is equal to 0.5 per unit so the net steady-state voltage across the circuit breaker is equal to 1.5 per unit. However, during the transient period, if the effects of any damping are neglected, the voltage can oscillate to a maximum amplitude equal to 3.0 per unit. It would then be reasonable to say that in any practical application the maximum peak of the TRV across the first pole to interrupt a three phase short circuit current could be between 1.5 to 3.0 per unit. When regulation and damping factors, which were obtained from digital studies (and verified by field tests), were factored in the final recommended value of 1.88 was used.

3.2.2 Double Frequency Recovery Voltage: General Case

In the majority of cases, relatively simple equivalent circuits composed of lumped capacitive and inductive elements can represent the actual system circuits that are connected to the terminals of a circuit breaker. The substitution of the distributed capacitance and reactance of transformers and generators makes it possible to convert complex circuits into simple oscillatory circuits, which may be easier to handle mathematically. One such system circuit, which is often found in practice, is shown in Figure 3.7 (a), and its simplified version in 3.7 (b).

As easily recognized, finding the response of this circuit is not a difficult task since the two frequencies are not coupled together and, in fact, they are totally independent of each other. The solution of this circuit is given by the following relationships that define each one of the two independent frequencies. Their resulting waveform and the total voltage amplitude for the recovery voltage, is obtained from the summation of the waveforms that are generated by each independent frequency. The frequencies are given by:

$$f_S = \frac{1}{2\pi\sqrt{L_S C_S}} \quad \text{and}$$

$$f_L = \frac{1}{2\pi\sqrt{L_L C_L}}$$

The magnitude and wave form for the total voltage is proportional to the inductance and is given by:

$$E_{TRV} = V\left[a_L(1 - \cos\omega_L t) + a_S(1 - \cos\omega_S t)\right]$$

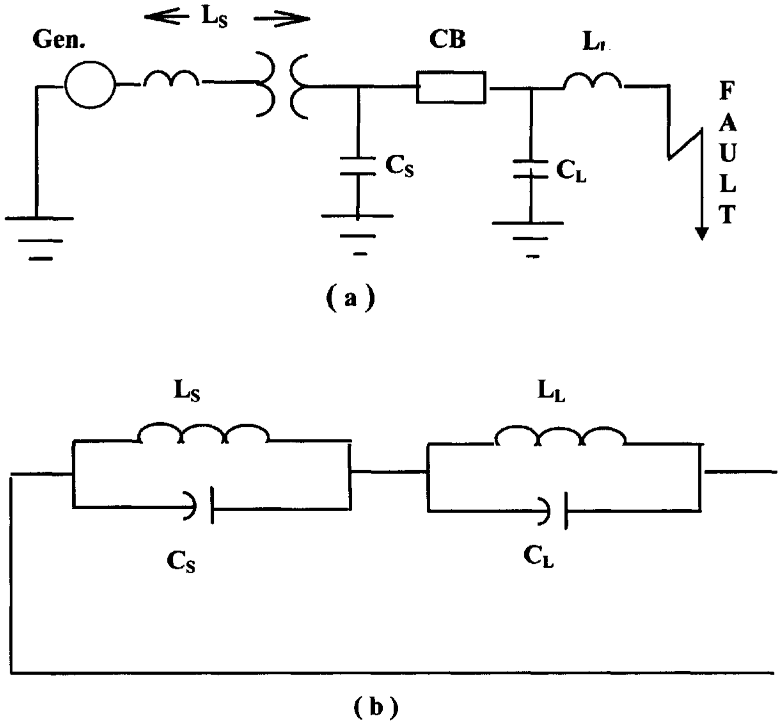


Figure 3.7 Schematic of a simple, double-frequency circuit used as a comparison basis for the calculation of other simplified circuits.

where:

$$a_L = \frac{L_L}{L_L + L_S}; \text{ and}$$

$$a_S = \frac{L_S}{L_L + L_S}$$

$$\omega_L = \frac{1}{\sqrt{L_L C_L}}; \text{ and}$$

$$\omega_S = \frac{1}{\sqrt{L_S C_S}}$$

The above equation describing the transient recovery voltage of the circuit is applicable only during the first few hundred microseconds following the interruption of the current and until the power frequency source voltage begins to change by more than a few percent from its peak value. In addition, and since this was one of the original assumptions, the equation is accurate only for purely inductive circuits. If the power factor of the power source is such that the phase angle between the current and the voltage is not exactly 90°, a more exact expression could be used as shown below.

$$E_{TRV} = V\left[\frac{a_L}{1-\left(\frac{\omega}{\omega_L}\right)^2}\left(\cos\omega t - \cos\omega_L t\right) + \frac{a_s}{1-\left(\frac{\omega}{\omega_s}\right)^2}\left(\cos\omega o - \cos\omega_s t\right)\right]$$

where:

$\omega = 2\pi f = 377$ for a 60 Hz power frequency (f)

3.2.2.1 Circuit Simplification

The aim of the circuit simplification process is to obtain representative circuits from which relationships can be established that relate the inductances and the capacitances of these circuits to those of the model circuit described above. For example the relatively complicated network scheme that is shown in Figure 3.8 (a) can be simplified to the one shown in Figure 3.8 (b). The simplified circuit can then be mathematically related to the circuit of Figure 3.7 by using the following relationships [2], [3].

For the frequency relationships:

$$\omega_L = \left(\frac{a-b}{a+b}\right)^{1/4}\left(\omega_A\omega_B\right)^{1/2}$$

$$\omega_s = \left(\frac{a+b}{a-b}\right)^{1/4}\left(\omega_A\omega_B\right)^{1/2}$$

For the amplitude relationships:

$$a_L = \frac{\left(a+b-\alpha^2\right)\left(a+b\right)}{2\left(\beta+1\right)b}$$

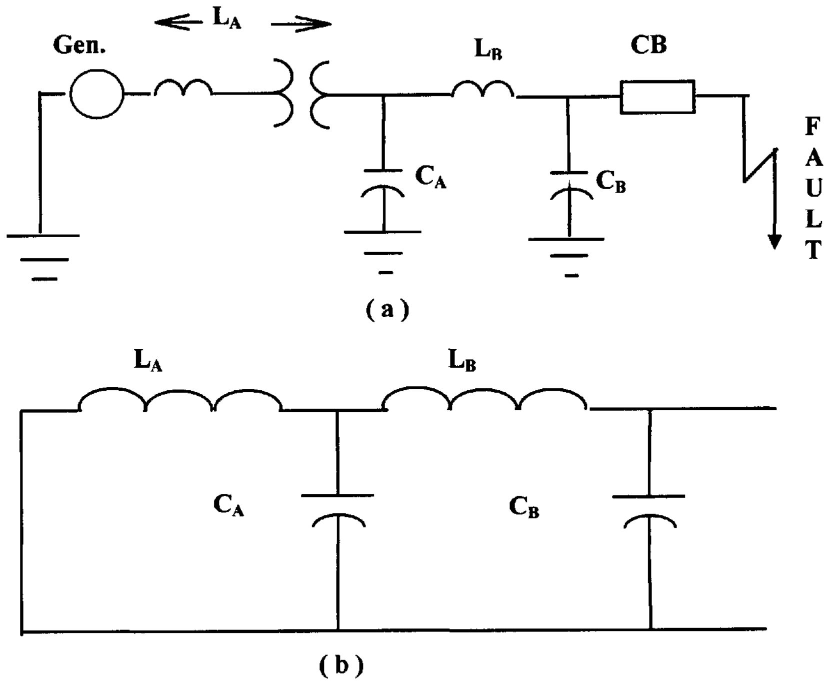


Figure 3.8 Example of circuit simplification.

$$a_S = 1 - a_L$$

where:

$$a = \frac{1}{2}\left(1 + \beta + \alpha^2\right)$$

$$b = \left(a^2 - \alpha^2\right)^{1/2}$$

$$\alpha = \left(\frac{L_A\ C_A}{L_A\ C_B}\right) = \left(\frac{\omega_B}{\omega_A}\right)$$

$$\beta = \frac{L_A}{L_B}$$

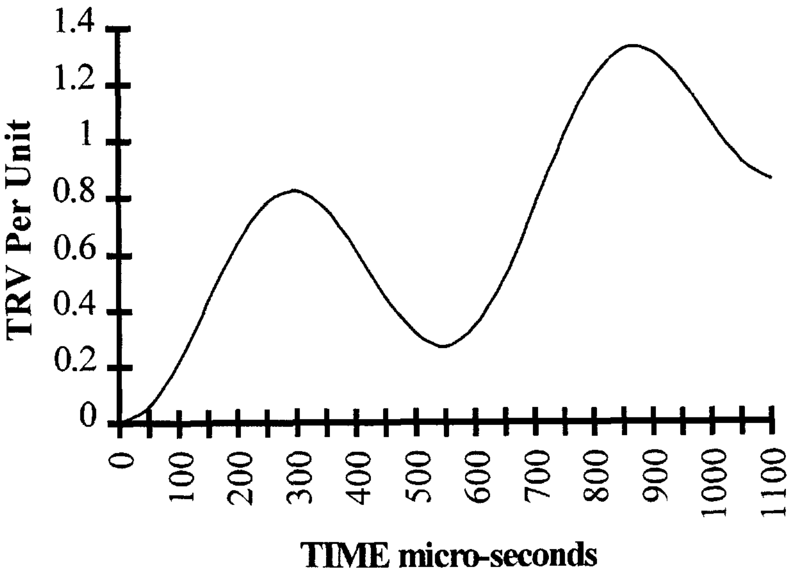


Figure 3.9 Resultant transient recovery voltage from the circuit in Figure 3.8.

$$\omega_A = \frac{1}{(L_A C_A)^{1/2}}$$

$$\omega_B = \frac{1}{(L_B C_B)^{1/2}}$$

To illustrate the procedure, the following numerical example is given. The above equations are solved using the following assumed values for the various circuit elements:

$L_A = 1.59$ mH = source inductance
$L_B = 2.39$ mH = reactor inductance
$C_A = 0.01$ μF = capacitance of all equipment on the bus
$C_B = 500$ pF = capacitance of breaker and reactor

The resultant TRV is shown graphically in Figure 3.9.

3.2.2.2 *Circuit Simplification Procedures*

It must be recognized that absolute guidelines for simplifying a circuit are not quite possible. One of the major difficulties in the procedure is the proper choice of those circuit components that have a significant influence on the transient phenomena under consideration.

In many instances this selection is based solely on experience acquired through practice. Despite the limitations, a few generalized rules designed to facilitate the circuit reduction task can be provided.

1. The initial circuit is constructed, at least initially, with all the principal components such as: generators, cables, reactors, transformers, and circuit breakers.
2. Starting at the location of the fault and going toward the circuit power source, first choose a point where the system is fairly stable. Denote this point as an infinite source or as a generator with zero impedance.
3. The distributed capacitances of generators and transformers are shown as lumped capacitances. One-half of its total capacitance of the generator, can be substituted as the equivalent capacitance of each phase.
4. The inductance of each transformer in the original circuit is replaced by a π-type circuit. One-half of the total capacitance to ground of the phase winding should be connected at each end of the transformer coil, which corresponds to the leakage inductance of the transformer. The capacitances to ground of both windings must be considered.
5. Whenever two or more capacitances are located in close proximity to each other and are joined by a relatively low impedance, in comparison to the rest of the circuit, the capacitances may be combined into a single equivalent capacitance.
6. The value of inductance is calculated from the total parallel reactance of all of the reactances that are connected to the bus bars of the transformers, generators, and reactors coils, with the exception of the reactance of the faulted feeder. If cables are used (and if they are very short), their inductance will be negligible compared with that of the generator and transformer, and it can be ignored.
7. A capacitance representing the sum of one-half of the faulted phase reactor's capacitance to ground, plus one-half of the circuit breaker capacitance to ground, and the total capacitance to ground of the connecting feeder, is connected at the breaker terminals.
8. Show the total capacitance to ground of the cables in the particular phase under consideration. Generally this capacitance is much larger than all others unless the cables are very short, in which case a capacitance that includes all connected branches and the equivalent capacitances of the reactors, transformers, and generators is considered. This capacitance is always equal to one-half of the total capacitance of the circuit components.

9. At the connection point of the generator, the cables, transformer, and the individual capacitances are combined into a single equivalent capacitance.
10. If the transformer is unloaded, the magnetizing inductance of the transformer is much greater than that of the generator, and therefore the generator's inductance can be ignored.
11. If motors are included in the circuit and they are located remotely from the fault, their impedances are the single equivalent impedance of all of the motors in parallel.

3.2.2.3 Three phase to Ground Fault in a Grounded System

In a three phase system, when the neutral of the system is solidly grounded and a three phase fault to ground occurs, each phase will oscillate independently. It is therefore possible to calculate the response of the circuit using the solution that was previously obtained for a simplified single phase circuit of the configuration that was shown in Figure 3.8b.

3.2.2.4 Three phase Isolated Fault in a Grounded System

As already known, the worst case TRV is always observed in the first-phase to clear the fault. In the event of an isolated three phase fault, which occurs within a solidly grounded system, the influence exerted in the recovery voltage by the other two phases must be taken into consideration.

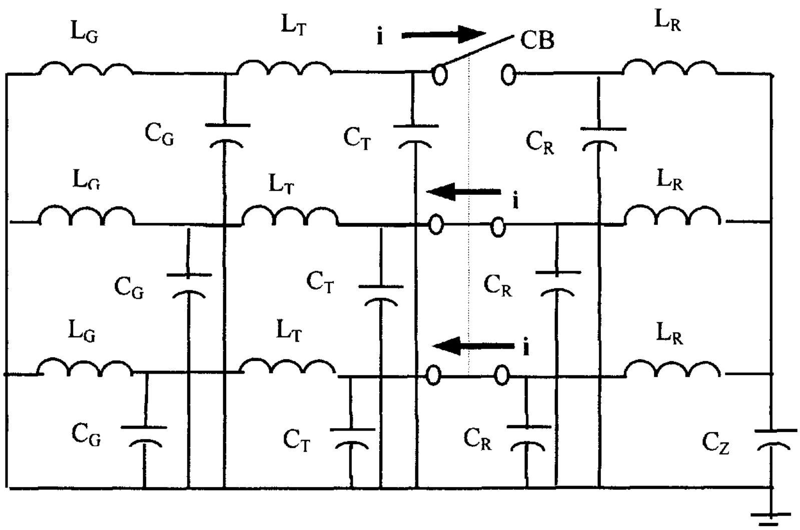


Figure 3.10 Schematic diagram of the equivalent circuit for a three phase isolated fault in a grounded system.

In Figure 3.10, a representative three phase circuit is shown. What is significant in this new circuit is the addition of the capacitance shown as C_Z that is equal to the total capacitance to ground as seen from the location of the load inductance to the fault location. This capacitance also includes one-half of the capacitance to ground of any reactor present in the system. In Figure 3.10, phase A is assumed to be the first phase to clear the fault and therefore it is shown as being open.

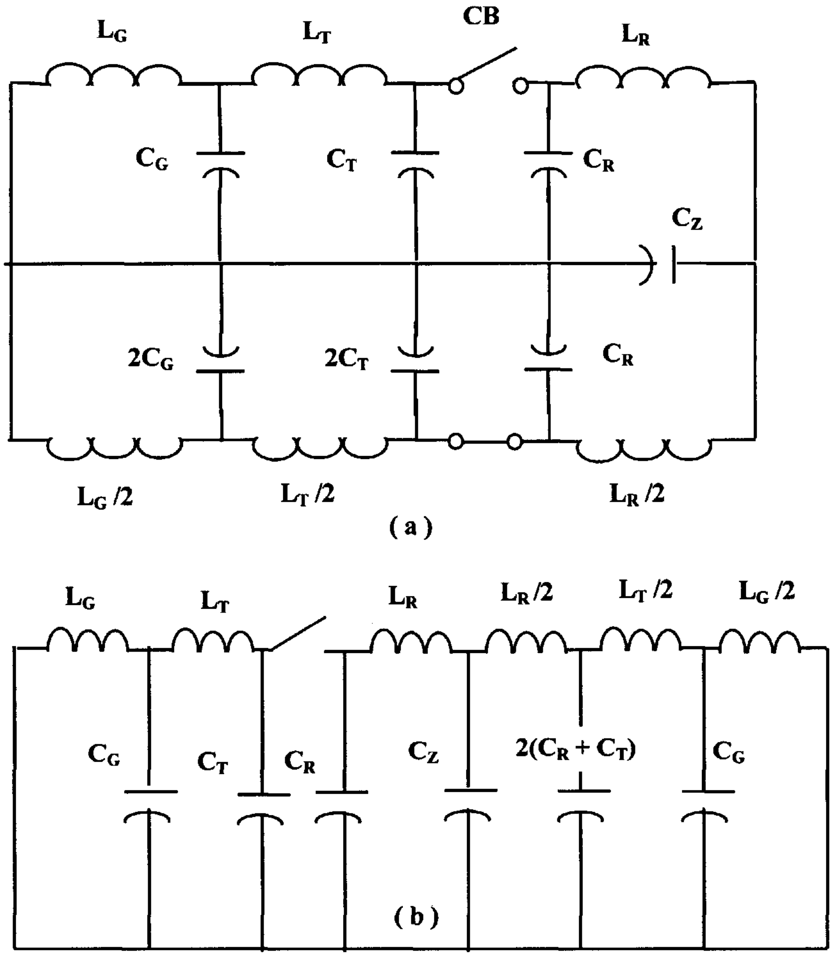


Figure 3.11 Circuit simplification from the original circuit of Figure 3.10.

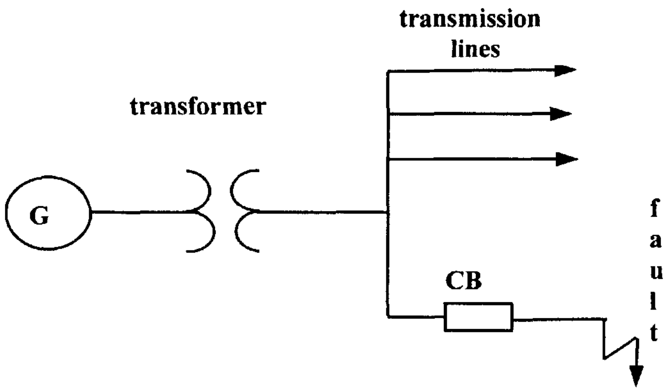


Figure 3.12 Typical system configuration used as the basis for defining TRV ratings of high-voltage transmission class circuit breakers.

In the meantime, phases B and C are assumed to be going through the process of interrupting the current and therefore they can be assumed to still be closed. As it can be seen, the current flowing through phase A in the direction of the arrow will return through the parallel paths of phases B and C. Therefore, these two phases can be represented by a single path having one-half the inductance and twice the capacitance to ground of the original phases. This is shown in the circuit of Figure 3.11 (a).

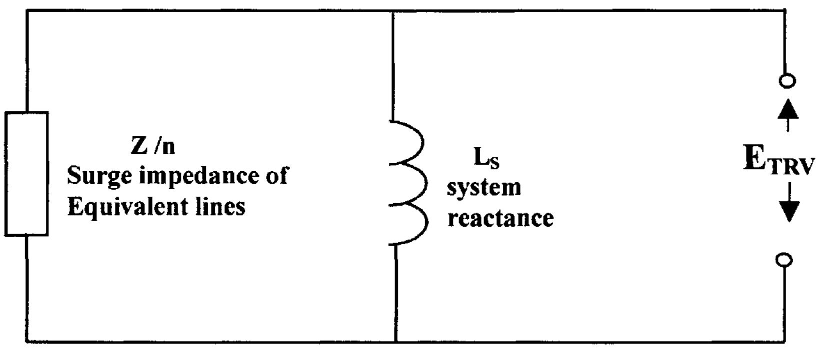


Figure 3.13 Equivalent circuit for the transmission system configuration shown in Figure 3.12.

The circuit can be simplified even further as shown in Figure 3.11 (b). In this figure it can be observed that the portion of the diagram, to the left-hand side of the switch, is composed of two oscillatory circuits that are similar to one of the circuits for which a solution has already been provided.

The right-hand side of the diagram is made up of four oscillatory circuits, which makes the calculation of this portion of the circuit rather difficult. As a rule, further simplification can generally be achieved by omitting the smallest inductance and/or capacitance, and by assuming that such omission will have only a negligible effect on the amplitude of the oscillation.

3.2.3 Particular Case of Double Frequency Recovery Voltage

From the more practical point of view of circuit breaker applications, it is useful to evaluate the transient recovery voltage that appears on a typical transmission circuit as is commonly found in an actual high-voltage power system application. This typical circuit, shown in Figure 3.12, has been used in the past for establishing the standard basis of ratings for some types of circuit breakers. As can be seen in the figure, one of the characteristics of this circuit is that a source consisting of a parallel combination of one or more transformers and one or more transmission lines may feed the fault. It is possible to reduce this original circuit to a simpler circuit consisting of a parallel combination of resistive, inductive, and capacitive elements.

In such a circuit, the inductance L represents the leakage reactance of the transformer, and the capacitance C corresponds to the total stray capacitance of the installation. The resistance, in this case, represents the total surge impedance Z_n of the transmission lines and is equal to the individual surge impedance Z_o of each line divided by the "n" number of lines interconnected in the system.

In the majority of applications, the parallel resistance of the surge impedance of the lines is such that it effectively swamps the capacitance of the circuit and, therefore, it is a common practice to neglect the capacitance. The resulting equivalent circuit, which is shown in Figure 3.13, is the one that consists of a parallel combination of only inductance (L) and resistance (Z_n).

The operational impedance, for this type of circuit, is given by the following expression:

$$Z_{(s)} = \frac{1}{\dfrac{1}{SL} + \dfrac{1}{Z_n}} = \frac{SLZ_n}{Z_n + SL}$$

Now using the injection current technique, an expression is obtained for the voltage that appears across the recently calculated circuit impedance. The resulting voltage, which happens to be the TRV of the circuit, is given by:

$$V_{(S)} = I_{rms}\sqrt{2} \times \omega \left(\frac{Z_n}{S\left(S + \frac{Z_n}{L}\right)} \right)$$

The solution of this equation in the time domain gives the following result:

$$V_{(t)} = \sqrt{2}(I_{rms})\omega L\left(1 - \varepsilon^{-\alpha t}\right)$$

where:

$$\alpha = \frac{Z_n}{L}$$

$V_{(t)} = E_{TRV}$ = the exponential component of the total response.

Since the voltage for the first pole to clear is equal to 1.5 times the maximum system voltage, then the corresponding transient recovery voltage for this portion of the total envelope is:

$$E_{1(TRV)} = 1.5\sqrt{2}(I_{\text{rms}})\omega L\left(1 - \varepsilon^{-\alpha t}\right) \text{ or}$$

$$E_{1(TRV)} = 1.5\sqrt{\frac{2}{3}}E_{(Rated)}\left(1 - \varepsilon^{-\omega t}\right)$$

where $E_{(Rated)}$ is equal to the rated maximum voltage of the device.

This voltage, which initially appears across the first phase that clears the fault, also appears in the form of a traveling wave, beginning at the bus and traveling down along each of the connected transmission lines. As is already known, the first reflection of the traveling wave takes place as a result of a discontinuity in the line. At the point of this discontinuity the traveling wave is reflected back toward the breaker terminal, where the travelling wave voltage is added to the initial exponential voltage wave.

Using the lattice diagram method, previously discussed in Section 3.1.3, the value of the reflected wave was determined to be equal to the product of the coefficient of reflection K_{Rb}, which was determined by the line termination, multiplied by the peak value of the $E_{1\,(TRV)}$ envelope. Once again, and according to the travelling wave theory, after the reflected wave arrives at the point where the fault is located, it encounters a terminating impedance. Its effective value becomes equal to the product of the reflected wave multiplied by the coefficient for the refracted wave or K_{Rb} x K_{Ta} x $E_{1\,(TRV)}$.

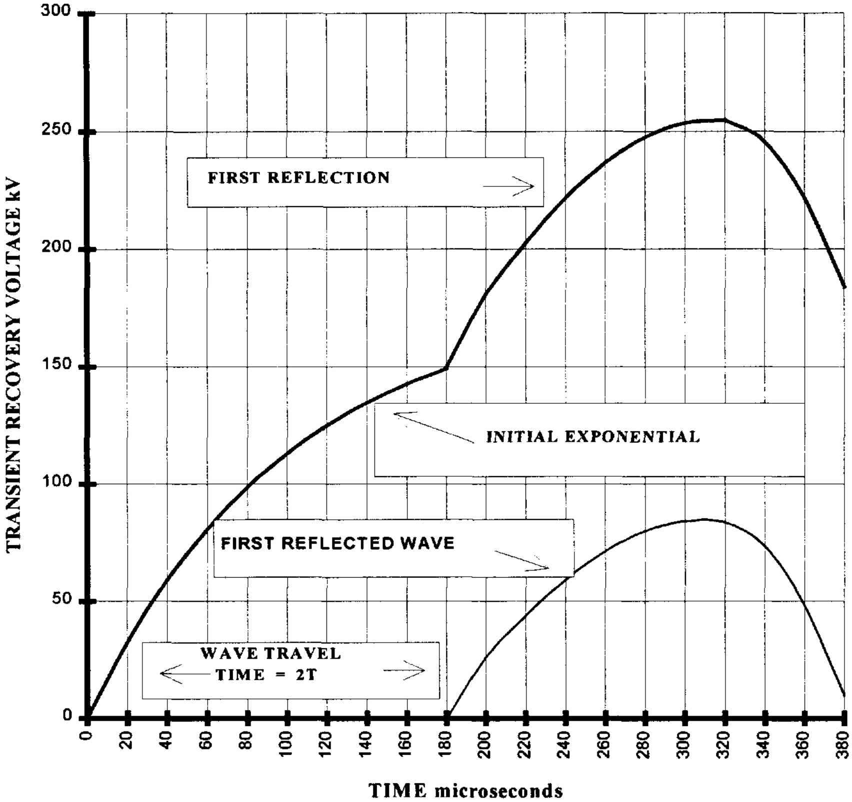


Figure 3.14 Typical transient recovery voltage corresponding to the circuit shown in Figure 3.13.

When simple reflection coefficients are used (equal to minus one for a shorted line and plus one for an open line), are used and if the line terminal impedances are resistive in nature, then the coefficients become simply amplitude multipliers.

The TRV calculation can then be reduced by first finding the initial exponential response $E_{I\ (TRV)}$ and then adding, at a time equal to 10.7 microseconds per mile, a voltage equal to K_{Ra} x K_{Ta} x $E_{1\ (TRV)}$. A typical waveform is illustrated in Figure 3.14.

Primarily, to facilitate the representation of this particular form of TRV, the American National Standards Institute (ANSI), has recommended a composite exponential–cosine model waveform (see Figure 3.15), which closely approximates the assumed transient recovery voltage waveform.

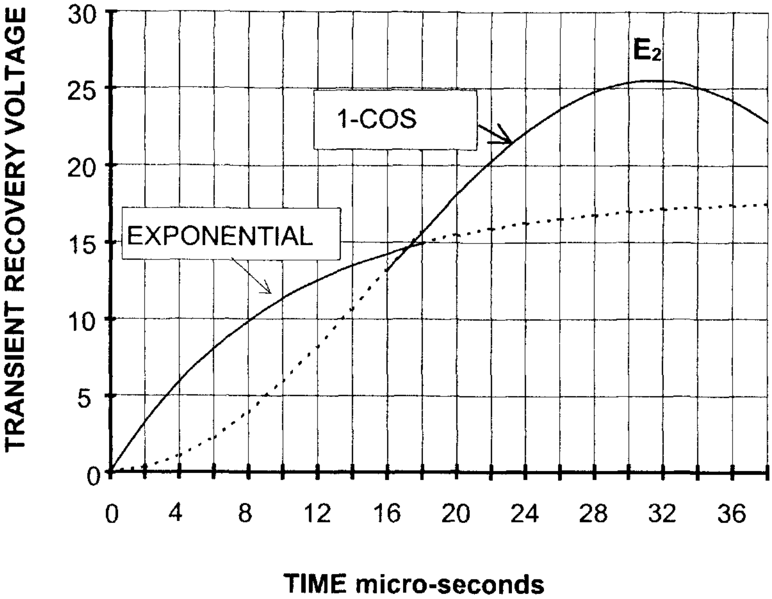


Figure 3.15 Equivalent wave form for testing TRV requirements of circuit breakers.

The initial exponential component of the response is calculated in the same way as discussed before. The equation describing the 1-cosine portion of the response is written as:

$$E_2 = 1.76E_{(Rated)}(1 - cos\omega_0 t)$$

where:

$$\omega_0 = \frac{\pi}{t_2}$$

ANSI, following the recommendations made by the Association of Edison Illuminating Companies [4], specified 1.76 as the multiplier. This multiplier is the product of a statistically collected value of 1.51 multiplied by an assumed damping factor of 0.95 and multiplied by the now familiar 1.5 factor for the first pole to clear the fault.

The peak value of the voltage was specified by ANSI [5] as the standard requirement for transmission class circuit breakers, which is the class of circuit breakers rated above 72.5 kV. The standards also specified T_2 as the time in microseconds required to reach the peak of the maximum voltage. Both numerical values are given as a function of the specific rating of the circuit breaker [5].

3.2.3.1 Initial Rate of Rise

The initial slope or initial rate of rise of the TRV, which is also specified in the standards documents, is an important parameter that defines the circuit breaker capabilities for it represents one of the limiting values of the recovery voltage.

The initial slope is obtained by first taking the derivative of the exponential component of the recovery voltage waveform.

$$\frac{dE_{(TRV)}}{dt} = 1.5\sqrt{2}(I_{rms}\omega L)\left(0 - \varepsilon^{-\alpha t}\left(-\frac{Z_n}{L}\right)\right)$$

Substituting

$t = 0$ into the equation, the following is obtained,

$$\text{Initial Rate} = R_0 = 1.5\ \sqrt{2}\left(I_{\text{rms}}\omega Z_{\text{n}}\right)$$

Inspection of the above equation suggests that the initial TRV rate is directly proportional to the fault current interrupted and inversely proportional to the number of transmission lines that remain connected to the bus. In a subtransmission class system, the feeders are generally in a radial configuration and therefore the fault current does not depend upon the number of connected lines. Thus, as the number of lines decreases, the fault current remains constant. In the case of transmission class systems, as the number of lines is decreased, the fault current also decreases.

3.2.4 Short-Line Fault Recovery Voltage

A short-line fault is a short circuit condition that occurs a short distance away from the load side terminals of a circuit breaker. This short distance is not precisely defined but it is generally thought to be in the range of several hundred meters up to a couple of kilometers. As is generally recognized throughout the industry, what makes this type of fault significant is the fact that it imposes the most severe voltage recovery conditions upon a circuit breaker.

The difficulties arise because the line-side recovery voltage appears as a sawtooth wave and therefore the instantaneous, and rather steep initial ramp of voltage imposes a severe stress on the gap of an interrupter before it has enough time to recover its dielectric withstand capability.

When dealing with the recovery voltage due to a short-line fault, it must be realized that when a fault occurs at some finite distance from the terminals of the protective device there is always a certain amount of line impedance involved.

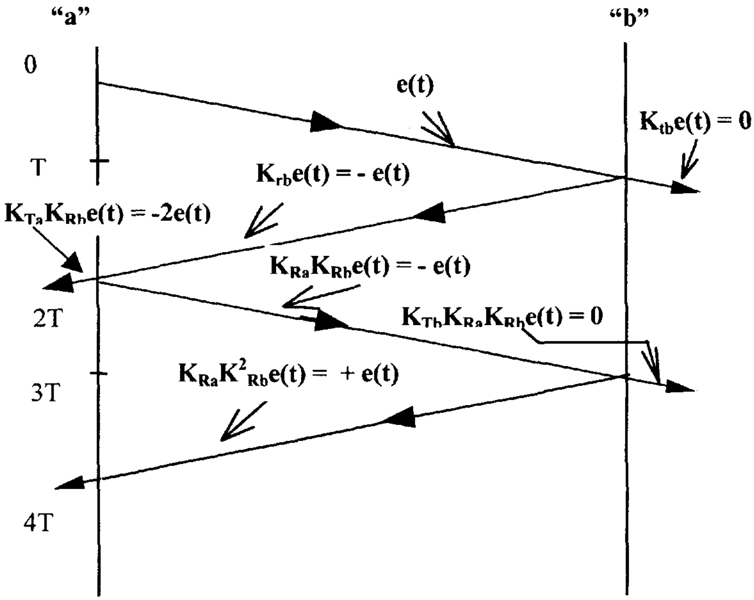


Figure 3.16 Latice diagram to evaluate characteristics of a short-line fault traveling wave.

The line impedance reduces, to some extent, the fault current but it also serves to sustain some of the system voltage. The further away from the terminals that the fault is located, the greater the fraction of the system voltage drop sustained by the line across the load terminals of the circuit breaker.

Consequently, since an unbounded charge cannot remain static, then following the interruption of the short circuit current the voltage drop trapped along the line will begin to re-distribute itself in the form of a traveling wave.

To evaluate the characteristics of the traveling wave, it is convenient to use a lattice diagram (Figure 3.16), where the numerical values of the coefficients, for the reflected and transmitted waves, show the amplitude multiplier for the voltage wave as it travels back and forth along the line.

To finally determine the waveform of the line-side voltage, a simple graphical method (shown in Figure 3.17), can be used. In this graph, the horizontal scale represents the time elapsed since the interruption of the current and it is divided in time intervals that are multiples of T, where T is the one-way travel time from the circuit breaker to the location of the fault. On the vertical axis, representing volts at the breaker terminal, the divisions are set at values corresponding to $E = Z\omega IT$.

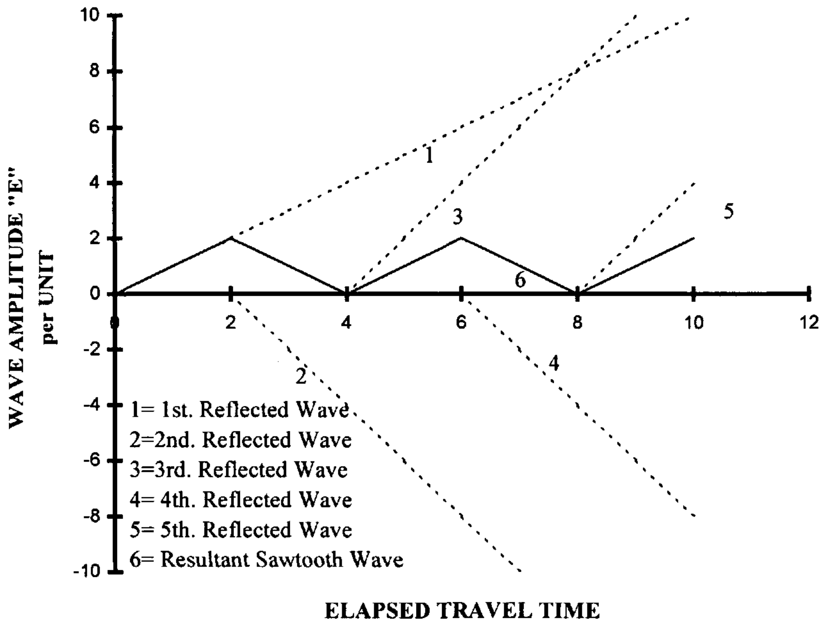


Figure 3.17 Resultant composite wave for a short fault produced by the traveling wave phenomena.

When the values from the lattice diagram in Figure 3.16 are transferred into Figure 3.17, one can notice that the first rising ramp of voltage is a straight line starting at the origin and passing through the locus points $t = 2T$ and $e = 2E$. This line has the slope $Z\omega I$ and corresponds to the voltage that is sustained at the breaker terminals until the first reflection returns. At $t = 2T$ another wave starts from the open end, which according to the lattice diagram of Figure 3.16, has a voltage value equal to $-2e_t = -2Z\omega It$. This wave has a zero value at $t = 2T$ and a slope of $-2\ Z\omega I$, which is double that of the preceding ramp and in the opposite (or negative) direction.

The lattice diagram further shows that a third wave starts at $t = 4T$ with a positive double slope. Adding up the ordinates of the successive ramps we obtain the expected typical sawtooth wave, which characterizes the load-side recovery voltage of a short-line fault.

The frequency of the response is dependent on the distance to the fault and the travel time of the wave. The voltage amplitude is also dependent on the distance to the fault and on the magnitude of the current.

Specific equations describing the rate of rise and the amplitude of the saw-tooth wave are given by:

$$R_L = \sqrt{2} I \omega Z \times 10^{-6} \quad \text{kV/}\mu\text{s and}$$
$$e = dI\sqrt{2}(0.58V)(1-M) \quad \text{kV}$$

where:

M= percentage of rated interrupting current
d = an amplitude factor, generally given as 1.6.

The time required to reach the voltage peak is given by:

$$T_L = \frac{e}{R_L} \quad \mu\text{s}$$

The total transient recovery voltage is equal to the sum of the load-side transient voltage associated with the travelling wave plus, either the 1-cosine or the exponential-cosine waveform representing the source-side component of the TRV. The choice of the source-side waveform depends on the type of system under consideration and is calculated in accordance with the guidelines presented previously.

3.2.5 Initial Transient Recovery Voltage

The term initial transient recovery voltage (ITRV) refers to the condition during the first microsecond or so, following a current interruption, when the recovery voltage in the source-side of the circuit breaker is influenced by the proximity of the system component connections to the circuit breaker. Among those components are the buses, isolators, measuring transformers, capacitors, and so on.

Following interruption, a voltage oscillation is produced that is similar to the short-line fault but this new oscillation has a lower voltage peak magnitude. However, the time to crest has a shorter duration due to the close distance between the circuit breaker and the system components.

The travelling wave will move down the bus to the point where the first discontinuity is found. In an IEC report [6], the first discontinuity is identified as being the point where a bus bar branches off, or the point where a capacitor of at least one nanofarad is connected.

The following expression for the ITRV is defined in reference [12].

$$E_i = \omega\sqrt{2} I Z_b T_i 10^{-6} \quad \text{kV}$$

where

TABLE 3.1
ITRV Values

Rated Maximum Voltage kV rms.	121	145	169	242	362	550	800
Time to First Voltage Peak T_i μ s	0.3	0.4	0.5	0.6	0.8	1.0	1.1

Z_b = surge impedance = 260 Ohms
T_i = wave travel time in microseconds
I = fault current kA
ω = $2 \pi f$

The above expression shows that:

1. The first peak of the ITRV appears at a time equal to twice the traveling time of the voltage wave, from the circuit breaker terminals to the first line of discontinuity.
2. The initial slope of the ITRV depends only on the surge impedance of the bus and the rate of change of current (*di/dt* at *I*=0).

The above statements suggest that since the travel time is a function of the physical location of the component, it is practically impossible to define a general form of ITRV. One can expect that there are as many ITRV variations as there are station layouts. Nevertheless, representative values for various voltage installations have been established [7]. These values are given in Table 3.1.

The initial slope deals with the rate of change of current. It suggests that if the slope of the current is modified by the action of the circuit breaker during interruption, then it can be expected that the ITRV will also be modified.

All this indicates that, at least in theory, the ITRV exists. However, in practice there are those who question its existence citing that the ideal circuit breaker assumed for the calculations does not exist.

It appears that it is better to state that there could be some circuit breakers that may be more sensitive than others to the ITRV. More sensitive breakers are those that characteristically produce a low-arc voltage and have negligible or no post-arc current. In other words, it is an ideal circuit breaker.

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4

SWITCHING OVERVOLTAGES

4.0 INTRODUCTION

Aside from lightning strikes, the most common reasons for dielectric failures in an electric system are the overvoltages produced by the switching that is normally required for the ordinary operation of the electrical network.

It is appropriate at this point to emphasize that although circuit breakers participate in the process of overvoltage generation they do not generate these voltages, but rather these voltages are generated by the changes in configuration of each system which occur as a consequence of the switching operations. Circuit breakers, however, can provide means for decreasing, or controlling, these voltage surges. This can be done either by using timing controls for synchronized switching or by incorporating additional hardware such as closing resistors as an integral part of the circuit breaker design [1].

Switching overvoltages can be produced by closing an unloaded line, by opening an isolating switch or by interrupting low currents in inductive or capacitive circuits where the possibility of restrikes exists.

Switching overvoltages are probabilistic in nature and their appearance in a system depend mainly upon the number of faults that must be cleared on a line and on how frequently routine switching operations are performed on a particular system. This implies that not only opening operations that are intended for interrupting a short circuit current are responsible for switching overvoltages, but also the many routine operations that are performed, sometimes daily, in a system. These routine operations are fully capable of producing overvoltage effects by virtue of them altering the system configuration.

As it has been said repeatedly, overvoltages in transmission and distribution systems cannot be totally avoided, but their effects can be minimized. Generally, the occurrence and the magnitude of the overvoltage can be limited by the use of appropriate measures such as series or parallel compensation, closing resistors, surge suppressors, metal oxide varistors or snubbers containing combinations of resistors and capacitors, and in some cases by simply following basic established procedures for the proper design and operation of a system [2].

It is a general practice to characterize switching overvoltages as being either transient or temporary [3]. The distinction between each particular type is simply based upon the duration of the transient condition. Any voltage that disappears within less than five cycles is deemed to be a transient overvoltage. While those lasting significantly longer than five cycles are considered to be temporary overvoltages.

The distinction between the two types is established primarily because of special considerations that must be given for insulation coordination since the breakdown of any type of insulation is a voltage–time dependent relationship. Furthermore the temporary overvoltage factor is in most cases the determining parameter for the selection of a particular method of control.

Although surge arresters still are used for control of temporary overvoltages it is important to consider the required permanent overvoltage level for the material used and the impact that this selection may have on its cost.

4.1 CONTACTS CLOSING

The simple closing of a switch or of a circuit breaker can produce significant overvoltages in an electric system. These overvoltages are due to the system adjusting itself to an emerging different configuration of components as a result of the change in the load impedance. Furthermore, there are charges that are trapped in the lines and in the equipment that is connected to the system and these charges now must be redistributed within the system.

In addition and whenever the closure of the circuit occurs immediately after a circuit breaker opening operation the trapped charges left over from the preceding opening can significantly contribute to the increase in the magnitude of the overvoltages that may appear in the system. It is important to note that in most cases the fast reclosing of a line will produce the highest overvoltages. It should also be realized that the higher magnitudes of the overvoltages produced by the closing or the reclosing operation of a circuit breaker would always be observed at the open end of the line.

Although the basic expressions describing the voltage distribution across the source and the line are relatively simple, defining the effective impedance that controls the voltage distribution within the elements of the circuit is rather difficult and generally can only be adequately handled with the aid of a computer [4],[5].

Because of the complexity of the problem no attempt will be made here to provide a quantitative solution. The aim of this chapter will be to describe qualitatively the voltage surge phenomena that take place during a closing or a reclosing operation and during some special cases of current interruption. The upper limits of overvoltages that have been obtained either experimentally or by calculation will be quoted but only as general guidelines.

4.1.1 Closing of a Line

A cable that is being energized from a transformer represents the simplest case of a switching operation as is shown in Figure 4.1 (a). For the sake of simplicity, the transformer has been represented by its leakage inductance, while the cable is represented by its capacitance. As a result of this simplification the equivalent circuit can take the form of the circuit illustrated in Figure 4.1 (b).

The transient voltage, shown in Figure 4.1 (c), oscillates along the line at a relatively low single frequency. It has an amplitude that reaches a peak value approximately equal to twice the value of the system voltage that was present at the instant at which the closure of the circuit took place.

Although the above described circuit may be found in some very basic applications, in actual practice it is more likely that a typical system will consist of one or more long interconnected overhead lines, as depicted in Figure 4.2 (a). The equivalent circuit and the transient response of this system are shown in Figure 4.2 (b) and (c) respectively. The transient response, as it can be seen in the figure, is determined by the combined impedance of the transformer that is feeding the system and by the total surge impedance of the connected lines. The total surge impedance, as it can be recalled, is equal to the surge impedance of each individual line divided by the number of connected lines.

The total closing overvoltage is given by the sum of the power frequency source overvoltage and the transient overvoltage being generated at the line.

The overvoltage factor for the source is given by the following equation.

$$K_S = \frac{1}{\cos 2\pi f\ \sqrt{LC}\, l - \frac{X_s}{Z}\sin 2\pi f\ \sqrt{LC}\, l}$$

where:

f = power frequency
L = positive sequence inductance per length of line
C = positive sequence capacitance per length of line
l = line length
X_s = short circuit reactance of source
Z = surge impedance of the line

It is evident, by simple observation of the above equation, that higher power frequency overvoltage factors can be expected as a result of the following conditions:

1. When the length of the lines increase,
2. When the source reactance increases,

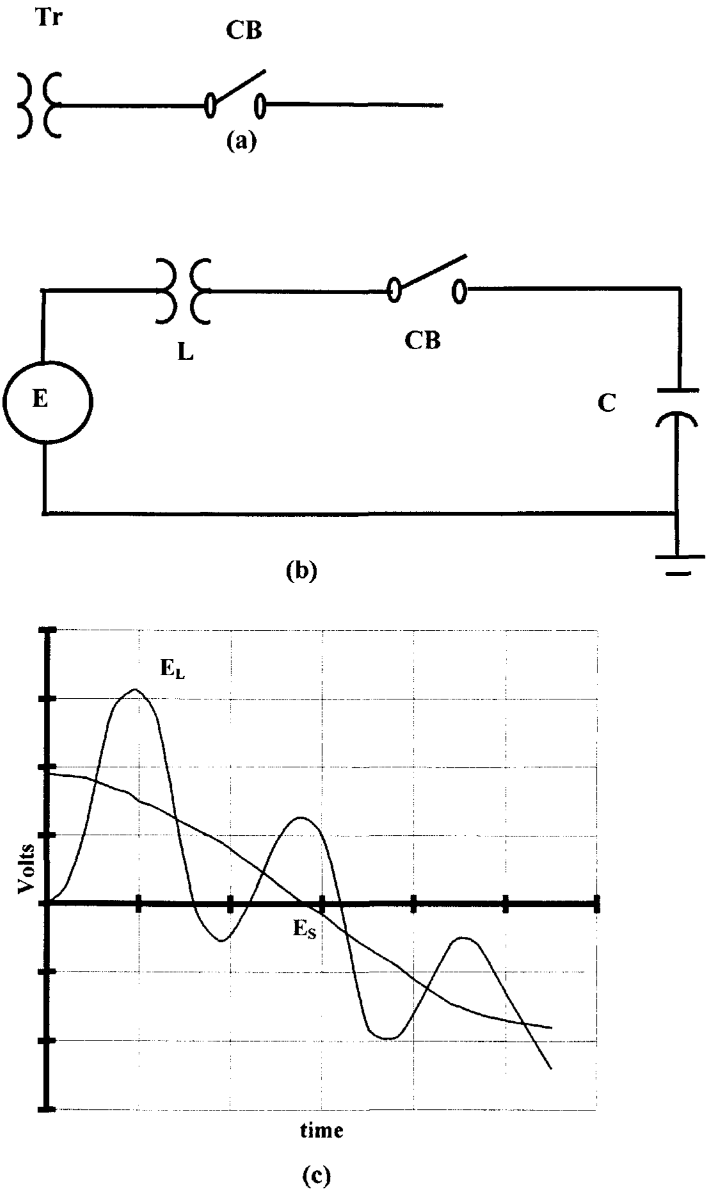


Figure 4.1 Representation of the simplest case of closing into a line. (a) Single line schematic. (b) Equivalent circuit. (c) Transient overvoltage.

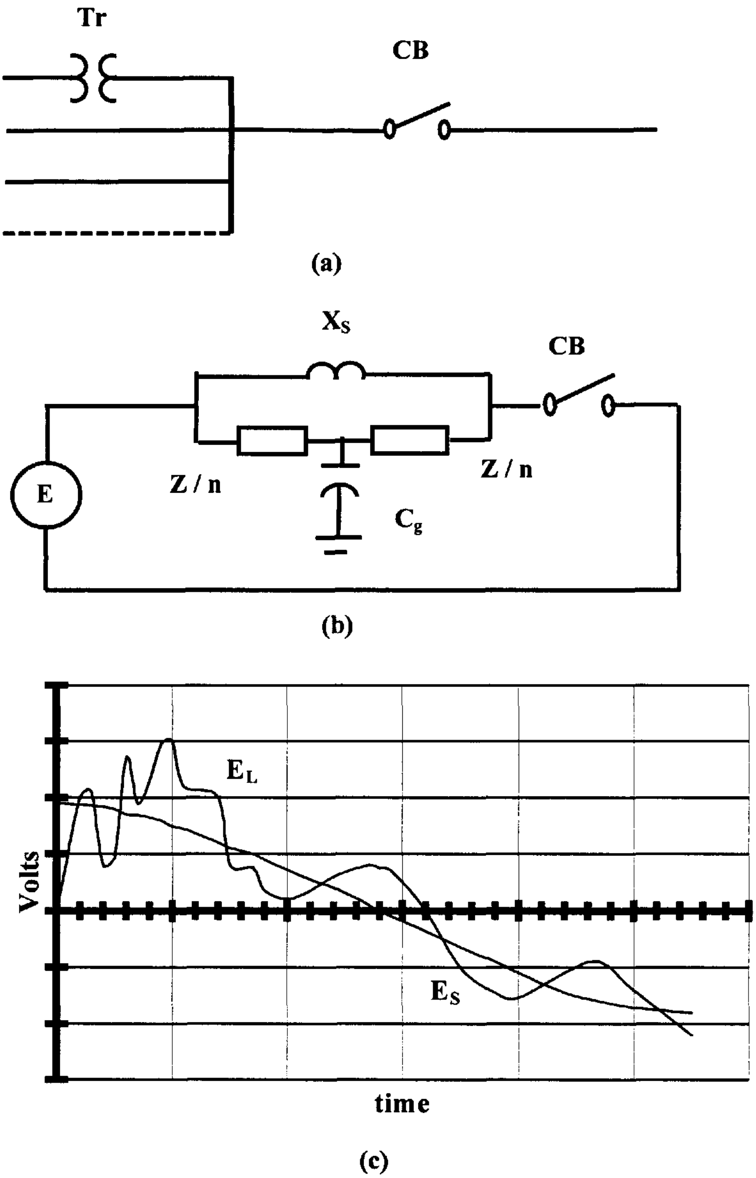


Figure 4.2 Switching surge resulting from energizing a complex system. (a) Single line schematic of the system. (b) Equivalent circuit. (c) Surge voltage.

3. When the surge impedance of the line is lowered as a direct result of an increased number of connected lines and
4. When the power frequency is increased, which means that the overvoltage is higher in a 60 Hz system than in a 50 Hz one.

The overvoltage factor for the transient response portion of the phenomenon is not as easy to calculate manually and a simple formula as in the preceding paragraph is just not available. However, it is possible to generalize and it can be said that the overvoltage factor for the transient response is proportional to:

1. The instantaneous voltage difference between the source voltage and the line voltage as the contacts of the circuit breaker close,
2. The damping impedance of the lines connected at the source side of the circuit and
3. The terminal impedance of the unloaded line/lines being energized

In any case what is important to remember is:

1. When switching a number of lines the amplitude factor of the overvoltage is always reduced as the size of the system increases, and
2. The reduction of the amplitude factor is not due to the damping effects of the system but rather to the superposition of the individual responses each having a different frequency.

4.1.2 Reclosing of a Line

Since in order to improve the stability of the system it is desirable to restore service as quickly as possible, it is a common operating practice to reclose a circuit breaker a few cycles after it has interrupted a fault.

If the interrupted fault happens to be a single phase to ground fault, then it is possible that a significant voltage may remain trapped in the unfaulted phases. This happens because the three phases represent a capacitor that has been switched off at current zero and therefore, because of the inductive nature of the system, this coincides with the instant where a maximum voltage is present in the line.

Auto-reclosing of shunt compensated lines is a typical example of a rather difficult switching operation in terms of overvoltage generation. As in all cases following a successful interruption there is a trapped charge that remains on the unloaded line. The magnitude of this charge can be as much as 1.2 pu depending on the degree of compensation. The voltage across the open circuit breaker can have the characteristics illustrated in Figure 4.3. The beat frequency that is observed is the result of the superposition of the power frequency voltage on the source side and a higher ringing frequency voltage that is produced by the combination of the inductance and capacitance on the load side.

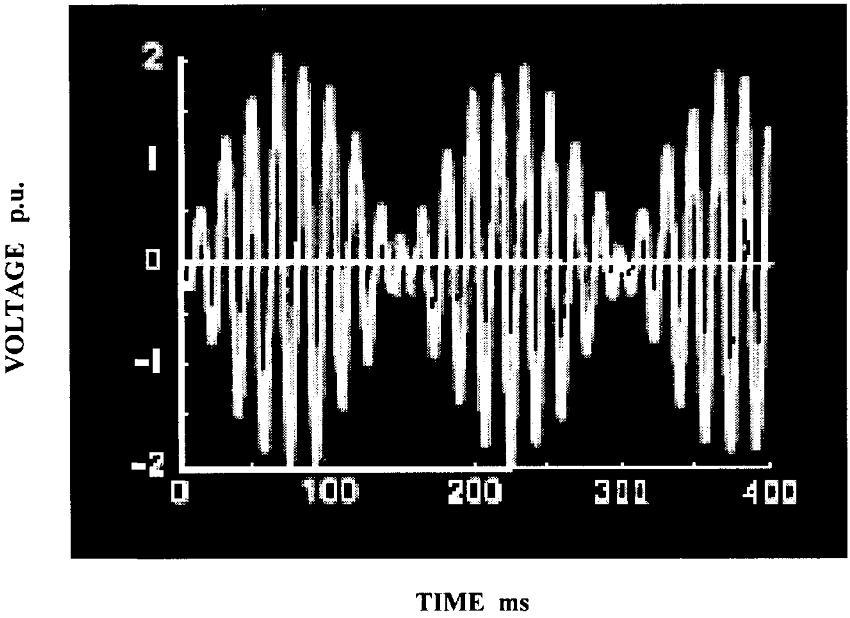


Figure 4.3 Transient voltage resulting from shunt reactor switching with 80% compensation.

Since the closing of the contacts may take place at any point in the voltage wave, it could then be expected that when reclosing the circuit, the circuit breaker contacts may close at the opposite polarity of the trapped charge, which, when it is coupled with the voltage doubling effect produced by the traveling wave, leads to the possibility of an overvoltage across the contacts that can reach a magnitude as high as 4 per unit.

4.1.3 Energizing Unloaded Transformers

Energizing an unloaded transformer, which may be connected through a cable, poses the likelihood of generating substantial overvoltages. Energizing of a transformer generally will occur after a switching operation that had been brought about by some transient fault condition that initially had opened the circuit.

When closing the transformer a path for the discharge of the current trapped along the cable is established through the magnetizing impedance of the transformer and as long as the core of the transformer is not saturated it represents a high impedance and the discharge is very slow.

This condition can be thought of as the equivalent of having a battery which can support the line voltage as long as the flux on its core is changing connected to the transformer terminals. But as it goes into saturation its impedance drops rather quickly resulting in an increase in current and in a rapid discharge of the cable. As the core comes out of saturation the process reverses and the interchange of stored energies will continue to repeat it. The voltage will oscillate with a square wave and with each oscillation a certain amount of the original energy will be dissipated until the oscillation dies out.

The condition just described in reality represents a long-term scenario but it is against this background that further switching operations are executed and any new transients will originate starting from these pre-existing threshold levels [6].

The energizing of an unloaded transformer can also bring up a situation where extremely high voltages achieving values several times higher than the primary voltage can be generated not only at the terminals of the transformers but, depending on the type of its windings, within the transformer itself thus leading to a transformer failure. The overvoltages develop whenever the resonant frequencies of the cable feeder and of the transformer match themselves. The critical length of the cable will be determined by the travel time of the resonant frequency of the cable and the transformer [7].

It is rather apparent that to decrease the effects of these switching transients the simplest alternative would be to change the length of the cable. Another method of control is the addition of capacitors connected at the secondary terminals of the transformer.

4.2 CONTACT OPENING

The opening of a circuit was previously discussed in the context of interrupting a large magnitude of current where that current was generally considered to be the result of a short circuit. However, there are many occasions where a circuit breaker is required to interrupt currents that are in the range of a few amperes to several hundred amperes, and where the loads are characterized as being either purely capacitive or purely inductive.

The physics of the basic interrupting process, that is the balancing of the arc energy are no different whether the interrupted currents are small or large. However, since lower currents will contribute less energy to the arc it is natural to expect that interrupting these lower currents should be a relatively simpler task; but this is not always the case because, as it will be shown later, the very fact that the currents are relatively low in comparison to a short circuit current promotes the possibility of arc instability or of restrikes or reignitions occurring across the contacts during interruption.

According to standard established practice, a restrike is defined as being an electrical discharge that occurs one quarter of a cycle or more after the initial current interruption. A reignition is defined as a discharge that occurs not later than one eighth of a cycle after current zero. These occurrences can be responsible for significant increases in the magnitude of the recovery voltage.

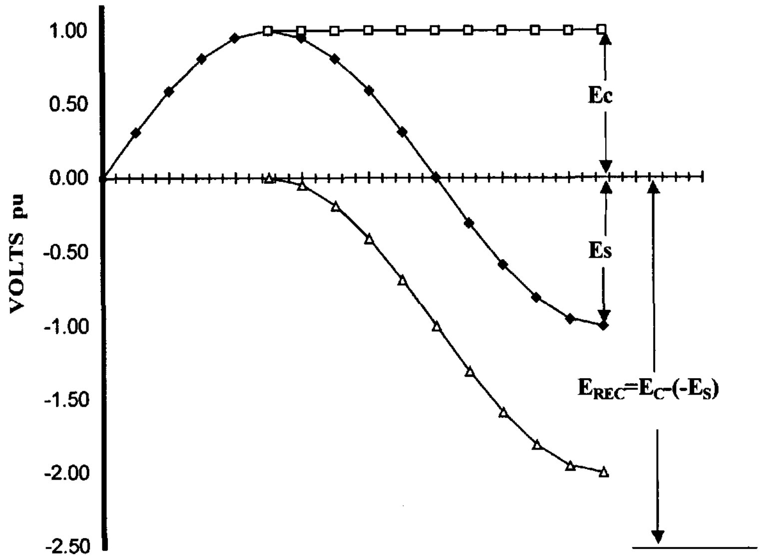


Figure 4.4 Recovery voltage resulting from the switching of capacitor bank.

4.2.1 Interruption of Small Capacitive Currents

The switching of capacitor banks and unloaded lines requires that the circuit breaker interrupts small capacitive currents. These currents are generally less than ten amperes for switching unloaded lines and most often less than one thousand amperes for switching off capacitor banks.

Interruption, as we well know, always takes place at current zero and therefore, for all practical purposes, the system voltage is at its peak. The source side, on the other hand, will follow the oscillation of the power frequency voltage and therefore in approximately one half of a cycle the voltage across the contacts would reach its peak value but with a reversal of its polarity [8].

This, as it should be recalled, makes current interruption relatively easy but, again as it was said before, this is not necessarily so because those low currents may be interrupted when the gap between the circuit breaker contacts is very short and, consequently, a few milliseconds later as the system recovery voltage appears across the circuit breaker contacts the gap is still rather small and it may be very difficult for the circuit breaker to withstand the recovery voltage.

At the time when current interruption takes place the line to ground voltage stored in the capacitor in a solidly grounded circuit is equal to 1.0 per unit and since one half cycle later the source voltage reaches its peak then at this time the total voltage across the contacts reaches a value of 2.0 per unit which corresponds to the algebraic difference of the capacitor voltage charge and the source voltage as is shown in Figure 4.4.

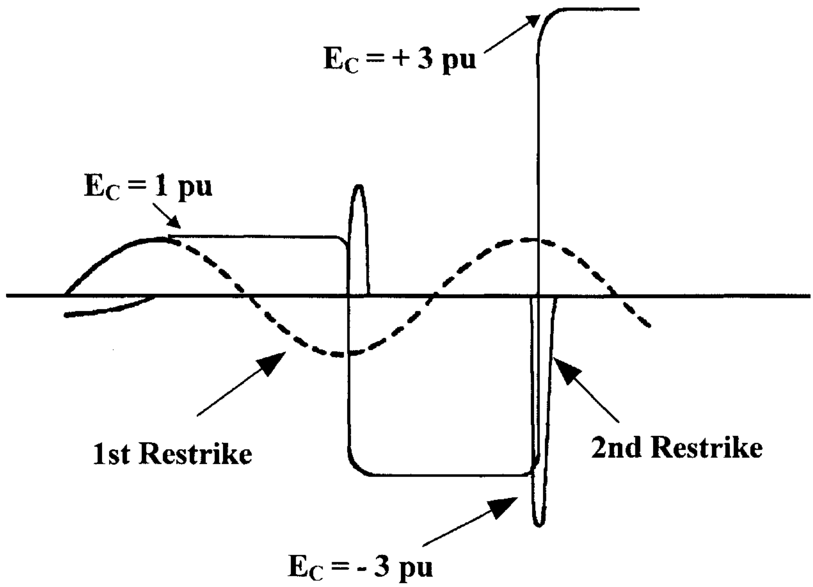


Figure 4.5 Voltage escalation due to restrikes during a capacitance switching operation.

If the circuit has an isolated neutral connection, then the voltage trapped in the capacitor for the first phase to clear has a line to ground value of 1.5 per unit and the total voltage across the contacts one half of a cycle later will be equal to 2.5 per unit.

Restrikes can be thought of as being similar to a closing operation where the capacitor is suddenly reconnected to the source. Therefore it is expected that there will be a flow of an inrush current which due to the inductance of the circuit and in the absence of any damping effects will force the voltage in the capacitor to swing with respect to the instantaneous system voltage to a peak value that is approximately equal to the initial value at which it started but with a reversed polarity.

If the restrike happens at the peak of the system voltage, then the capacitor voltage will attain a charge value of 3.0 per unit. Under these conditions, if the high frequency inrush current is interrupted at the zero crossing, which depending on the interrupting medium is an inherent capability found in some types of circuit breakers, then the capacitor will be left with a charge corresponding to a voltage of 3.0 per unit and one half of a cycle later there will be a voltage of 4.0 per unit applied across the circuit breaker contacts. If the sequence is repeated, the capacitor voltage will reach a 5.0 per unit value, as is illustrated in Figure 4.5.

Theoretically, and if damping is ignored, the voltage across the capacitor can build up according to a series of 1, 3, 5, 7, ..., and so on without limit.

4.2.2 Interruption of Inductive Load Currents

The switching of shunt reactors constitutes a difficult and yet common operating duty. It imposes severe demands upon the performance of an interrupter because it is rather easy for a circuit breaker that has an interrupting capability of several tens of kiloamperes to interrupt inductive load currents that are generally in the range of a few tens to some hundreds of amperes. To accomplish interruption these low currents need only a short arcing time, which translates to a rather small gap between the contacts. When interrupting full fault level currents, minimum arcing times of 8 or more milliseconds are typical for SF_6 circuit breakers and 4 milliseconds is rather common for vacuum interrupters, but when dealing with low inductive currents these minimum arcing times are reduced, in most cases, to less than half.

Due to the short arcing time at the instant of interruption the gap between the contacts is relatively short, and since the voltage is at its peak, then in many cases this small gap may not be sufficient to withstand the full magnitude of the recovery voltage, which begins to appear across the contacts immediately following the interruption of the current. A further complication that may take place is that due to the low magnitude of the currents the currents may be forced to zero prematurely due to arc instabilities, thus creating the condition known as current chopping. This suggests that the overvoltages generated during the switching of reactive loads are the result of current chopping, reignitions or a combination of both.

In a successful interruption the energy trapped in the load side will redistribute itself between the load capacitance C_L and the load inductance L_L (refer to Figure 4.6).

If there is a reignition, the energy trapped in the load side inductance and capacitance of the circuit will oscillate between the inductance and the parallel capacitance thus generating an overvoltage. However, because of the randomness of the point at which the reignition takes place and due to the inherent damping of the circuit, it is very unlikely that the upper limit of these overvoltages will exceed a value of 2 per unit. Unless an attempt is made to interrupt the high frequency current oscillation, which is in the range of 50 to 1000 kHz, that is superimposed on the source current which at this instant is essentially zero.

Nevertheless, since the elapsed time between the reignition and the new interruption attempt is extremely short it is possible that the change in the contact gap is not enough to withstand the new recovery voltage and therefore another reignition may occur.

However, the motion of the contacts during the interval between the two reignitions do increase the gap distance and therefore the breakdown voltage had to be somewhat higher than for the prior reignition. During this interval more magnetic energy is accumulated in the inductance of the load and consequently additional energy is available to trigger a breakdown which would occur at a voltage that is higher than the previous one.

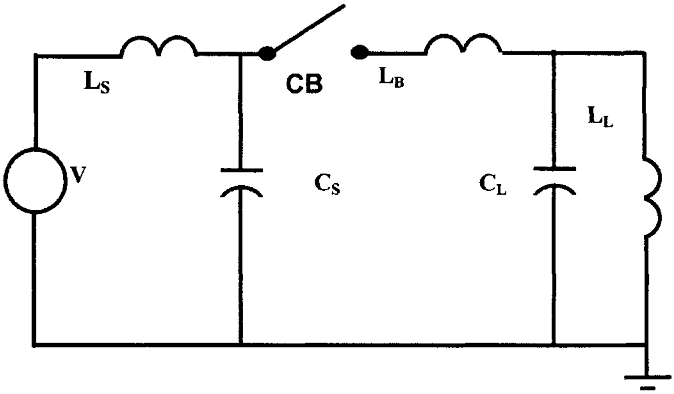


Figure 4.6 Shunt reactance equivalent single phase circuit.

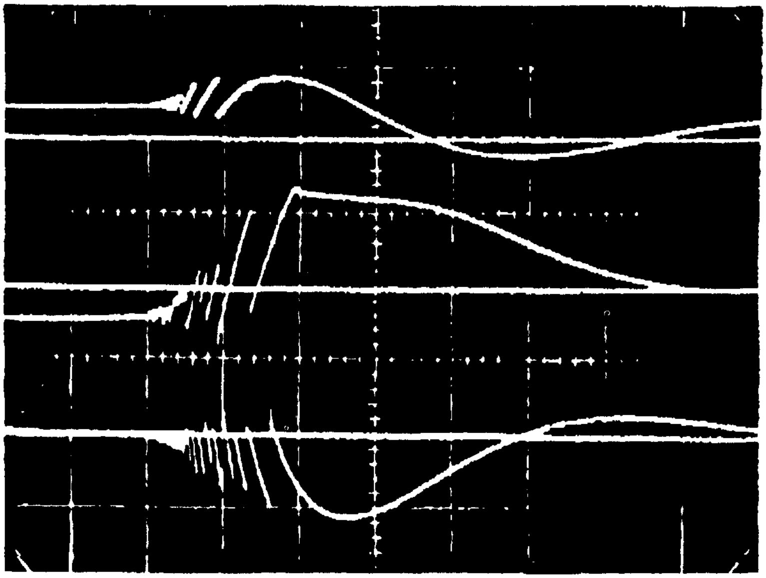


Figure 4.7 Voltage surges caused by successive reignitions when interrupting low inductive currents.

This process may repeat itself as successive reignitions occur across a larger gap and at increased magnetic energy levels, and therefore at higher mean voltage levels, resulting in a high frequency series of voltage spikes such as those shown in Figure 4.7.

It has been reported [9] that multiple reignitions do not necessarily result in overvoltages and that in some circumstances they may even result in a decrease of the overvoltage level and that reignitions by themselves do not always result in voltage escalation since what is also important is the instant at which the reignitions occur in relation to the current in the load side of the system.

By observing Figure 4.5 it is evident that from a system point of view the reignition voltages can be reduced by increasing the load side capacitance C_L, which suggests the use of a C-R surge suppressor. It can also be seen that a reduction of the source side capacitance C_S will reduce the prospective overvoltage and that the load side inductance, which is often the inductance of the busbar connecting the circuit breaker to the load, can directly influence the amplitude and frequency of the reignition current by changing the rate of change of current (di/dt) at the critical current zero instant.

Because of the statistical nature of the phenomenon it is not possible to establish an upper limit for the possible overvoltage; however, it has been recommended [10] that the suppression peak overvoltage be limited to 2.0 pu for applications at voltages above 72.5 kV and to 2.5 pu for applications below 72.5 kV.

4.2.3 Current Chopping

Current chopping is the result of the premature extinction of the power frequency current before a natural current zero is reached. This condition is produced by the arc instability as the current approaches zero.

It is commonly believed that only vacuum circuit breakers are capable of chopping currents. However, this is not the case, all types of circuit breakers can chop. Nevertheless, what is different is that the instantaneous current magnitude at which the chopping occurs varies among the different types of interrupting mediums and indeed it is higher for vacuum interrupters [11], [12].

In theory, when current chopping happens the current is reduced instantaneously from a small finite value to zero, but in reality this event does not happen so suddenly simply because of the inductance that is present in the circuit and as it is well known current cannot change instantaneously in an inductor. It is therefore to be expected that some small finite element of time must elapse for the transfer of the magnetic energy that is trapped in the system inductance.

At the instant when current chopping occurs the energy stored in the load inductance is transferred to the load side capacitance and thus creating a condition where overvoltages can be generated. In Figure 4.8 (a) the simplified equivalent circuit is shown and in (b) the voltage and current relationships are illustrated.

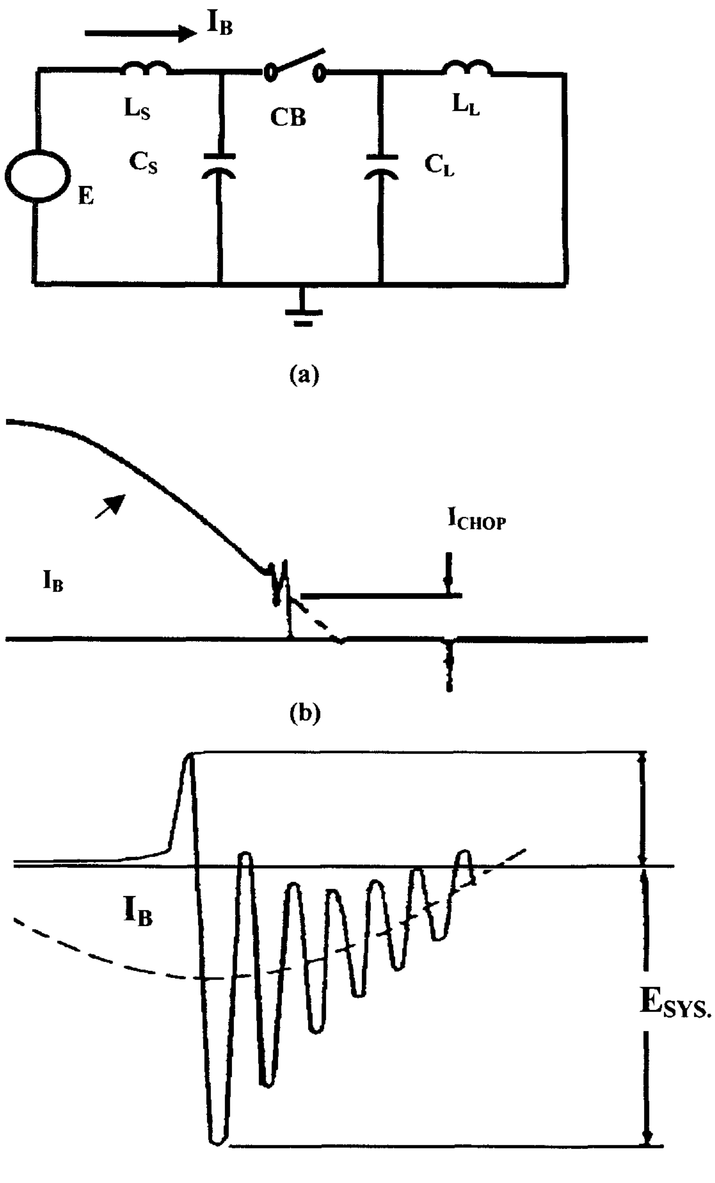


Figure 4.8 Typical current chopping. (a) Equivalent circuit. (b) Chopped current across the circuit breaker. (c) Transient voltage across the circuit breaker.

Referring to the equivalent circuit the energy balance equations can be written as:

$$\frac{1}{2}CE_m^2 = \frac{1}{2}CE_c^2 + \frac{1}{2}LI_0^2$$

and the overvoltage factor K is given by:

$$K = \frac{E_m}{E_s} = \sqrt{\left(\frac{I_0}{E_s}\right)^2\left(\frac{L}{C}\right) + \frac{E_c}{E_s}}$$

where:

E_m = overvoltage peak
E_0 = peak voltage at supply side
E_c = capacitor voltage at instant of chop
I_0 = instantaneous value of chopped current

$\frac{L}{C}$ = surge impedance of the circuit

As it can be seen, the magnitude of the overvoltage factor K is highly dependent upon the instantaneous value of the chopping current.

4.2.3.1 Current Chopping in Circuit Breakers Other than Vacuum

For air, oil, or SF_6 interrupters, the arc instability that leads to current chopping is primarily controlled by the capacitance of the system. In Figure 4.9 the effects of the system capacitance on the chopping level are illustrated [13].

For gas or oil circuit breakers the approximate value of the chopping current is given by the formula

$$I_0 = \lambda\sqrt{C_L}$$

where:

λ = chopping number

The following are typical values for chopping numbers:

For minimum oil circuit breakers	7 to 10 x 10^4
For air blast circuit breakers	15 to 40 x 10^4
For SF_6 puffer circuit breakers	4 to 17 x 10^4

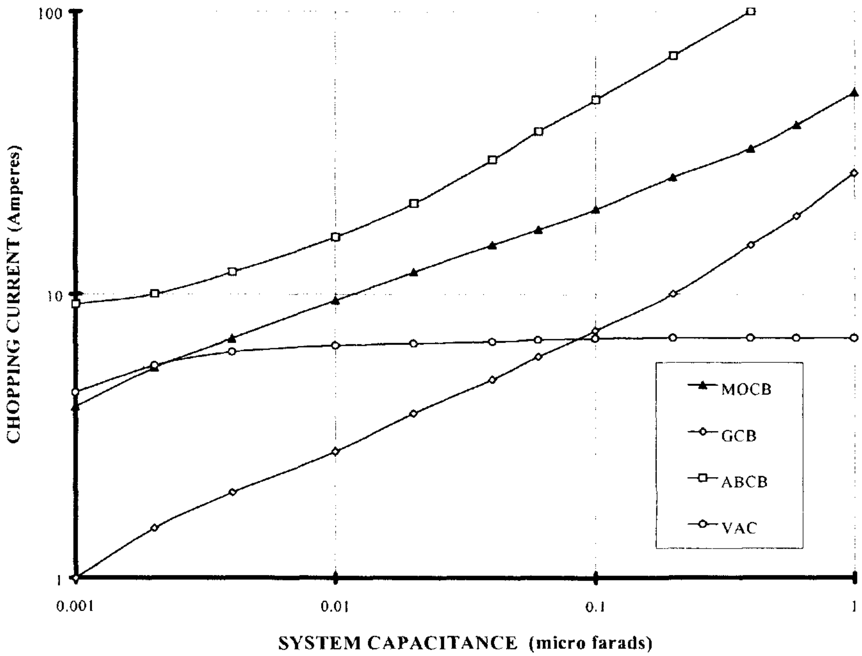


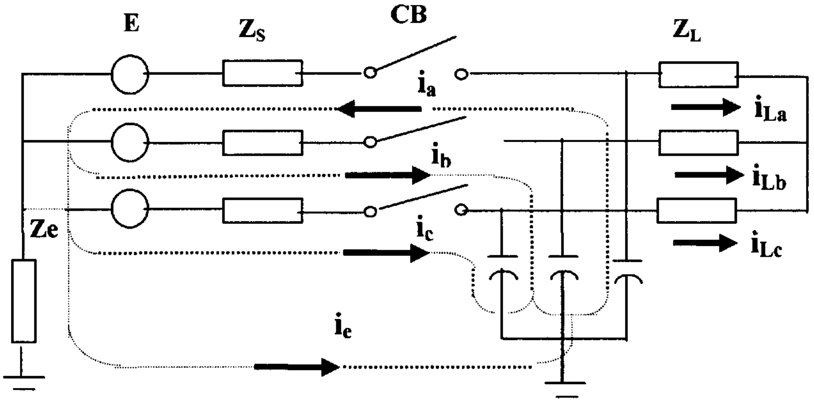
Figure 4.9 Current chopping level as function of system capacitance for minimum oil circuit breakers (MOCB), SF_6 gas circuit breakers (GCB), air blast circuit breakers (ABCB), and vacuum circuit breakers (VAC).

For most of the applications the values of the system capacitance can be assumed to be in the range of 10 to 50 nanofarads.

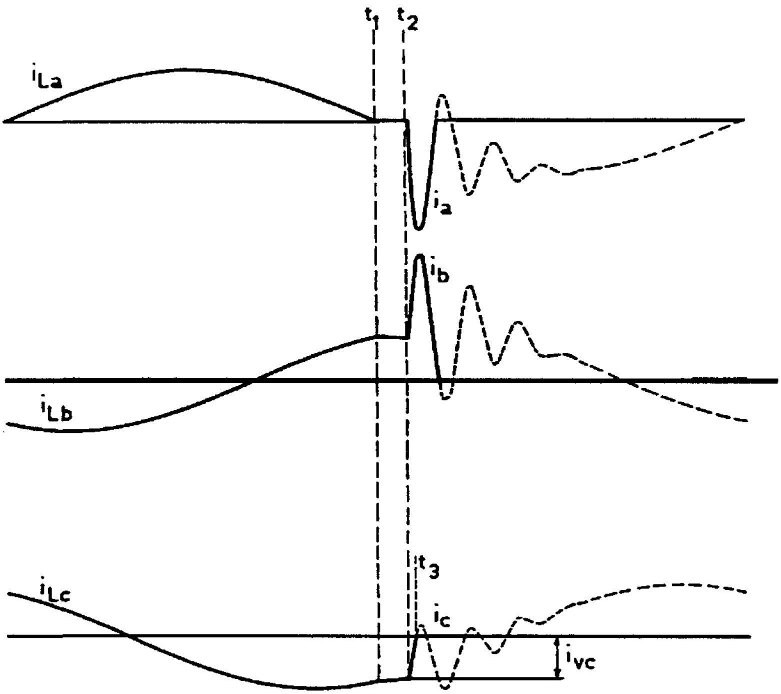
4.2.3.2 Current Chopping in Vacuum Circuit Breakers

In contrast to other types of circuit breakers the current instability in vacuum interrupters is not strongly influenced by the capacitance of the system (see Figure 4.9), but is dependent upon the material of the vacuum contacts and by the action of the anode spot created by the vacuum arc. There is no chopping number for vacuum interrupters but instead the chopping current itself can be specified as follows:

For copper-bismuth contacts current chopping	5 to 17 Amperes
For chrome copper contacts current chopping	2 to 5 Amperes



(a)



(b)

Figure 4.10 Virtual current chopping. (a) Circuit showing the flow of the induced currents. (b) Relationships between the three phase currents (from ref. 14).

4.2.4 Virtual Current Chopping

Virtual current chopping in reality is not a true chopping phenomenon but rather it is the normal interruption of a fast transient current. Virtual chopping is a phrase that has been coined to describe the condition illustrated in the simplified circuit shown in Figure 4.10.

Referring to this figure, the power frequency currents are shown as I_A, I_B and I_C. Assuming that, for example, a current reignition occurs shortly after the interruption of the power frequency current in phase A, the reignition current i_a will then flow to ground through the line to ground capacitance C_g in the load side of the circuit breaker in phase A and the components i_b and i_c flow in phases B and C due to the coupling of their respective line to ground capacitances.

The high frequency transient current produced by the reignition superimposes itself on the power frequency; furthermore, the high frequency current could be larger in magnitude than the power frequency current and therefore it can force current zeroes at times other than those expected to occur normally with a 50 or 60 Hz current.

As it has been stated before there are some types of circuit breakers which are capable to interrupt these high frequency currents, and therefore it is possible to assume that in some cases the circuit breaker may clear the circuit at a current zero crossing that has been forced by the high frequency current and that the zero crossing occurs at a time prior to that of the natural zero of the power frequency current. When this happens, as far as the load is concerned, it looks the same as if the power frequency current has been chopped since a sudden current zero has been forced.

Since the high frequency current zeroes will occur at approximately the same time in all three phases the circuit breaker may interrupt the currents in all three phases simultaneously thus giving rise to a very complicated sequence of voltage transients that may even include reignitions in all three phases.

Considering that, when compared to a "normal" current chopping, we find that the instantaneous value of current, from which the load current is forced to zero, is significantly higher but also that the surge impedance is somewhat lower, then the line to ground overvoltage could be assumed to be at about the same order of magnitude as the overvoltages that are generated by the conventional current chopping; however, in the worst case, if the neutral is ungrounded one half of the reignition current would return through each of the other two phases and they both will be in phase but with opposite polarities which will result in the line to line overvoltage of the two phases being twice their corresponding line to ground overvoltage.

4.2.5 Temporary Overvoltages

Temporary overvoltages represent an oscillatory voltage of a relatively long duration. As it may be recalled, earlier they were defined as those overvoltages lasting longer than five cycles. Temporary overvoltages usually are preceded by a transient overvoltage resulting from a switching operation.

Temporary overvoltages can be characterized or defined by their oscillating frequency, which may be equal, higher or lower than the natural power frequency of the system. They can also be defined based upon their origin or by the mechanism by which they are sustained.

For temporary overvoltages to exist there has to be either very small or no damping provided by the resistance of the system. It can also be assumed that there is either a source of voltage driving the system at an elevated level or there is some mechanism that is counteracting the damping. One of the conditions for this to occur is that the system at that moment is carrying a light load or is not loaded at all. This really means that that any possible damping resulting from the active power consumption is not existent or is greatly reduced.

A typical case of a temporary overvoltage having a frequency equal to the power frequency can be observed following a load rejection where due to the Ferranti effect the voltage on the load side is higher than at source side. Other examples of temporary overvoltages would be those that are the result of ferroresonance and those produced across series capacitors.

Temporary overvoltages on EHV and UHV systems reach values in the range of 1.8 to 2.0 pu but generally it is required that means be provided to limit these overvoltages to between 1.2 to 1.5 pu. The most effective means for controlling temporary overvoltages is the inclusion of reactive compensation although other methods that are used for the control of transient overvoltages, i.e. damping resistors or surge arresters also can be used.

4.2.6 Controlling Overvoltages

Circuit breakers themselves do not generate overvoltages, but they do initiate them by changing the quiescent conditions of the circuit. As it has been stated before, the switching overvoltages are the result of two overvoltage components, the power frequency overvoltage and the transient overvoltage component. Limiting the magnitude of the first is usually sufficient to reduce the total overvoltage to within acceptable limits. However, this does not exclude the possibility of using appropriate measures to additionally limit the magnitude of the overvoltage by limiting the transient response.

Among the measures that can be taken to reduce the magnitudes of the power frequency overvoltages are:

(a) Provide polarity controlled closing
(b) Add closing and or opening resistors across the circuit breaker contacts
(c) Provide a method combining polarity control and closing resistors
(d) Add parallel compensation
(e) Reduce the supply side reactance

The transient overvoltage factor can be controlled by:

(a) Removing the trapped charges from the line
(b) Synchronizing closing which can be accomplished either by closing at a voltage zero of the supply side or by matching the polarity of the line and the supply side
(c) Synchronizing opening which optimizes the contact gap at current zero
(d) Using pre-insertion resistors

From all the listed alternatives only resistors can be considered to be an integral part of a circuit breaker. The practice of including opening and/or closing resistors as part of a circuit breaker is relatively common for circuit breakers intended for applications at voltages above 123 kV.

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5

TYPES OF CIRCUIT BREAKERS

5.0 INTRODUCTION

Circuit breakers are switching devices which according to the American National Standards Association (ANSI) C37.100 [1] are defined as: "A mechanical device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specific time and breaking currents under specified abnormal circuit conditions such as those of short circuit."

Historically, as the operating voltages and the short circuit capacities of the power systems have continued to increase, high voltage, high power circuit breakers have evolved trying to keep pace with the growth of the electric power systems. New technologies, primarily those involving the use of advanced interrupting mediums, have been developed and continue to be studied [2].

To achieve current interruption some of the early circuit breaker designs simply relied on stretching the arc across a pair of contacts in air. Later, arc chute structures, including some with magnetic blow-out coils were incorporated, while other devices used a liquid medium, including water but more generally oil as the interrupting medium.

Some of those early designs have been significantly improved and variations of those types of circuit breakers are still in use, especially in low voltage applications where presently plain air circuit breakers constitute the dominant type of circuit breakers used.

For indoor applications, at system voltages that range from approximately 5 kV up to 38 kV, air magnetic circuit breakers were the circuit breakers of choice in the US until the mid nineteen seventies, while in Europe and other installations outside of the US, minimum oil circuit breakers were quite popular. Bulk oil and air blast circuit breakers were quite common until the mid seventies for outdoor applications at voltages ranging from 15 kV up to 345 kV. For indoor, medium voltage applications minimum oil circuit breakers enjoyed a great deal of popularity outside of the US and especially in Europe.

With the advent of vacuum and sulfurhexafluoride the older types of circuit breaker designs have been quickly superseded and today they can be effectively considered as being obsolete technologies.

What we just described suggests that circuit breakers can be used for different applications, that they can have different physical design characteristics and that they also can perform their interrupting duties using different quenching mediums and design concepts.

5.1 CIRCUIT BREAKER CLASSIFICATIONS

Circuit breakers can be arbitrarily grouped using many different criteria such as the intended voltage application, the location where they are installed, their external design characteristics, and, perhaps most importantly, by the method and the medium used for the interruption of current.

5.1.1 Circuit Breaker Types by Voltage Class

A logical starting point for establishing a classification of circuit breakers is the voltage level at which the circuit breakers are intended to be used. This first broad classification divides the circuit breakers into two groups:

1. Low voltage circuit breakers, which are those that are rated for use at voltages up to 1000 volts and
2. High voltage circuit breakers which are those that are applied or that have a rating of 1000 volts or more.

Each of these groups is further subdivided and in the case of the high voltage circuit breakers they are split between circuit breakers that are rated 123 kV and above and those rated 72.5 kV and below. Sometimes these two groups are referred to as the transmission class and the distribution or medium voltage class of circuit breakers, respectively.

The above classification of high voltage circuit breakers is the one that is currently being used by international standards such as ANSI C37.06 [3] and the International Electrotechnical Commission (IEC) 62271-100 (formely IEC 60056) [4].

5.1.2 Circuit Breaker Types by Installations

High voltage circuit breakers can be used in either indoor or outdoor installations. Indoor circuit breakers are defined in ANSI C37.100 [1] as those "designed for use only inside buildings or weather resistant enclosures."

For medium voltage circuit breakers ranging from 4.76 kV to 34.5 kV it generally means that indoor circuit breakers are designed for use inside of a metal clad switchgear enclosure.

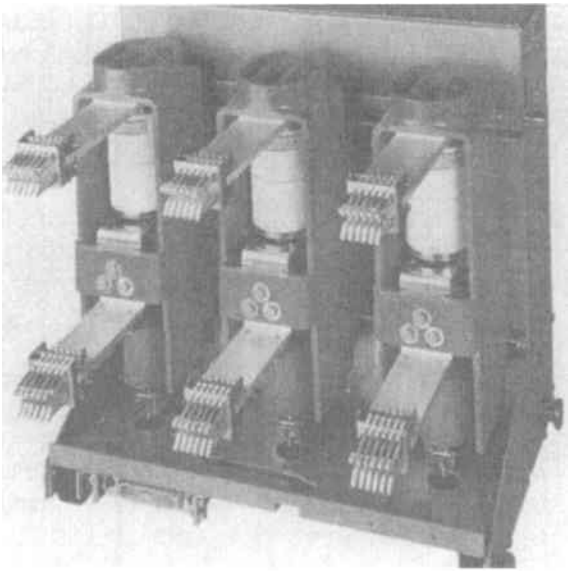

Figure 5.1 Indoor type circuit breaker.

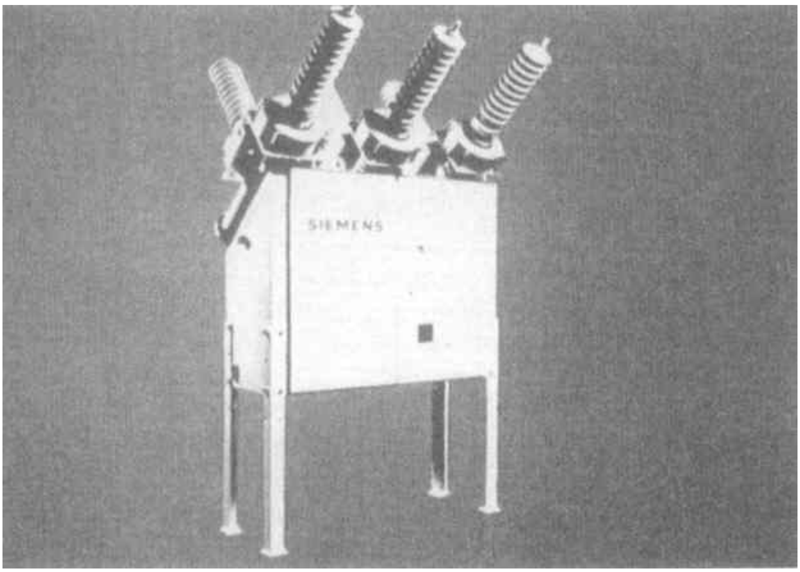

Figure 5.2 Outdoor type circuit breaker.

In practice, the only differences between indoor and outdoor circuit breakers are the external structural packaging and the enclosures that are used, as illustrated in Figures 5.1 and 5.2. The internal current carrying parts, the interrupting chambers and the operating mechanisms, in many cases, are the same for both types of circuit breakers provided that they have the same currents and voltage ratings and that they utilize the same interrupting technology.

5.1.3 Circuit Breaker Types by External Design

From the point of view of their physical structural design, outdoor circuit breakers can be identified as either the dead tank or live tank type circuit breakers. These two circuit breaker types are shown in Figures 5.3 and 5.4.

Dead tank circuit breakers are defined in ANSI C37.100 [1] as "A switching device in which a vessel(s) at ground potential surrounds and contains the interrupter(s) and the insulating mediums."

A live tank circuit breaker is defined in the same standard as: "A switching device in which the vessel(s) housing the interrupter(s) is at a potential above ground."

Dead tank circuit breakers are the preferred choice in the US and in most countries that adhere to ANSI published standards. These circuit breakers are said to have the following advantages over the live tank circuit breakers:

1. Multiple low voltage bushing type current transformers can be installed at both the line side and the load side of the circuit breaker.
2. They have a low, more aesthetic silhouette.
3. Their unitized construction offers a high seismic withstand capability.
4. They are shipped factory assembled and adjustments are factory made.

In applications where the IEC standards are followed live tank circuit breakers are the norm. The following advantages are generally listed for live tank circuit breakers:

1. Lower cost of circuit breaker (without current transformers)
2. Less mounting space requirements
3. Uses a lesser amount of interrupting fluid

5.1.4 Circuit Breaker Types by Interrupting Mediums

In the evolutionary process of the circuit breaker technology, the main factors that have dictated the overall design parameters of the device are the interrupting and insulating medium that is used, together with the methods that are utilized to achieve the proper interaction between the interrupting medium and the electric arc.

The choice of air and oil, as the interrupting mediums, was made at the turn of the century and it is remarkable how well and how reliably these mediums have served the industry.

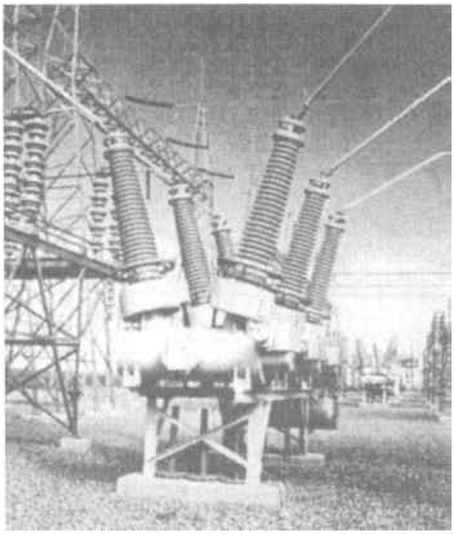

Figure 5.3 Dead tank type circuit breaker (grounded enclosure).

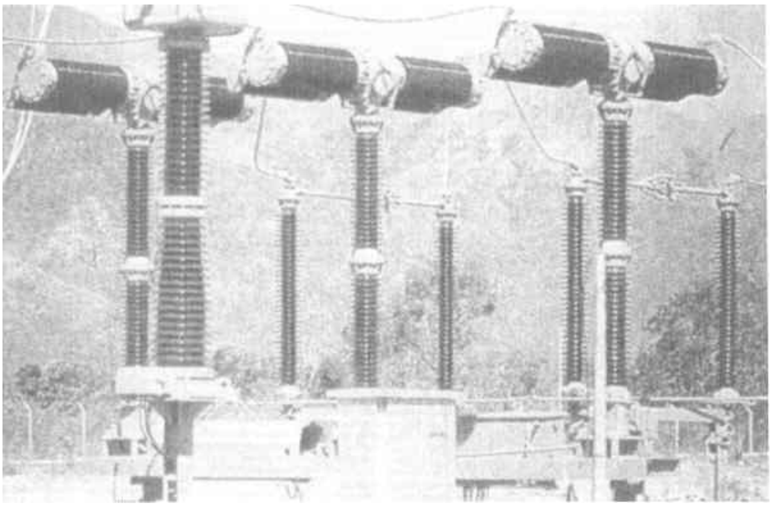

Figure 5.4 Live tank type circuit breaker (ungrounded enclosure).

Two newer technologies, one using vacuum and the other sulfurhexafluoride (SF_6) gas as the interrupting medium, made their appearance at about the same time in the late 1950's, and are now what is considered to be the new generation of circuit breakers.

Although vacuum and SF_6 constitute today's leading technologies, a discussion of air and oil circuit breakers is provided because many of these devices are still in service, moreover, because many of the requirements specified in some of the existing standards were based on the operating characteristics of those old circuit breaker technologies.

5.2 AIR MAGNETIC CIRCUIT BREAKERS

A plain break knife switch operated in free air, under normal atmospheric conditions, is one of the earliest versions known of a circuit breaker. However, this simple device had a very limited capacity in terms of voltage and of interrupting current.

The interrupting capability limitations of such a switch spurred investigations that led to the development of improved designs. Those improvements involved the inclusion of a number of components whose function was to enhance the cooling of the arc.

The most significant advancement was the development of the arc chute, which is a boxlike component device that contains a number of either metallic or insulated plates. Additionally, in most of the designs, when intended for medium voltage applications, the arc chute includes a magnetic blow-out coil.

It is a well-known fact that air at atmospheric pressure has a relatively low dielectric strength; it is also known that in still air nothing accelerates the process of recombination and therefore the time constant for deionization is fairly large.

It should be recalled that a low time constant is highly desirable, in fact is indispensable for high voltage devices. However, a high time constant is acceptable in low and at the lower end of the medium voltage devices, where it offers the advantages of substantially reducing the possibility of generating switching overvoltages, and in many cases of modifying the inherent TRV of the system. This influence may be such that for all practical purposes this type of circuit breaker can be considered to be insensitive to TRV problems in the thermal recovery region.

Since current interruption across an air break is based only upon the natural deionization process that takes place in the air surrounding the arc, then in order to improve the interrupting capability it is necessary to enhance the deionization process by means of some appropriate external cooling method.

We should recall that in order to maintain the ionization of the gas, when the arc is effectively cooled, the magnitude of the arc voltage must increase. What this means is simply that as the arc cools, the cooling effectively increases the deionization of the arc space, which in turn increases the arc resistance. As a consequence of the increase in resistance, the short circuit current and the phase angle are reduced and thus the likelihood of a successful interruption is significantly enhanced.

In an air circuit breaker, increasing the resistance of the arc in effect increases the arc voltage. Thus, to effectively increase the arc voltage any of the following means can be used:

1. Increase the length of the arc, which increases the voltage drop across the positive column of the arc.
2. Split the arc into a number of shorter arcs connected in series. What this does is that instead of having a single cathode and anode at the ends of the single arc column there are now a multiplicity of cathode and anode regions, which have additive voltage drops. Although the short arcs reduce the voltage of each individual positive column, the summation of all the voltage drops is usually greater than that of a single column; furthermore, if the number of arcs is large enough so that the summation of these voltage drops is greater than the system voltage a quick extinction of the arc is possible.
3. Constricting the arc by constraining it between very narrow channels. This in effect reduces the cross-section of the arc column and thus increases the arc voltage.

With both of the last two suggested methods there is an added benefit, which is the additional cooling of the arc as the result of the high energy storage capacity provided by the arc chute plates that are housed inside of the arc chute itself.

5.2.1 Arc Chute Type Circuit Breakers

An arc chute can be described as a box shaped structure made of insulating materials. Each arc chute surrounds a single pole of the circuit breaker independently, and it provides structural support for a set of arc plates and in some cases, when so equipped, it houses a built-in magnetic blow-out coil.

Basically there are two types of arc chutes, where each type is characterized primarily by the material of the arc plates that are used. Some arc plates are made of soft steel and in some cases are nickel plated. In this type of arc chute the arc is initially guided inside the plates by means of arc runners, which is simply a pair of modified arc horns. Subsequently the arc moves deeper into the arc chute due to the forces produced by the current loop and the pressure of the heated gases.

To enhance and to control the motion of the arc, vertical slots are cut into the plates. The geometrical pattern of these slots varies among circuit breaker manufacturers, and although there may be some similarities in the plate designs, each manufacturer generally has a unique design of its own.

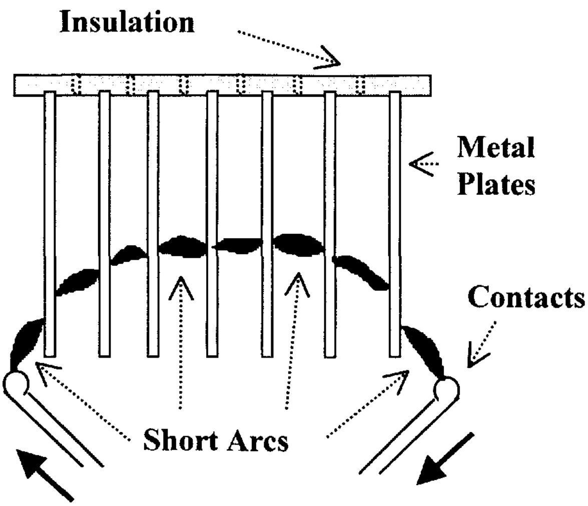

Figure 5.5 Outline of a plain arc chute used in low voltage circuit breakers.

When the arc comes in contact with the metal plates it divides into a number of shorter arcs that burn across a set of adjacent plates. The voltage drop that is observed across each of these short arcs is usually about 30 to 40 volts, the majority of this voltage being due to the cathode and anode drop of each arc. The voltage drop of the positive column depends on the plate spacing, which in turn determines the length of the arc's positive column. A schematic representation of this type of arc chute, which is used almost exclusively in low voltage applications, is shown in Figure 5.5.

A second type of arc chute is one that is generally synonymous with magnetic blow-out assist and which is used in circuit breakers intended for applications at medium voltages of up to 15 kV and for interrupting symmetrical fault currents of up to 50 kA. This type of arc chute almost invariably uses insulated arcing plates that are made of a variety of ceramic materials such as zirconium oxide or aluminum oxide. An example of this type of circuit breaker is shown in Figure 5.6.

With this particular type of arc chute the cooling of the arc and its final quenching is effected by a combination of processes. First, the arc is elongated as it is forced to travel upwards and through a tortuous path that is dictated by the geometry and the location of the insulating plates and their slits.

Simultaneously the arc is constricted as it travels through the slots in the arc plates and as the arc fills the narrow space between the plates. Finally, when the arc gets in contact with the walls of the insulating plates the arc is cooled by diffusion to these walls.

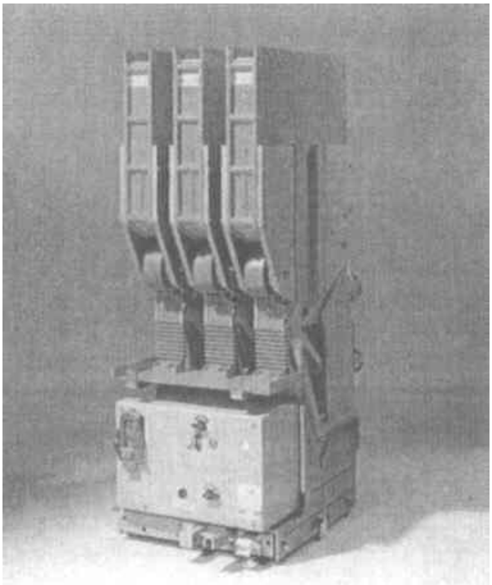

Figure 5.6 Typical 15 kV air magnetic circuit breaker.

The diffusive cooling is strongly dependent upon the spacing of the plates, this dependence has been shown by G. Frind [5] and his results are illustrated in Figure 5.7.

Since the arc behaves like a flexible and stretchable conductor, it is possible to drive the arc upwards forcing it into the spaces between the arcing plates, and thus rather effectively increasing the length of the arc and its resistance

Motion of the arc is forced by the action the magnetic field produced by a coil that is generally found embedded into the external supporting plates of the arc chute. In Figures 5.8 and 5.9 a complete arc chute assembly and a coil that is to be potted are shown.

The coil, which is not a part of the conducting circuit during normal continuous operation, is connected to the ends of an arcing gap as shown schematically in Figure 5.10 (a). When the circuit breaker begins to open, the current transfers from the main contacts to the arcing contacts where, upon their separation, the arc is initiated (Figure 5.10 (b)). As the contacts continue to increase their separation, the arc is forced into the arc runners where the coil is connected, and in so doing the coil is inserted into the circuit (Figure 5.10 (c)). The magnetic field created by the coil will now exert a force upon the arc that tends to move the arc up deeper inside the arc chute (Figure 5.10 (d)).

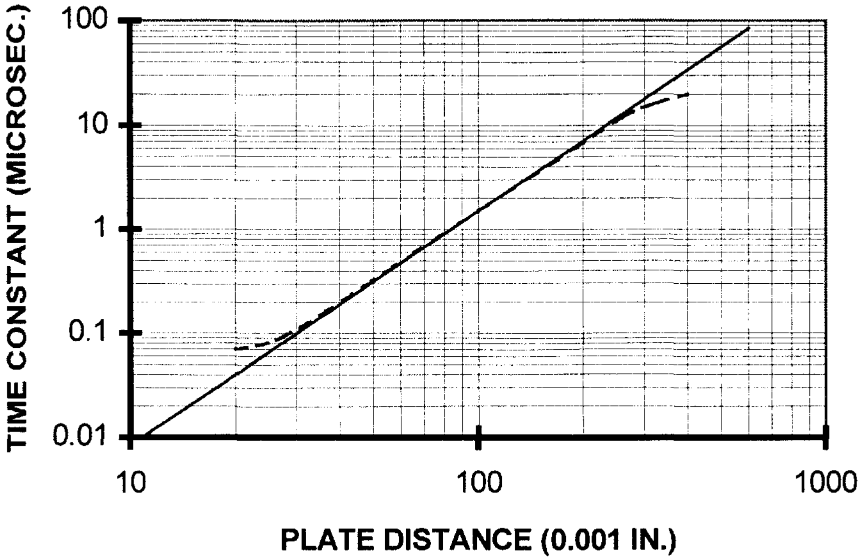

Figure 5.7 Recovery time constant in air as a function of the spacing between the arc chute plates.

The heating of the arc plates and their air spaces results in the emission of large amounts of gases and vapors that must be exhausted through the opening at the top of the arc chute.

The mixture of gases and vapor is prevented from flowing back and into the contacts by the magnetic pressure that results from the interaction of the arc current and the magnetic field. As long as the forces produced by the gas are lower than the magnetic forces, the flow of the gases will be away from the contacts.

An important requirement for the connection of the coil is to maintain the proper polarity relationships so the arc is driven upwards and into the interrupting chamber. It is also important to have a phase lag between the magnetic flux and the current being interrupted so that at current zero there is still a force being exerted on the extinguishing arc.

Because at low current levels the magnetic force is relatively weak most air magnetic circuit breakers include some form of a puffer that blows a small stream of air into the arc, as the arcing contacts separate, to help drive the arc upwards and into the plates.

In most designs, to avoid the possibility of releasing hot, partially ionized gases which may cause secondary flashovers, a flat horizontal stack of metal plates is placed at the exhaust port of the arc chute.

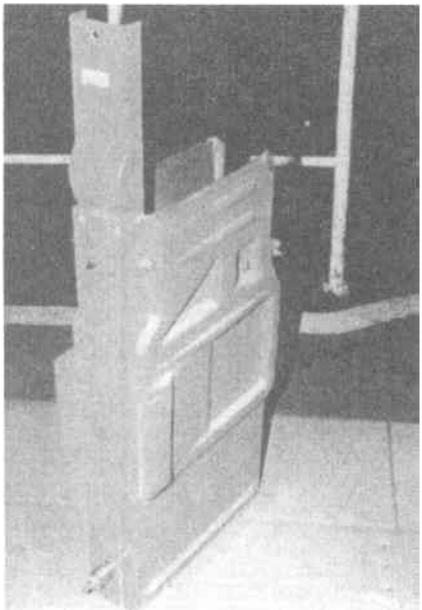

Figure 5.8 Complete assembly of a 15 kV arc chute.

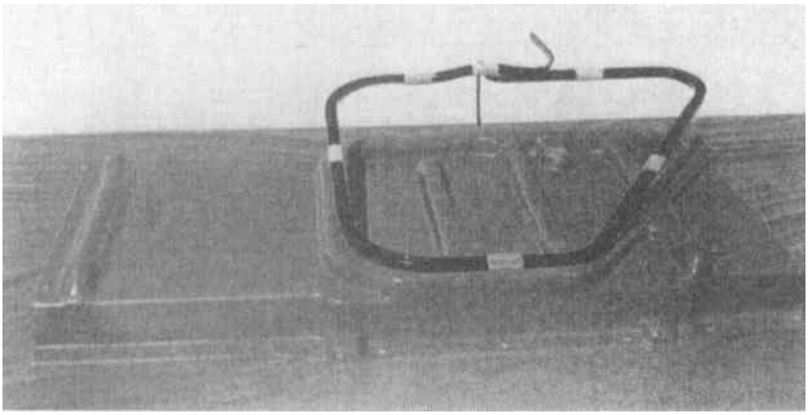

Figure 5.9 Side plate of an arc chute showing the blow-out coil and its assembly location.

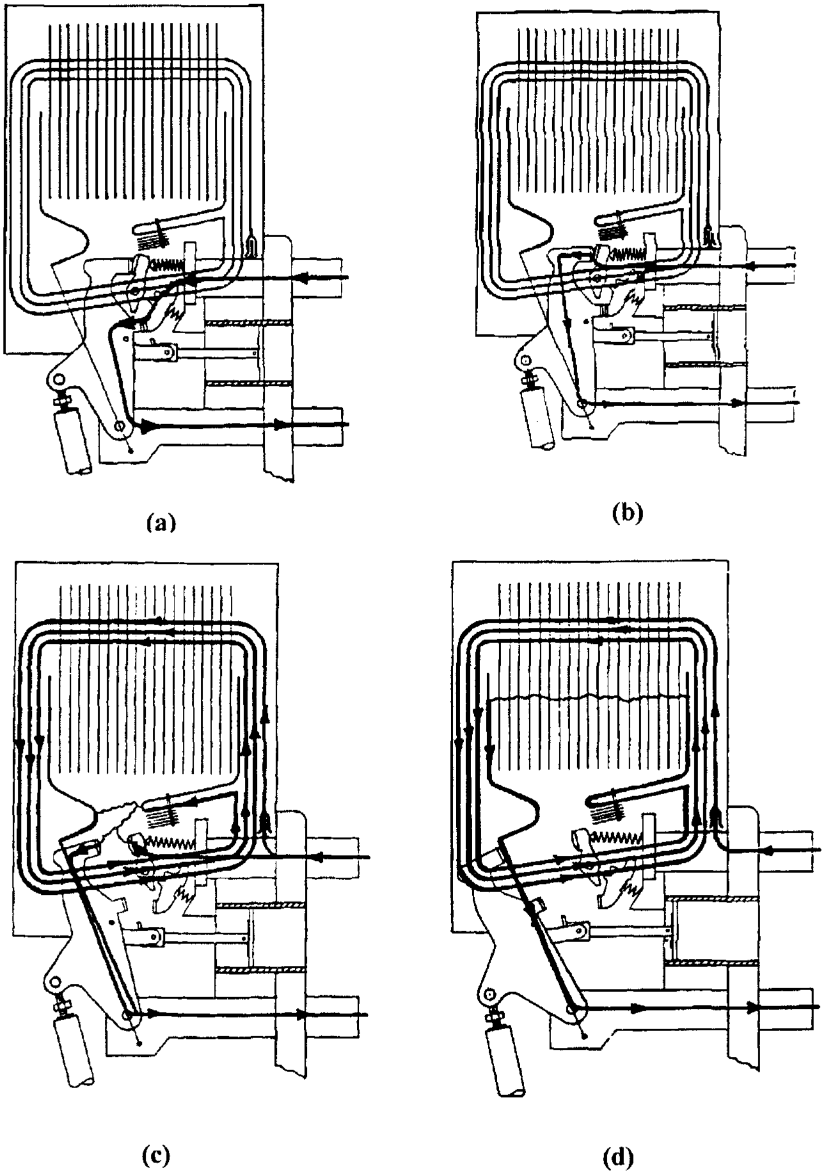

Figure 5.10 Blow-out coil insertion sequence of an air magnetic circuit breaker. (a) Circuit breaker closed, coil by-passed. (b) Main contacts open, current transferred to arcing contact. (c) Arcing contacts open, coil inserted. (d) Arc fully developed across the plates.

Finally, it should be noted that even though this is one of the oldest techniques of current interruption and that in spite of all the theoretical and experimental knowledge that has been gained over the years, the design of arc chutes remains very much an art. Theoretical evaluation of a design is very difficult and the designer still has to rely primarily on experimentation.

5.2.2 Air Magnetic Circuit Breaker Typical Applications

One important characteristic of air magnetic circuit breakers is that their interrupting capability is greatly influenced by the magnitude of the system voltage. It has been demonstrated that the interrupting current capability increases as the voltage decreases and consequently these circuit breakers can be referred to as being a voltage controlled interrupter. This characteristic, as it will be shown in a later chapter, is reflected in some existing performance standards where within some specific limits the interrupting current capability is given by:

$$\frac{V_{Max}}{V_{Min}} = \frac{I_{Max}}{I_{Min}}$$

Because of the high arc resistance that is characteristically exhibited by these circuit breakers, they are capable of modifying the normal wave form of the fault current to the point that they may even advance the occurrence of a current zero. This represents a significant characteristic of these circuit breakers, especially for applications in circuits where the fault current asymmetry exceeds 100% and where there may not be current zeroes for several cycles. This high asymmetry condition is common in applications related to the protection of large generators.

Among some of the significant disadvantages of these circuit breakers when compared to modern type circuit breakers of the same ratings are their size and their cost. Other disadvantages include short interrupting contact life which is due to the high energy levels that are seen by the interrupter, their need for a relatively high energy operating mechanism, and the risks that are posed by the hot gases when they are released into the switchgear compartment following the interruption of a short circuit current.

5.3 AIR BLAST CIRCUIT BREAKERS

Although there was a patent issued in 1927, air blast circuit breakers were first used commercially some time around the year 1940, and for over five decades this technology has proved to be quite successful.

Air blast circuit breakers have been applied throughout the complete high voltage range, and until the advent of SF_6 circuit breakers, they totally dominated the higher end of the transmission voltage class. In fact, at one time they were the only type of circuit breaker that were available for applications at voltages higher than 345 kV.

In reality, air blast circuit breakers should be identified as a specific type of the more generic class of gas blast circuit breakers because air is not necessarily the only gas that can be used to extinguish the arc; other gases such as nitrogen, carbon dioxide, hydrogen, freon and of course SF_6 can be used. Furthermore, it is well known, and as is generally agreed, the interrupting process is the same for all gas blast circuit breakers and most of the differences in performance observed between air blast and SF_6 circuit breakers are the result of the variations in the cooling capabilities, and therefore in the deionization time constant of each of the gases. For this reason the detailed treatment of the interrupting process will be postponed to later in this chapter, when describing the more modern SF_6 technology.

Because there are some differences in the basic designs of air blast interrupters, and because the newer concepts for gas blast interrupters have evolved from the knowledge gained with the air blast circuit breaker, there are a number of subjects which need to be addressed in this section, if for no other reason than to provide a historical frame of reference.

In all of the designs of air blast circuit breakers the interrupting process is initiated by establishing the arc between two receding contacts and by, simultaneously with the initiation of the arc, opening a pneumatic valve which produces a blast of high pressure air that sweeps the arc column subjecting it to the intense cooling effects of the air flow.

5.3.1 Blast Direction and Nozzle Types

Depending upon the direction of the air flow in relation to the arc column [6] there are, as shown in Figure 5.11 (a), (b) and (c), three basic types of blast orientations:

1. Axial blast
2. Radial blast
3. Cross blast

From the three blast types, the axial or the radial type are generally preferred for extra high voltage applications, while the cross blast principle has been used for applications involving medium voltage and very high interrupting currents.

To effectively cool the arc the gas flow in an axial blast interrupter must be properly directed towards the location of the arc. Effective control of the gas flow is achieved by using a D'Laval type of a converging-diverging nozzle.

These nozzles can be designed either as insulating, or as metallic or conducting nozzles. Additionally and depending on the direction of flow for the exhaust gas, each of the nozzles in these two groups can be either what is called a single or a double flow nozzle.

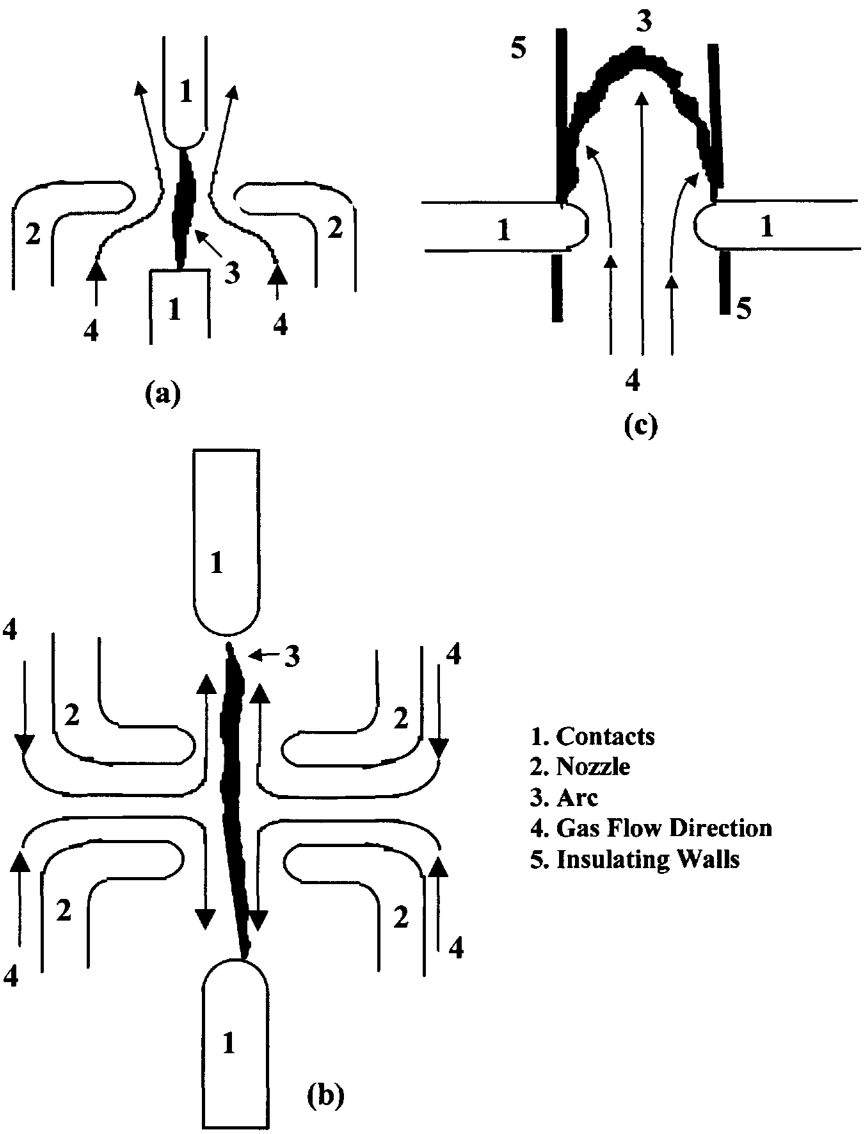

Figure 5.11 Air blast direction: (a) axial direction, (b) radial direction, and (c) cross blast or transverse direction.

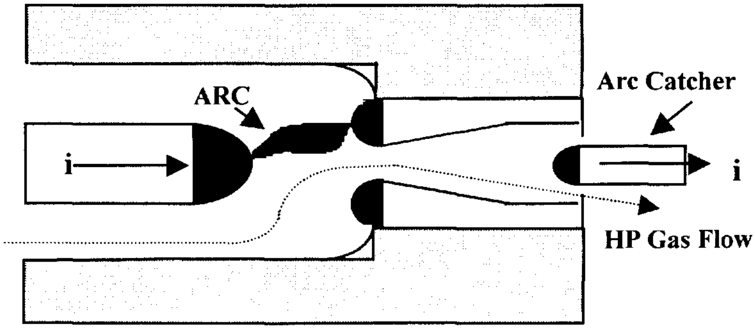

Figure 5.12 Outline of a conducting single flow nozzle.

A conducting single flow nozzle, as shown in Figure 5.12, is one where the main stationary contact assembly serves a dual purpose. It carries the continuous current when the circuit breaker is closed and as the circuit breaker opens the arc is initiated across one of its edges and its corresponding mating moving contact. After the gas flow is established, the pneumatic force exerted by the gas on the arc effectively transfers the arc to a stationary arc terminal, or arc catcher, that is disposed longitudinally at the center of the nozzle.

It is easily observed that with this design the arc length can be increased considerably and at a faster rate than that which is possible with an insulating nozzle where the arc is initiated directly across a pair of receding arcing contacts. Under these conditions the time needed for the arc to reach its final length is dependent upon the final contact gap and consequently on the opening speed of the circuit breaker contacts that is normally in the range of 3 to 6 meters per second (10 to 20 feet per second).

An axial insulating nozzle is geometrically similar to the conducting nozzle as shown in Figure 5.13, and as its name implies, the insulating nozzle is made of an insulating material. The material of choice is generally teflon, either as a pure compound or with some type of filler material. Fillers are used to reduce the rate of erosion of the throat of the nozzle.

It should be noted that once the arc is properly attached to the intended arcing contacts, the gas flow characteristics and the interaction between the gas and the arc are the same for both types of nozzles.

The cross blast design is among the earliest concepts used on air circuit breakers. As shown schematically in Figure 5.11 (c) the arc is initiated across a pair of contacts and is subjected to a stream of air that flows perpendicular to the axis of the arc column. It was contended that a considerable amount of heat could be removed from the arc since the whole length of the arc is in contact with the air flow. However, this is not the case, mainly because the core of the arc has a lower density than the surrounding air and therefore at the central part of the arc column there is very little motion between the arc and the gas. Nevertheless, at the regions

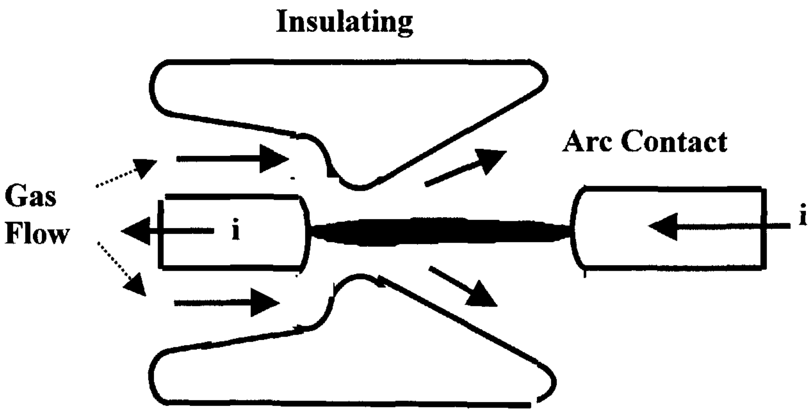

Figure 5.13 Outline of an axial insulating nozzle.

lying alongside the contacts where the roots of the arc are being elongated the gas flows in an axial direction and a substantial amount of cooling can be achieved. Most of the circuit breakers that were made using a cross blast were applied only at medium voltages and high currents.

5.3.2 Series Connection of Interrupters

Without a doubt a single break interrupter is the simplest and more economical solution. However, significant improvements in the interrupting capacity of a circuit breaker can be achieved by connecting a number of interrupters in series.

It is easy to see that by connecting a number of interrupters in series, the recovery voltage, at least in theory, is equally divided across each interrupter. It also can be seen that the number of deionizing chambers is increased and thus the energy balancing process is increased proportionally to the number of interrupters connected in series.

One of the main difficulties encountered with this type of application is to ensure that during the transient period of the interruption process each of the interrupters operates under the exact same conditions of the other. This sameness requirement applies to both the aerodynamic and the electrical conditions.

From the aerodynamic point of view the flow conditions must be maintained for each interrupter. This generally requires the use of individual blast valves for each interrupter. It also requires that the lines connecting each interrupting chamber are properly balanced to avoid pressure drops that may affect the gas flow.

Electrically, the restriking voltages and consequently the recovery voltages must divide evenly across each set of contacts. However, in actual practice this does not happen and an uneven distribution of voltage occurs due to the unbalanced inherent capacitance that exists across the interrupting device itself and between the line and the grounded parts of the circuit breaker. To improve the voltage distribution it is a common practice to use grading capacitors or resistors connected across the contacts or between the live parts and ground.

5.3.3 Basic Interrupter Arrangements

Medium voltage air blast circuit breakers were normally dead tank designs. Air circuit breakers intended for applications at system voltages greater than 72.5 kV were almost without exception of the live tank design type.

In some of the earlier designs the blast valve was located inside of the high pressure storage tank, at ground level, while the interrupters were housed at the end of insulating columns. The tripping operation was initiated by opening the blast valve which in turn momentarily pressurized the interrupter causing the contacts to move. The blast valve was closed later, in about 100 milliseconds, and as the pressure inside of the interrupters was decreased the circuit breaker contacts reclosed.

To maintain system isolation in the open position of the circuit breaker there was a built-in plain air break isolating switch that also served as a disconnecting switch for the grading capacitors or resistors. The isolating switch was timed to open in about 40 to 50 milliseconds after the opening time of the main contacts.

The disadvantages associated with this type of design were the larger gap length required by the isolator at the higher system voltages. As it can be expected the greater gaps required additional operating time and therefore fast reclosing times were difficult to achieve. Furthermore, since the exhaust was open to the atmosphere the air consumption was relatively large.

A number of improvements were made, focused primarily with the objective of removing the need for the air isolating switch. Many different arrangements of blast and exhaust valves where used until the present design in which the interrupters are maintained fully pressurized at all times was adopted. In this version tripping of the circuit breaker is executed by first opening the exhaust valves and then sequentially opening the contacts. After a few milliseconds the exhaust valves are closed while the contacts still are in the open position. For closing, the contacts are depressurized while the valves are held closed.

With this design, the air consumption was substantially reduced and what is more important, since the interrupting chambers were held at the maximum pressure at all times, the breaking and the withstand capacity of the interrupter was optimized. One last advantage that should be mentioned is that since the air consumption was reduced so was the operating noise level of the interrupter. This is significant because air blast circuit breakers are notorious for their high operating noise level.

5.3.4 Parameters Influencing Air Blast Circuit Breaker Performance

There are many factors that influence the performance of a gas blast circuit breaker. However, from all those factors there are some that can be easily measured such as the operating pressure, the nozzle diameter and the interrupting current.

These parameters have been used to establish a number of basic relationships [7],[8] that are directly related to the observed voltage recovery capability of the interrupter in the thermal region. These relationships which can be defined by means of an exponential equation are included in their graphic form in Figures 5.14, 5.15, and 5.16.

The significance of these relationships is not in the absolute values that are being presented because, depending on the specific design of the nozzle and on the overall efficiency of the interrupter, the magnitude of the variables change; however, the slope of the curves and therefore the exponent of the corresponding variables remains constant thus indicating a performance trend and giving a point of reference for comparison between interrupter designs. Furthermore and as it will be seen later there is a great deal of similarity between these curves and those obtained for SF_6 interrupters.

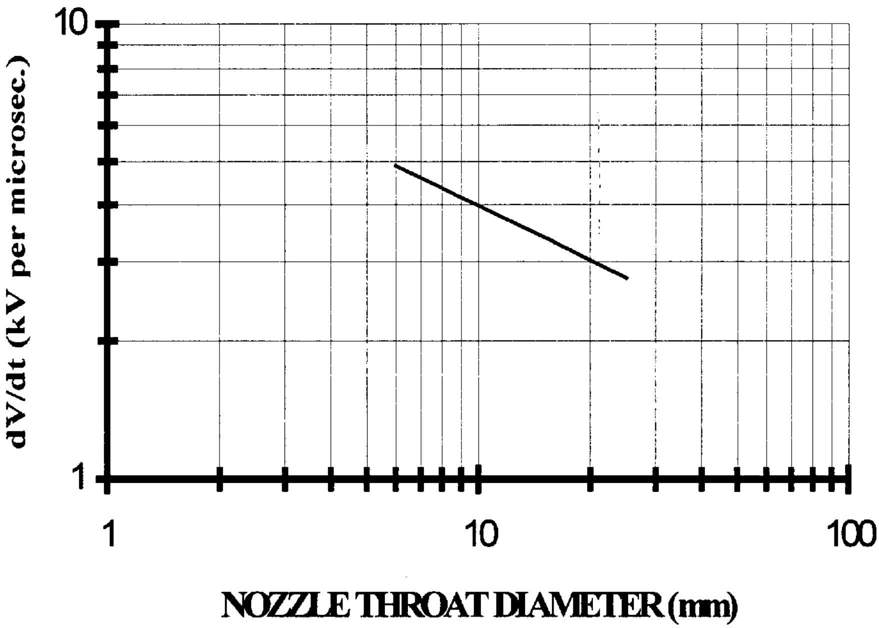

Figure 5.14 Voltage recovery capability in the thermal region as a function of nozzle throat diameter for an air blast interrupter.

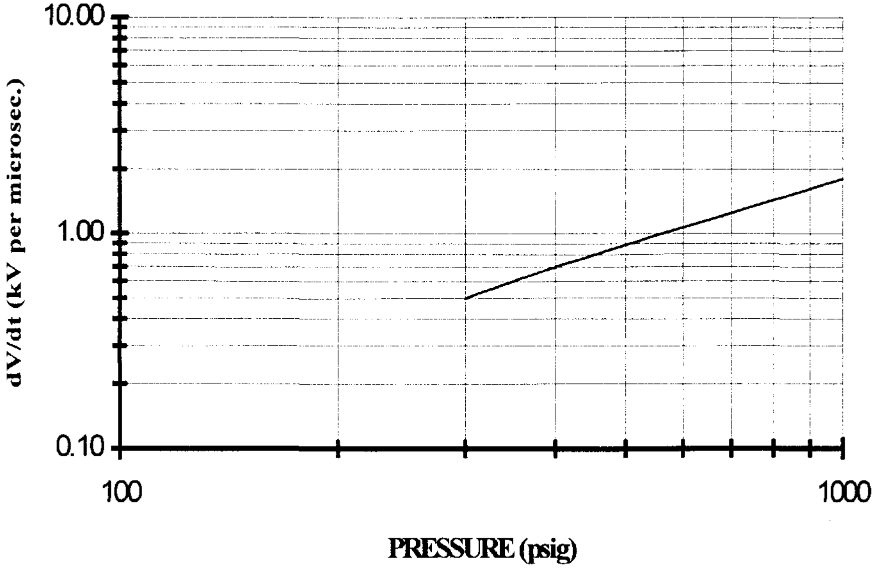

Figure 5.15 Voltage recovery capability in the thermal region as a function of pressure for an air blast interrupter.

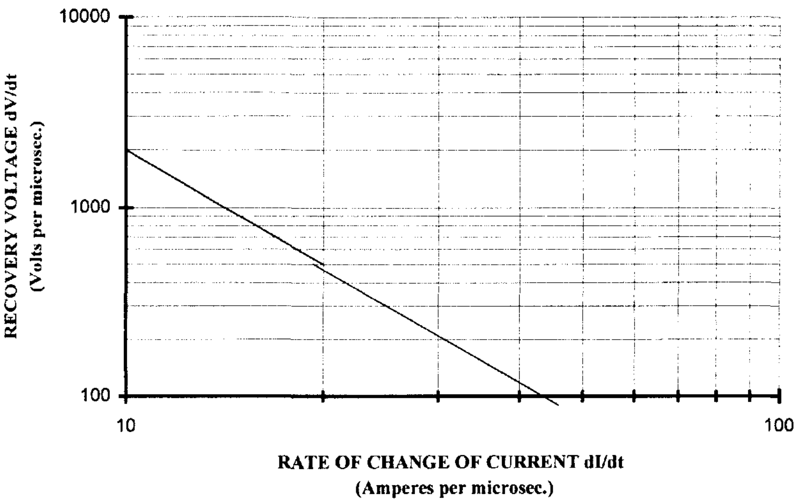

Figure 5.16 Voltage recovery capability in the thermal region as a function of rate of change of current for an air blast interrupter.

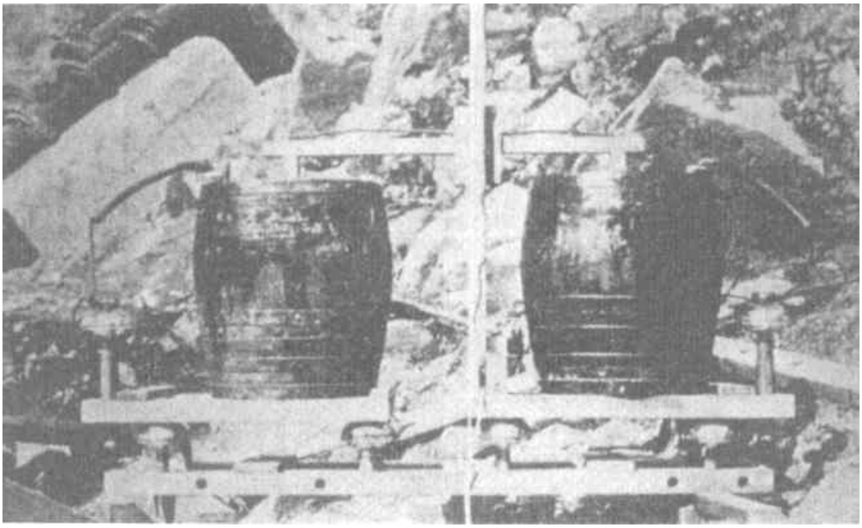

Figure 5.17 Oil circuit breaker built in 1901 by Kelman (from ref. 9).

5.4 OIL CIRCUIT BREAKERS

From a historical perspective, the oil circuit breaker is the first design of a circuit breaker for high power applications. It predates the air blast type by several decades.

One of the first designs of an oil circuit breaker on record in the US is the one shown in Figure 5.17. This circuit breaker was designed and built by J. N. Kelman in 1901. The circuit breaker was installed on a 40 kV system that was capable of delivering a maximum short circuit current of 200 to 300 amperes. Records indicate that the circuit breaker was in service from April 1902 until March of 1903, when following a number of circuit interruptions, at short time intervals, blazing oil was spewed over on the surrounding woodwork, starting a fire which eventually spread to the power house [9].

The design of this circuit breaker was extremely simple. It consisted of two wooden barrels filled with a combination of water and oil. The contacts consisted of two vertical blades connected at the top and arranged so that they would drop into the stationary contacts to close the circuit.

From these relatively humble beginnings the oil circuit breaker was refined and improved but throughout all these mutations it maintained its characteristic simplicity of construction and its capability for interrupting large currents.

Oil circuit breakers were widely used and presently there are many still in service. However, they have suffered the same fate as did the air blast circuit breaker, they have been made obsolete by the new SF_6 technology.

5.4.1 Properties of Insulating Oil

The type of oil that has been used in virtually all oil circuit breakers is one where naphthenic base petroleum oils have been carefully refined to avoid sludge or corrosion that may be produced by sulfur or other contaminants.

The resulting insulating oil is identified as type 10-C transformer oil. It is characterized by an excellent dielectric strength, by a good thermal conductivity (2.7×10^{-4} cal/sec cm °C) and by a high thermal capacity (0.44 cal/gm °C).

Some designs of oil circuit breakers take advantage of the excellent dielectric withstand capabilities of oil and use the oil not only as interrupting medium but also as insulation within the live parts of the circuit breaker and to ground.

Insulating oil at standard atmospheric conditions, and for a given contact gap, is far superior than air or SF_6 under the same conditions. However, oil can be degraded by small quantities of water and by carbon deposits that are the result of the carbonization of the oil. The carbonization takes place due to the contact of the oil with the electric arc.

The purity of the oil usually can be judged by its clarity and transparency. Fresh oil has a clear amber color, while contaminated oil is darken and there are some black deposits that show signs of carbonization. The condition of the oil normally is evaluated by testing for its withstand capability. The tests are made using a spherical spark gap with two spheres 20 mm in diameter and at a gap of 3 mm.

Fresh oil should have a dielectric capability greater than 35 kV. For used oil it is generally recommended that this capability be no less than 15 kV.

5.4.2 Current Interruption in Oil

At the time when the oil circuit breaker was invented no one knew that arcs drawn in oil formed a bubble containing mainly hydrogen and that arcs burning in a hydrogen atmosphere tend to be extinguished more readily than arcs burning in other types of gases. The choice of oil was then indeed a fortuitous choice that has worked very well over the years.

When an arc is drawn in oil the contacting oil surfaces are rapidly vaporized due to the high temperature of the arc, which as we already know is in the range of 5,000 to 15,000°K. The vaporized gas then forms a gas bubble, which totally surrounds the arc.

It has been observed that the approximate composition of this bubble is 60 to 80% hydrogen, 20% acetylene (C_2H_2) and the remainder consists of smaller proportions of methane and other gases.

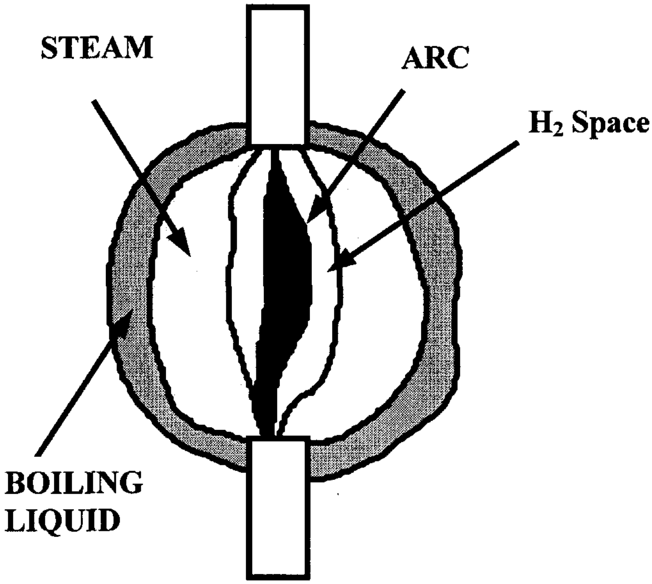

Figure 5.18 Gas bubble produced by an arc that is surrounded by oil.

Within the gas bubble, shown in Figure 5.18, there are three easily identifiable zones. In the innermost zone, which contains the dissociated gases and is the one in direct contact with the arc, it has been observed that the temperature drops to between 500 to 800 Kelvin. This gaseous zone is surrounded by a vapor zone where the vapor is superheated in its inside layers and is saturated at the outside layers. The final identifiable zone is one of boiling liquid where at the outside boundary the temperature of the liquid is practically equal to the relative ambient temperature.

Considering that the arc in oil circuit breakers is burning in a gaseous atmosphere it would be proper to assume that the theories of interruption developed for gas circuit breakers are also applicable to the oil circuit breaker. This assumption has been proven to be correct and therefore the performance of both gas blast circuit breakers as well as oil circuit breakers can be evaluated by applying the theories of arc interruption that were presented in Chapter 1.

It has been demonstrated that hydrogen is probably the ideal gas for interruption, but the complications for the safe handling of the gas and cost of a gas recovery system combine to make its application impractical.

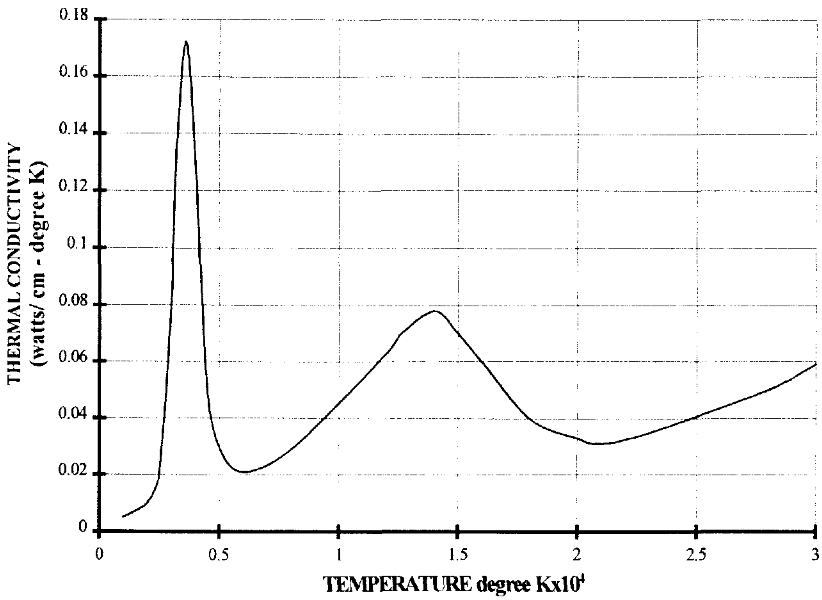

Figure 5.19 Thermal conductivity of hydrogen.

Even though comparatively speaking the dielectric strength of hydrogen is not particularly high, its reignition voltage is 5 to 10 times higher than that of air. Hydrogen also has a very high thermal conductivity that is faster during the period of gas dissociation, as shown in Figure 5.19, which results in a more rapid cooling and deionizing of the arc.

5.4.3 Types of Oil Circuit Breakers

In the earlier designs of oil circuit breakers the interrupters consisted of only a plain break and no consideration was given to include special devices to contain the arc or to enhance the arc extinguishing process. In those early designs the arc was merely confined within the walls of a rather large oil tank and deionization was accomplished by (a) elongation of the arc, (b) by the increased pressure produced by the heating of the oil in the arc region and (c) by the natural turbulence that is set by the heated oil. This plain break circuit breaker concept is illustrated in Figure 5.20.

To attain a successful interruption, under these conditions, it is necessary to develop a comparatively long arc. However, long arcs are difficult to control, and in most cases this leads to long periods of arcing.

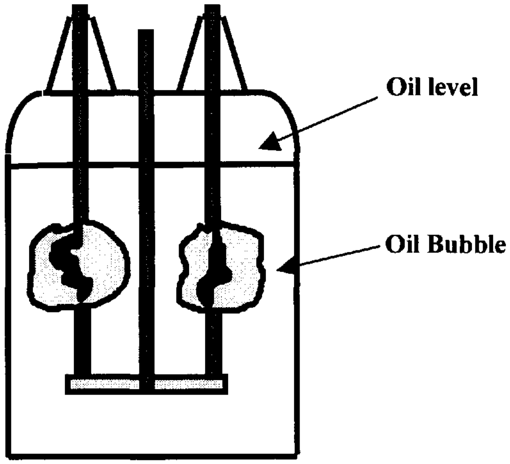

Figure 5.20 Outline of a plain break oil circuit breaker.

The random combinations of long arcs, which translate into high arc voltages, accompanied by long arcing times make unpredictable the amount of arc energy that has to be handled by the circuit breaker. This unpredictability presents a problem because it is not possible to design a device that can handle such a wide and non-well-defined range of energy.

Plain break oil circuit breakers were generally limited on their application to 15 kV systems and maximum fault currents of only about 200 amperes. Moreover, these circuit breakers were good only in those situations where the rate of rise of the recovery voltage was low.

The development of the explosion chamber, or interrupting pot, constituted a significant breakthrough for oil circuit breakers. It led to the designs of the so called "suicide breakers." Basically the only major change made on the plain circuit breaker design was the addition of the explosion pot, which is a cylindrical container fabricated from a mechanically strong insulating material. This cylindrical chamber is mounted in such a way as to fully enclose the contact structure. At the bottom of the chamber there is an orifice through which the moving contact rod is inserted.

The arc, as it was done before, is drawn across the contacts, but now it is contained inside the interrupting pot and thus the hydrogen bubble is also contained inside the chamber. As the contacts continue to move and whenever the moving contact rod separates itself from the orifice at the bottom of the chamber an exit similar to a nozzle becomes available for exhausting the hydrogen that is trapped inside the interrupting chamber. A schematic drawing of this design is included in Figure 5.21.

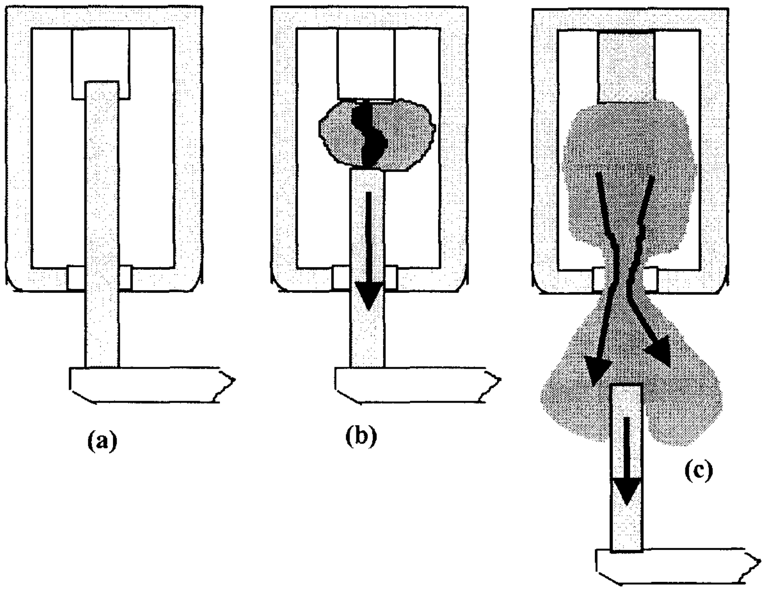

Figure 5.21 Outline of an explosion chamber type of oil interrupter. (a) Contacts closed. (b) Arc is initiated as contacts move. (c) Gas escapes through interrupter pot opening.

One of the disadvantages of this design is its sensitivity to the point on the current wave where the moving contact rod is separated from the interrupter chamber. If the first current zero occurs too early before the contact leaves the bottom orifice, then the interrupter must wait for the next current zero which may come a relatively long time after the contact has left the pot and consequently when the pressure inside the pot has decayed to an ineffective value due to the venting through the bottom orifice.

Another drawback of this interrupter chamber is its dependency on current magnitude. At high values of current the corresponding generated pressure is high and may even reach levels that would result in the destruction of the chamber. Sometimes the high pressure has a beneficial quasi-balancing effect because the high pressure tends to reduce the arc length and the interrupting time, thus decreasing the arc energy input. However, with lower values of current, the opposite occurs, the generated pressures are low and the arcing times increase until a certain critical range of current, reached where it is difficult to achieve interruption. This current level is commonly identified as the "critical current."

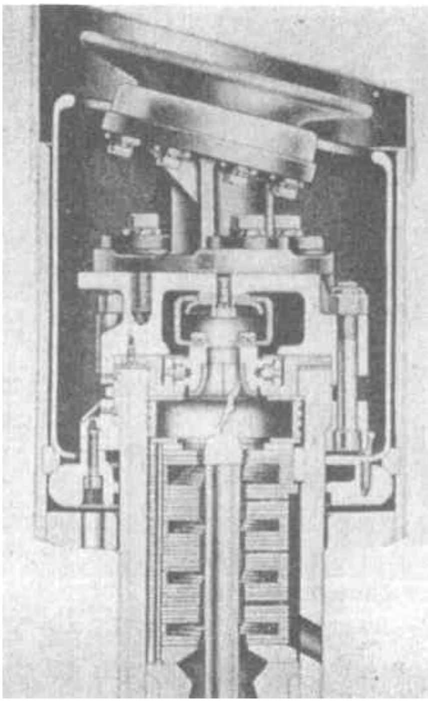

Figure 5.22 Cross baffle interrupter chamber.

Among the alternatives developed to overcome these limitations is the inclusion of pressure relief devices to limit the pressure due to the high currents. For the low current problem, the impulse circuit breaker was developed. This design concept provides a piston pump intended to squirt oil into the contacts at the precise time when interruption is taking place.

To reduce the sensitivity to the contact position at current zero the cross baffle interrupter chamber design was created. This design rapidly gained popularity and it became the preferred design for all the later vintage oil circuit breakers. A typical interrupting chamber of this type is shown in Figure 5.22.

The design consists of a number of specially designed insulated plates that are stacked together to form a passage for the arc that is alternately restricted and then laterally vented, as shown in Figure 5.23. This design permits the lateral venting of the pressure generated inside of the chamber. This arrangement subjects the arc to a continuous strong cross flow which has proven to be beneficial for extinguishing the arc.

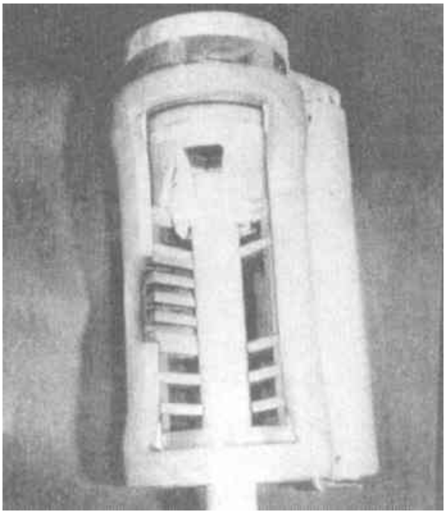

Figure 5.23 Oil circuit breaker interrupting chamber showing lateral vents.

Further developments of the interrupting chambers led to some designs that incorporated cross blast patterns, while others included what is known as compensating chambers where an intermediate contact is used to establish the arc sequentially. The first contact draws the arc in an upper chamber which preheats the oil prior to opening the second contact.

A typical relationship between the arcing time as a function of the interrupted current and as a function of the system voltage was established by F. Kesselring [10] and is shown in Figure 5.24 (a) and (b).

5.4.4 Bulk Oil Circuit Breakers

The main distinguishing characteristic of bulk oil circuit breaker types is the fact that these circuit breakers use the oil not only as the interrupting medium but also as the primary means to provide electrical insulation.

The original plain break oil circuit breakers obviously belonged to the bulk oil circuit breaker type. Later, the newly developed interrupting chambers were fitted to the existing plain break circuit breakers. Generally this adaptation did not required that any significant modifications be made to the circuit breaker structure and especially to the oil tank. This simple fact, coupled to the good acceptance this type of design had enjoyed, made the bulk oil type concept one of the preferred choices, especially in the US; and the bulk oil circuit breaker simply continued to be fabricated.

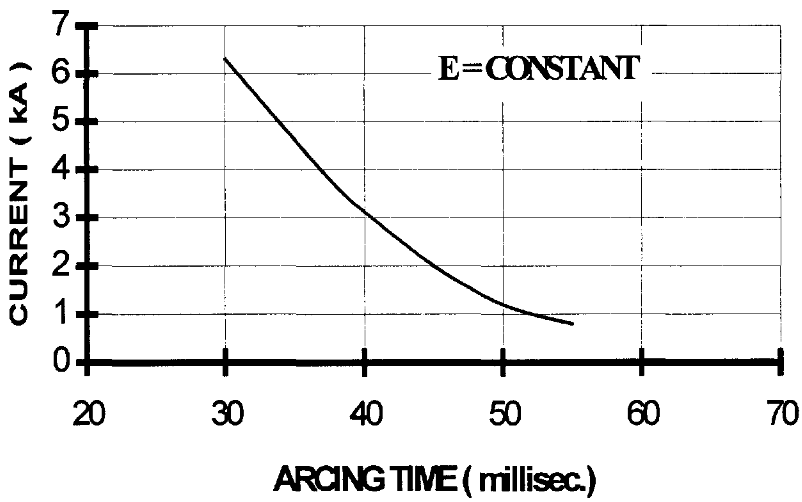

Figure 5.24 (a) Oil circuit breaker arcing time as function of current at constant voltage.

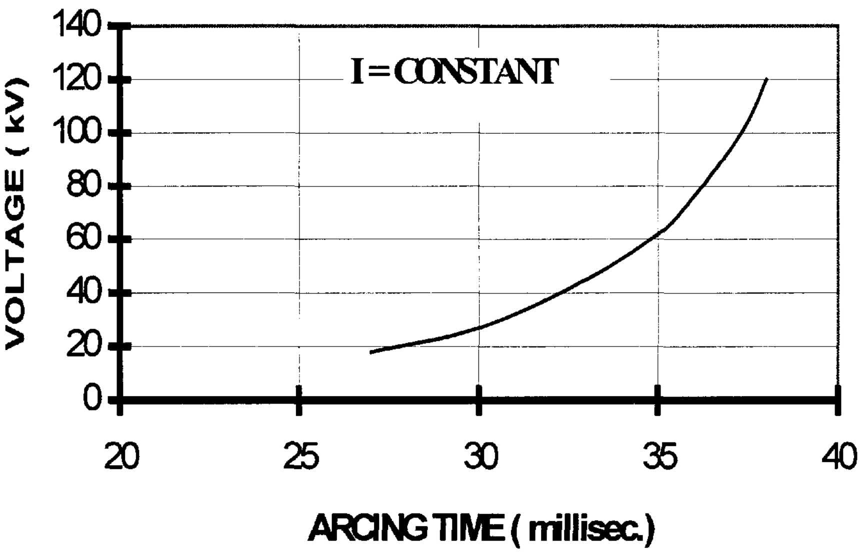

Figure 5.24 (b) Oil circuit breaker arcing time as function of voltage at constant current.

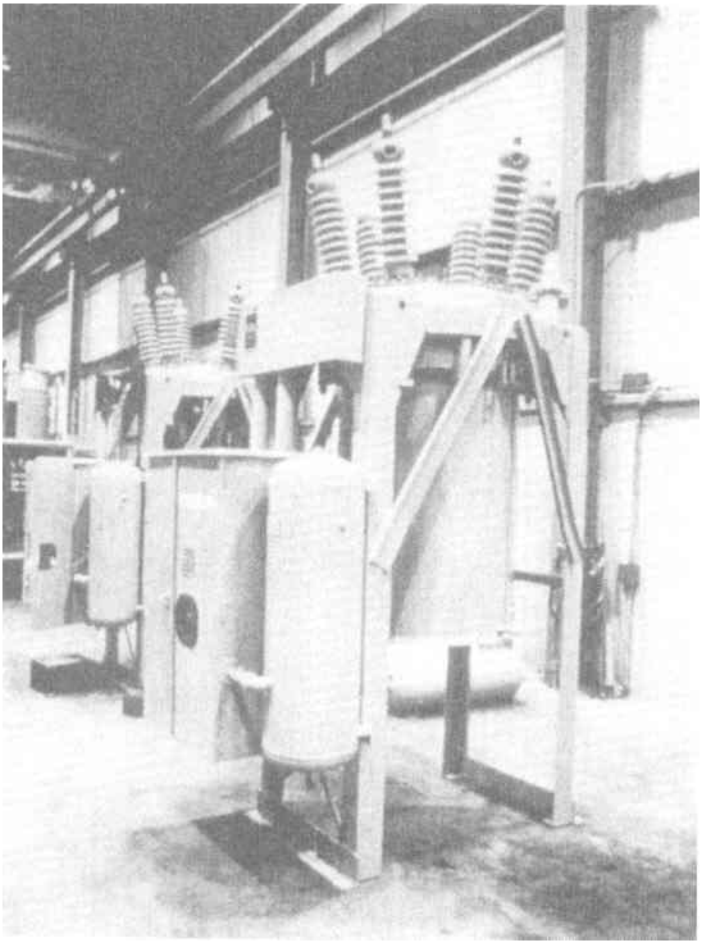

Figure 5.25 (a) 15 kV single tank oil circuit breaker.

In many cases, at voltages that generally extended up to 72.5 kV all three poles were enclosed into a single tank of oil. However, a number of circuit breakers in the medium voltage range had three independent tanks, as did those circuit breakers with voltage ratings greater than 145 kV. The three poles were gang operated by a single operating mechanism. The single and the multiple tank circuit breaker designs are shown in Figure 5.25 (a) and (b).

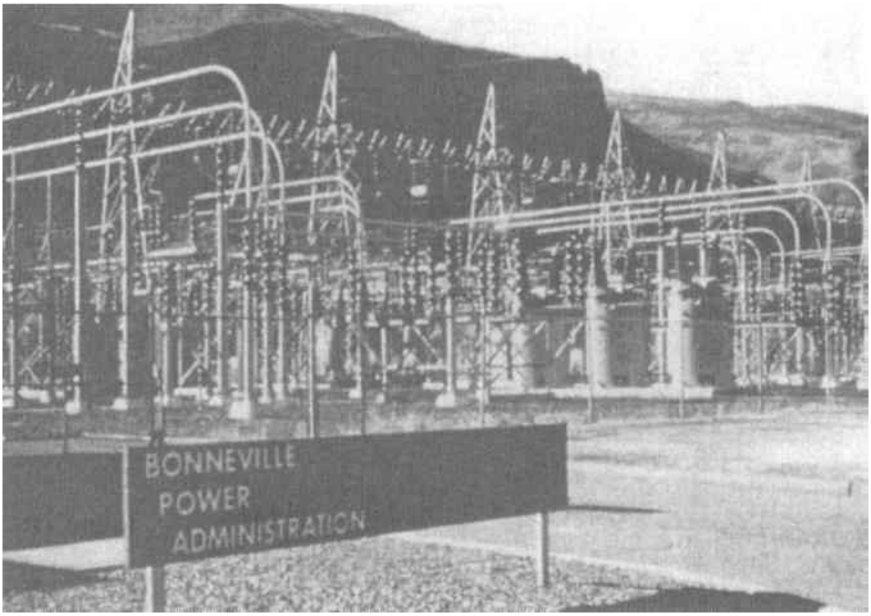

Figure 5.25 (b) 230 kV multi-tank oil circuit breaker.

To meet the insulating needs of the equipment, and depending on the magnitude of the application voltage, adequate distances must be provided between the live parts of the device and the grounded tank containing the insulating oil. Consequently this type of design required large tanks and large volumes of oil, for example for a 145 kV circuit breaker approximately 12,000 liters, or about 3,000 gallons of oil were required, and for a 230 kV circuit beaker the volume was increased to 50,000 liters, or approximately 13,000 gallons.

Not only the size of the circuit breakers was very large but also the foundation pads where the circuit breakers were mounted had to be big and quite strong. In order to withstand the impulse forces developed during interruption it is usually required that the pad be capable of supporting a force equal to up to 4 times the weight of the circuit breaker including the weight of the oil. This in the case of a 245 kV circuit breaker amounted to a force of about 50 tons.

5.4.5 Minimum Oil Circuit Breakers

Primarily in Europe, because of the need to reduce space requirements and the scarcity and high cost of oil, a type of circuit breaker that used very small volumes of oil was developed. This circuit breaker is the one known by any of the following names: minimum oil, low oil content, or oil poor circuit breaker.

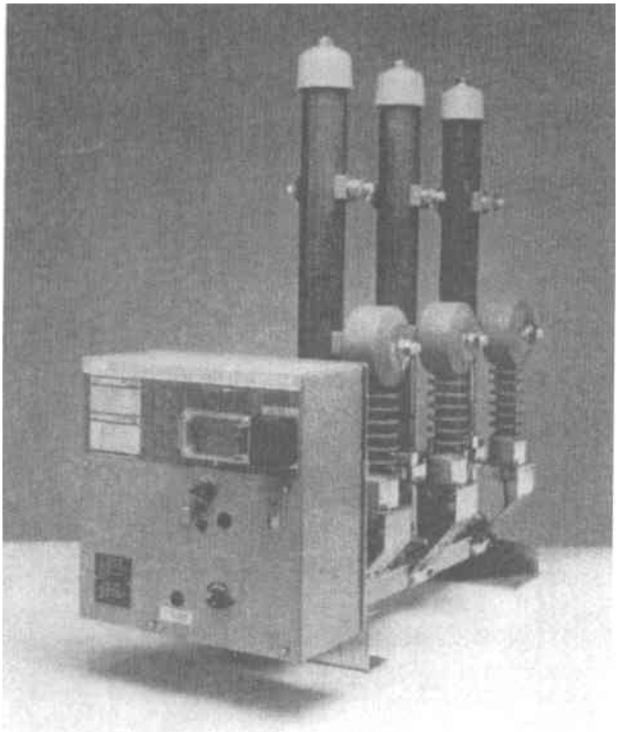

Figure 5.26 Typical 15 kV minimum oil circuit breaker.

The main difference between the minimum oil and the bulk oil circuit breakers is that minimum oil circuit breakers use oil only for the interrupting function while a solid insulating material is used for dielectric purposes, as opposed to bulk oil circuit breakers where oil serves both purposes.

In minimum oil circuit breakers a small oil filled, arc interrupting chamber is supported within hollow insulators. These insulators are generally fabricated from reinforced fiberglass for medium voltage applications and from porcelain for the higher voltages

The use of insulating supports effectively qualify this design as a live tank circuit breaker. By separating the live parts from ground by means of the insulating support the volume of oil required is greatly decreased as it can be seen in Figure 5.26 where a typical 15 kV low oil circuit breaker is shown.

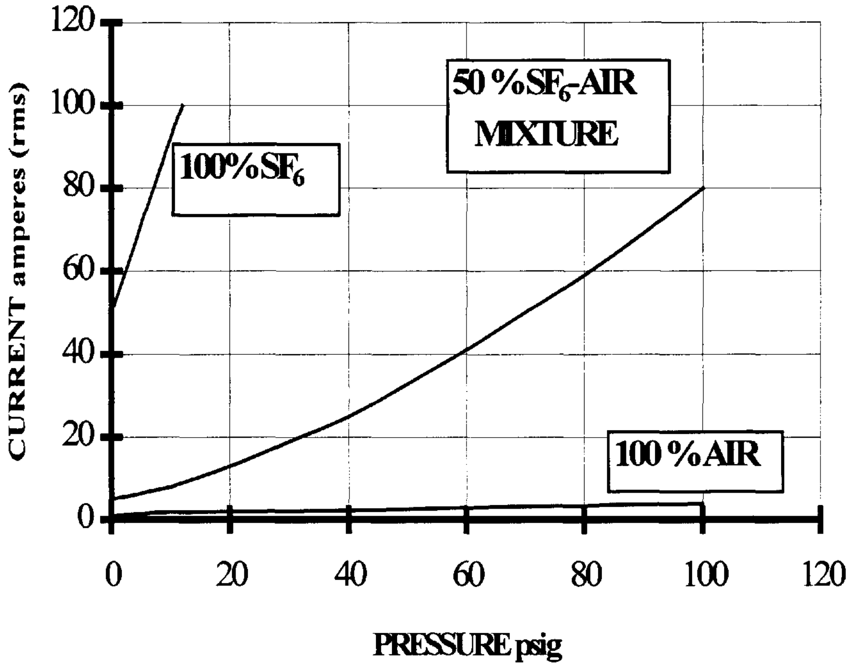

Figure 5.27 Comparison of interrupting capability between SF_6 and air (from ref. 12).

5.5 SULFURHEXAFLUORIDE

Considering the fact that oil and air blast circuit breakers have been around for almost one hundred years; sulfurhexafluoride circuit breakers are a relative newcomer, having been commercially introduced in 1956.

Although SF_6 was discovered in 1900 by Henry Moissan [11], the first report of investigations made exploring the use of SF_6 as an arc quenching medium was published in 1953 by T. E. Browne, A. P. Strom and H. J. Lingal [12]. These investigators made a comparison of the interrupting capabilities of air and SF_6 using a plain break interrupter.

The published results showing the superiority of SF_6 were simply astounding. As it can be seen in Figure 5.27 SF_6 was 100 times better than air. In the same report it was shown that the addition of even moderate rates of gas flow increased the interrupting capability by a factor of 30.

SF_6 circuit breakers, in their relatively short existence already have come to completely dominate the high voltage circuit breaker market and in the process they have made obsolete the air blast and oil technologies. Almost without exception SF_6 circuit breakers are used in all applications involving system voltages anywhere in the range of 72.5 kV to 800 kV.

In medium voltage applications, from 3 kV and up to about 20 kV, SF_6 has found a worthy adversary in another newcomer, the vacuum circuit breaker. Presently neither technology has become the dominant one, although there are strong indications that for medium voltage applications vacuum may be gaining an edge.

5.5.1 Properties of SF_6

SF_6 is a chemically very stable, non-flammable, non-corrosive, non-poisonous, colorless and odorless gas. It has a molecular weight of 146.06 and is one of the heaviest known gases. The high molecular weight and its heavy density limits the sonic velocity of SF_6 to 136 meters per second which is about one third that of the sonic velocity of air.

SF_6 is an excellent gaseous dielectric which, under similar conditions, has more than twice the dielectric strength of air and at three atmospheres of absolute pressure it has about the same dielectric strength of oil (Figure 5.28). Furthermore, it has been found that SF_6 retains most of its dielectric properties when mixed even with substantial proportions of air or nitrogen.

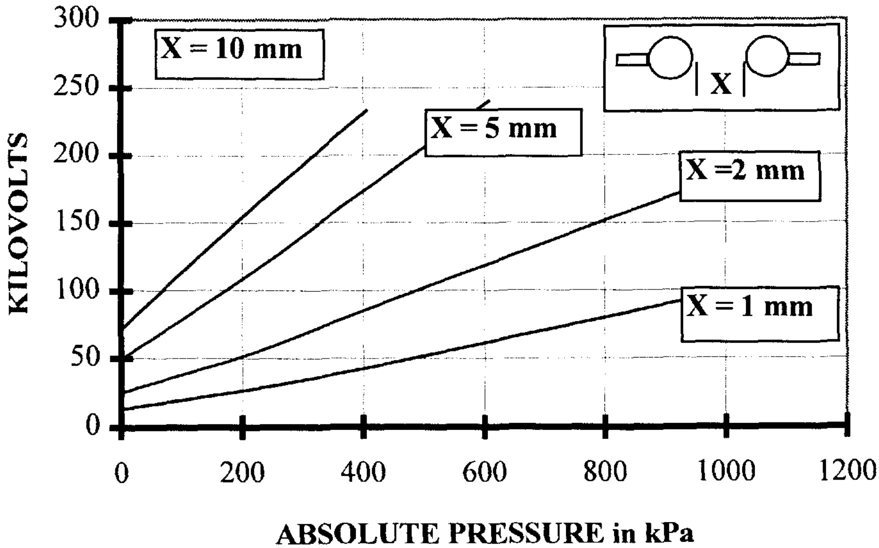

Figure 5.28 Dielectric strength of SF_6 as function of pressure.

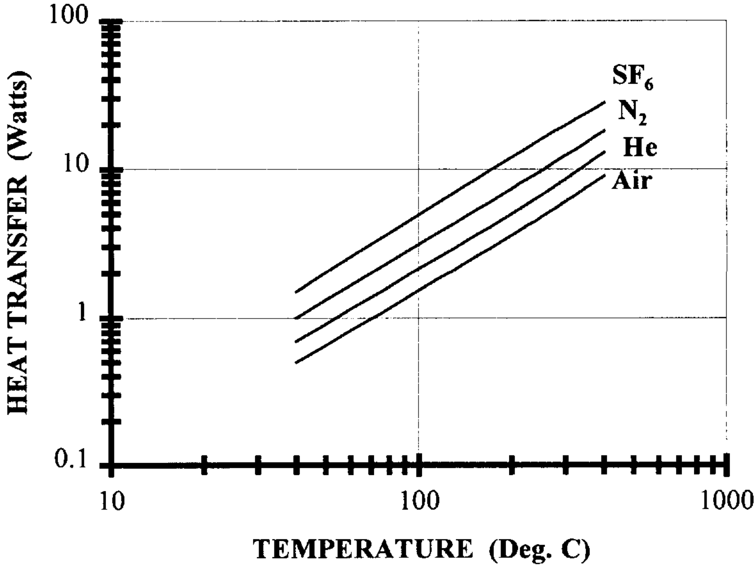

Figure 5.29 Heat transfer characteristics of SF_6.

Because of its superior heat transfer capabilities, which are shown in Figure 5.29, SF_6 is better than air as a convective coolant. It should be noted that while the thermal conductivity of helium is ten times greater than that of SF_6, the later has better heat transfer characteristics due to the higher molar heat capacity of SF_6 which together with its low gaseous viscosity enables it to transfer heat more effectively.

SF_6 is not only a good insulating gas but it is also an efficient electron scavenger due to its electron affinity or electronegativity. This property is primarily responsible for its high electric breakdown strength, but it also promotes the rapid recovery of the dielectric strength around the arc region following the extinction of the arc.

Because of its low dissociation temperature and its high dissociative energy SF_6 is an excellent arc quenching medium. Additionally, the outstanding arc extinguishing characteristics of SF_6 are also due to the exceptional ability of this gas to recover its dielectric strength very rapidly following a period of arcing, and to its characteristically small time constant which dictates the change of conductance near current zero.

The first characteristic is important for bus terminal faults while the second is essential for the successful interruption of short line faults.

5.5.2 Arc Decomposed By-Products

At temperatures above 500°C, SF_6 will begin to dissociate. The process of dissociation can be initiated by exposing SF_6 to a flame, electrical sparking, or an electric arc. During this process the SF_6 molecules will be broken down into sulfur and fluorine ions at a temperature of about 3000°C.

It should be recalled that during the interruption process the core of the arc will reach temperatures well in excess of 10,000 Kelvin; however, after the arc is extinguished and the arc region begins to cool down and when the temperature drops below approximately 1,000°C the gas will begin to recombine almost totally, and only a small fraction will react with other substances.

The small amounts of gas that do not recombine react with air, with moisture, with the vaporized electrode metal and with some of the solid materials that are used in the construction of the circuit breaker. These decomposition by-products may be gaseous or solid, but they essentially consist of lower sulfur fluorides, and of metal fluorides of which the most notable are CuF_2, AlF_3, WF_6, and CF_4.

Among the secondary sulfur fluoride compounds that are formed [13] are S_2F_2 and SF_4, but they quickly react with moisture to yield hydrogen fluoride (HF), sulfur dioxide (SO_2) and other more stable oxyfluorides such as thionyl fluoride (SOF_2).

The metallic fluorides are usually present in the form of a fine non-conductive dust powder that is deposited on the walls and in the bottom of the circuit breaker enclosure. In the case of copper electrodes the solid substances appear as a milky white powder that acquires some blue tinges when exposed to the atmosphere due to a reaction which yields a dehydrated salt.

5.5.2.1 Corrosive Effects of SF_6

Sulfurhexafluoride in its pure and uncontaminated form is a non-reactive gas and consequently there is no possibility for any type of corrosion that may be directly attributable to SF_6.

When the by-products of arced SF_6 come in contact with moisture some corrosive electrolytes may be formed. The most commonly used metals generally do not deteriorate and remain very stable. However, nylon, phenolic resins, glass, glass reinforced materials and porcelain can be severely affected. Other types of insulating materials such as polyurethane, Teflon (PTEE) and epoxies, either of the bisphenol A or the cycloaliphatic type, are unaffected.

It is therefore very important to take appropriate measures in the selection of materials and the utilization of protective coatings.

During normal operation corrosion can effectively be prevented by providing appropriate means for the elimination of moisture and by the use of commercially available desiccants.

5.5.2.2 By-Products Neutralization

The lower fluorides and many of the other by-products are effectively neutralized by soda lime (a 50-50 mixture of $NaOH + CaO$), by activated alumina (especially, dried Al_2O_3), or by molecular sieves.

The preferred granule size for soda lime or alumina is 8 to 12 mesh, but these do not exclude the possible use of other mesh sizes. The recommended amount to be used is approximately equal to 10% of the weight of the gas.

Removal of the acidic and gaseous contaminants is accomplished by circulating the gas through filters containing the above described materials. These filters can either be attached to the circuit breaker itself or they may be installed in specially designed but commercially available gas reclamation carts.

If it is desired to neutralize SF_6 which has been subjected to an electric arc, it is recommended that the parts be treated with an alkaline solution of lime ($Ca(OH)_2$), sodium carbonate (Na_2CO_3), or sodium bicarbonate ($NaHCO_3$).

5.5.3 SF_6 Environmental Considerations

The release of human made materials into the atmosphere has created two major problems. One is the depletion of the stratospheric ozone layer and the other is the global warming or "greenhouse effect."

5.5.3.1 Ozone Depletion Agent

SF_6 does not contribute to the ozone depletion for two reasons: First because due to the structure of the ultraviolet absorption spectrum of SF_6 the gas can not be activated until it reaches the mesosphere at about 60 kilometers above the earth and this altitude is far above the stratospheric one which is in the range of about 30 to 45 kilometers. The second reason is the fact that SF_6 does not contain chlorine which is the principal ozone destroying agent.

5.5.3.2 Greenhouse Effect Agent

SF_6 has been labeled as the most potent greenhouse gas ever evaluated by the scientists of the Intergovernmental Panel on Climate Change (IPCC) [14], [15].

What makes SF_6 such a potentially powerful contributor to global warming is the fact that SF_6, like all the compounds in the fully fluorinated family, has a super stable molecular structure. This structure makes these compounds very long lived, to the extent that within human time frames these gases are indestructible.

SF_6 is a very good absorber of infrared radiation. This heat absorption characteristic combined with its long life (3,200 years) [16] has led scientists to assign an extremely high Global Warming Potential (GWP) rating to SF_6.

The GWP rating is a comparative numerical value that is assigned to a compound. The value is arrived at by integrating over a time span the radiative forcing value produced by the release of 1 kilogram of the gas in question and then dividing this value by the value obtained with a similar procedure with CO_2. Because CO_2 is considered to be the most common pollutant it has been selected as the basis of comparison for assigning GWP values to other pollutants.

The radiative forcing, according to its definition, is the change in net irradiance in watts per square meter.

The GWP values for CO_2 and for the most common fully fluorinated compounds integrated over a one hundred years time horizon are given in Table 5.1 (taken from ref. 14).

TABLE 5.1
Global Warming Potential (GWP) for most common FFC's compared to CO_2

COMPOUND	LIFETIME YEARS	GWP
CO_2	50-200	1
CF_4	50,000	6,300
C_2F_6	10,000	12,500
SF_6	3,200	24,900
C_6F_{14}	3,200	6,800

Presently the concentration of SF_6 has been reported as being only about 3.2 parts per trillion by volume (pptv). This concentration is relatively low, but it has been observed that it is increasing at a rate of about 8% per year. This means that if the concentration continues to increase at this rate, in less than 30 years the concentration could be about 50 pptv.

More realistically, assuming a worst case scenario [16], the concentration of 50 pptv is expected to be reached by the year 2100. A more optimistic estimate is 30 pptv. At these concentrations the expected global warming attributable to SF_6 has been calculated as 0.02 and 0.014°C. for the most pessimistic and the most optimistic scenarios respectively. Additional data indicate that the expected global warming due to SF_6 through the year 2010 is about 0.004°C. In comparison with an increase of 300 parts per million by volume (ppmv) of CO_2, the expected change in the global temperature is 0.8°C.

It is apparent that based on the estimated emission rates the concentration of SF_6 would be very small [17]. Nevertheless, because of the long life time of SF_6 there is a potential danger, especially if the rate of emissions were to increase rather than to reach a level value. It is therefore essential that all types of release of SF_6 into the atmosphere be eliminated or at least reduced to an absolute minimum. This can be done by strict adherence to careful gas handling procedures and proper sealing for all new product designs.

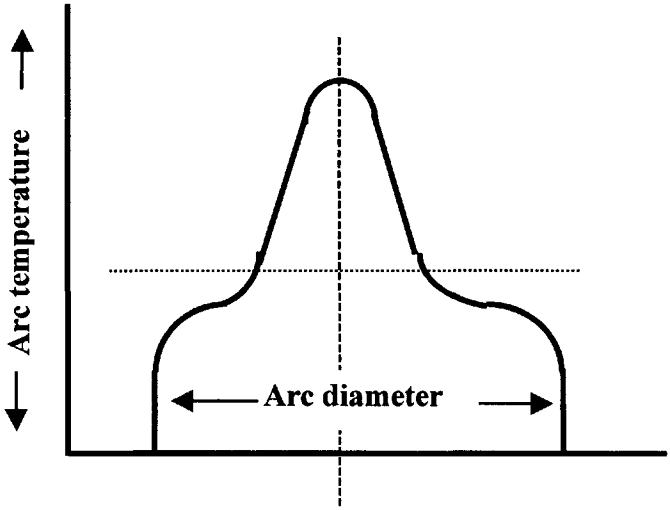

Figure 5.30 Electric arc, radial temperature profile.

5.5.4 Recycling of SF_6

The future impact of SF_6 on the atmosphere has been judged under the assumption that all the gas is always released to the atmosphere. However the SF_6 that is used in electrical equipment is not intentionally released to the atmosphere and designers of equipment always strive at finding methods, components and solutions that minimize gas leakage.

Nevertheless contamination of the gas and consequent deterioration of its capabilities can be expected under normal operating conditions.

Contamination can be produced by any of the following mechanisms:

- Improper gas handling
- Humidity and air from solid materials including desiccants
- Decomposition of gas caused by electric discharges
- Chemical reaction of decomposed materials

As stated earlier gas contamination will eventually cause deterioration of the equipment and in some cases it may even lead to complete failure. To avoid this risk it is necessary then to maintain the purity of the gas as close as possible to what is required for gas in a new condition; this is done, to some extent, using internal absorbers that help keep the contamination levels relatively low. Another benefit of using these absorbers is that maintaining a low level of contamination will also simplify the task of cleaning the gas during a recycling operation.

In most cases it is possible to perform a recycling operation on site but even in those rare cases where the level of contamination is much higher and a more complicated procedure is required to purify the gas it can be done using the services of one of the many companies that have emerged and specialize in arced SF_6 recovery. It is also likely that low users of SF_6 may find that it is not economically practical to own their own reclaiming equipment.

For SF_6 to be successfully re-used it is essential that it meet certain minimum requirements. The maximum contamination levels presently recommended [17] are:

- Less than 50 ppmv content of toxic and corrosive decomposition products
- Less than 120 ppmv humidity
- Less than 2% by volume of contamination by other gases

In those cases where SF_6 can not be properly recycled it can be safely disposed by heating the gas to a temperature above 1200° C and then scrubbing the resulting dissociated products using a wet scrubber filled with a calcium hydroxide solution.

5.5.5 Current Interruption in SF_6

As we know, the electric arc is a self-sustaining discharge consisting of a plasma that exists in an ionized gaseous atmosphere. We also know that the plasma has an extremely hot core surrounded by an atmosphere of lower temperature gases.

Figure 5.30 represents the typical temperature profile of an arc as a function of its radius, when the arc is being cooled by conduction. The figure shows that there is a relatively thin central region of very high temperature corresponding to the core of the arc. It also shows the existence of a broader, lower temperature region and the transition point between these two regions, where there is a rather sharp increase in temperature.

This characteristic temperature profile simply indicates that the majority of the current is carried by the hottest region of the arc's core which is located close to the central axis, the reason being, as we well know, that an increase in temperature corresponds to an increase in electrical conductivity.

Since the arc always tries to maintain its thermal equilibrium, its temperature will automatically adjust itself in relation to the current magnitude. However, once full ionization is attained further increases in current do not lead to increases in temperature. Nevertheless, as the current approaches zero the temperature about the core of the arc begins to drop and consequently the region starts losing its conductivity. The peak thermal conductivity of SF_6, as is seen in Figure 5.31, occurs at around 2,000°K; therefore, near current zero, when rapid cooling is needed for interruption, SF_6 is extremely effective in extinguishing the arc, simply because at this temperature electrical conductivity is very low.

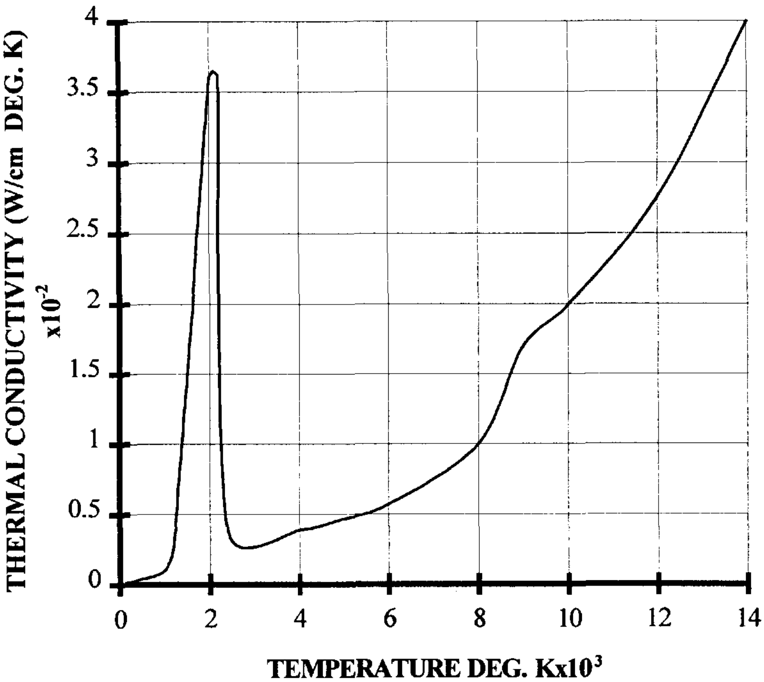

Figure 5.31 Thermal conductivity of SF_6.

At the other side of the spectrum, at high currents the thermal conductivity of SF_6 is not much different from that of other gases and therefore the arc cooling process in that region is about the same regardless of the kind of gas that is being used.

The main difference between interruption in air and in SF_6 is the temperature at which maximum thermal conductivity takes place. These temperatures are about 6,000°K for air and 2,000°K for SF_6.

This difference translates into the fact that SF_6 is capable of cooling much more effectively than air at the lower temperatures and therefore it is capable of withstanding higher recovery voltages sooner. In other words the time constant of SF_6 is considerably shorter than that of air.

The assigned time constant for SF_6 is 0.1 microseconds while for air is greater than 10 microseconds. The significance of this time constant is appreciated when consideration is given to applications where a high rate of TRV is expected, such as in the case of short line faults. Experience indeed has shown that SF_6 can withstand higher recovery rates than air.

5.5.6 Two Pressure SF_6 Circuit Breakers

The first SF_6 circuit breaker rated for application at voltages higher than 230 kV and a current interrupting capability of 25 kA was commercially introduced by Westinghouse in 1959.

The original design of this type of circuit breaker was an adaptation of the air blast and oil circuit breaker designs, and thus the axial blast approach, which was described before when discussing air blast circuit breakers, was used. Naturally, the main difference was that air had been replaced by SF_6.

The new circuit breakers were generally of the dead tank type. The construction of the tanks, together with their substantial size and strength, was quite similar to the tanks used for oil circuit breakers as it can be seen in Figure 5.32.

In many cases even the operating mechanisms that had been used for oil circuit breakers were adapted to operate the SF_6 circuit breaker.

The conscious effort made to use some of the ideas from the older technologies is understandable; after all, the industry was accustomed to this type of design and by not deviating radically from that idea made it easier to gain acceptance for the new design.

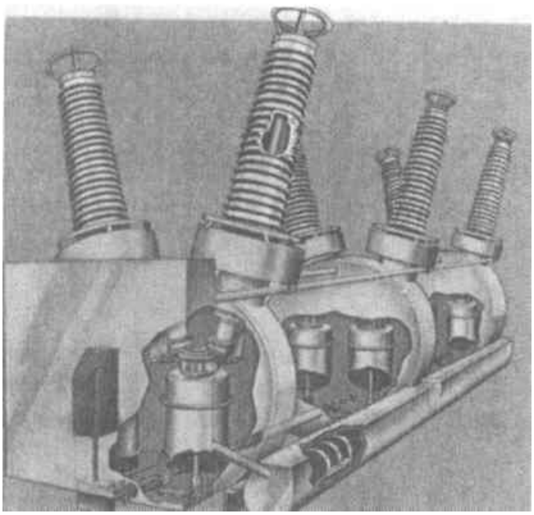

Figure 5.32 Cutaway view of an SF_6 two pressure ITE type GA circuit breaker.

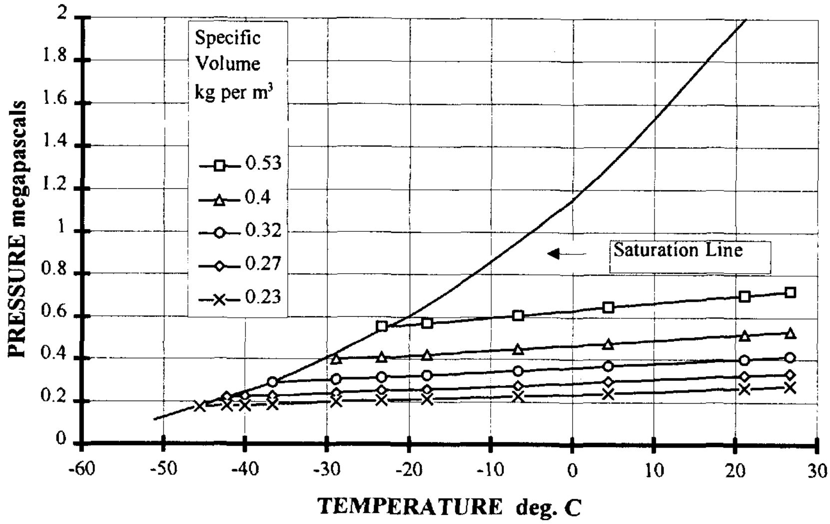

Figure 5.33 Pressure-temperature variation at constant density for SF_6.

Two pressure circuit breakers were fabricated in either a single or a three tank version, depending mainly in the assigned voltage rating of the device. Smaller high pressure reservoirs were installed next to the low pressure tanks and they were connected to blast valves that operated in synchronism with the contacts. The operating gauge pressures for these circuit breakers were generally around 0.2 MPa for the low side and 1.7 MPa for the high side (30 psig and 245 psig respectively).

The two pressure circuit breaker design prevailed in the US market until the mid-nineteen seventies. At around that time is when the single pressure circuit breakers began to match the interrupting capabilities of the two pressure circuit breakers and thus they became a viable alternative.

Cited among the advantages of the two pressure circuit breaker was that it required a lower operating energy mechanism when compared to the one that is used on single pressure circuit breaker designs. However, in the context of total energy requirements, one must take into account the energy that is spent in compressing the gas for storage and also the additional energy that is required to prevent liquefaction of the SF_6 at low ambient temperatures.

The liquefaction problem represents the main disadvantage of the two pressure circuit breaker. As it can be seen in Figure 5.33 at 1.7 MPa the gas will begin to liquefy at a temperature of approximately 13°C. To prevent liquefaction, and the consequent drop in the gas density electric heaters are installed in the high pressure reservoir.

Liquefaction of SF_6 not only lowers the dielectric capabilities of the gas but it can lead to another problem known as moisture pumping [18] which may happen because of the difference in the condensation point between air and SF_6.

The problem begins in the high pressure system when the gas liquefies in a region that is some distance away from the high pressure reservoir. If the temperature is not sufficiently low to cause condensation of whatever amount of moisture was present in that region then only the liquefied gas will flow back into the reservoir leaving the moisture behind.

Since in the mean time, the temperature of the gas in the high pressure reservoir is kept above the dew point, then the warmer gas will flow back into the circuit breaker attempting to maintain the original pressure. Whatever small amount of moisture is present in the gas contained in the reservoir it will then be transported to the region where liquefaction is taking place. As the gas liquefies again, then once more it will leave the moisture behind. This process can continue until the pressure-temperature conditions change. However, during this time, moisture can accumulate significantly at the coldest point of the gas system, thus increasing the total concentration and reducing the dielectric capability.

Other disadvantages noted are the high volumes of gas needed, the propensity for higher leak rates due to the higher operating pressures and the added complexity that results from the use of the blast valves.

5.5.7 Single Pressure SF_6 Circuit Breakers

Single pressure circuit breakers have been around at least as long as the two pressure circuit breakers have, but initially these circuit breakers were limited to applications requiring lower interrupting ratings. This limitation was due primarily to the extremely high energy output required from the operating mechanisms in order to overcome not only the puffing pressure but the pressure increase due to the release of the arc energy.

Later investigations and advanced developments provided answers that led to new designs that had greater interrupting capabilities and around the year 1965 high interrupting capacity puffer circuit breakers were introduced in Europe and in the US.

Puffer circuit breakers have been designed as either dead or live tank as illustrated in Figures 5.34 and 5.35.

Customarily, single pressure circuit breakers are described as belonging to either the puffer or the self blast family. But, in reality, all single pressure circuit breakers could be thought of as being a member of the self blast family because in either type of circuit breaker the increase in pressure that takes place inside of the interrupter is achieved without the aid of external gas compressors.

The most notable difference between these two circuit breaker types is that in puffer circuit breakers the mechanical energy provided by the operating mechanism is used to compress the gas, while self blast circuit breakers use the heat energy that is liberated from the arc to raise the gas pressure.

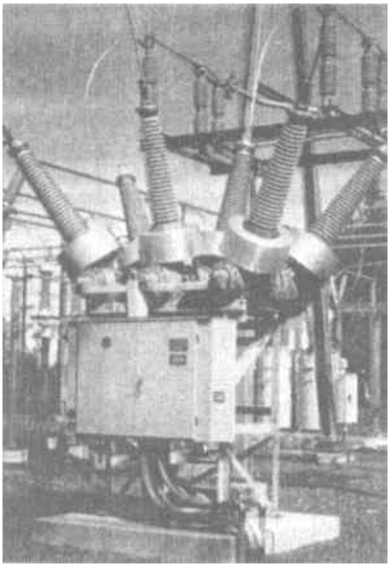

Figure 5.34 Dead tank puffer type circuit breaker ABB Power T&D.

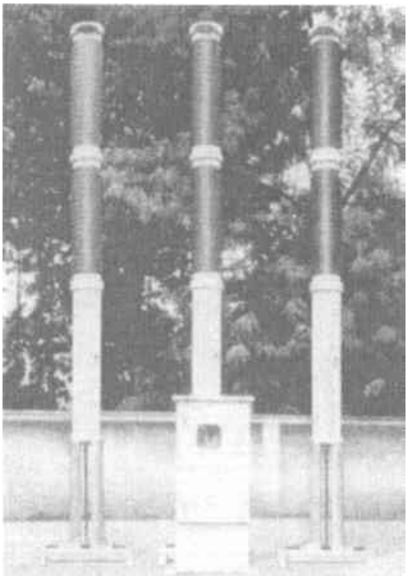

Figure 5.35 Merlin Gerin live tank puffer circuit breaker.

5.5.7.1 *Puffer Circuit Breakers*

The conceptual drawings and the operating sequence of a typical puffer interrupter is shown in Figure 5.36 (a), (b), (c), and (d). A unique characteristic of puffer interrupters is that all have a piston and cylinder combination which is assembled as an integral part of the moving contact structure.

Referring to Figure 5.36, (a) shows the interrupter in the closed position, where the volume (V) can be seen. During an opening operation the main contacts separate first, followed by the arcing contacts, Figure 5.36 (b). The motion of the contacts decrease the dead volume (V) and thus compress the gas contained within that volume.

As the contacts continue to separate the volume is further compressed, and at the instant when the arcing contact leaves the throat of the nozzle the flow of gas along the axis of the arc is initiated. It is important to recognize that at high currents the diameter of the arc may be greater than the diameter of the nozzle thus leading to the condition known as current choking. When this happens the nozzle is completely blocked and there is no flow of gas. Consequently, the pressure continues to rise due to the continuous change of the volume space V and to the heat energy that is extracted from the arc by the trapped gas.

It is not uncommon to see that when interrupting large currents, especially those corresponding to a three phase fault, the opening speed of the circuit breaker is slowed down considerably due to the thermally generated pressure acting on the underside of the piston assembly.

However, when the currents to be interrupted are low, the diameter of the arc is small and therefore is incapable of blocking the gas flow and as a result there is a lower pressure available. For even lower currents, as is the case when switching capacitor banks of just simply a normal load current, it is generally necessary to precompress the gas before the separation of the contacts. This is usually accomplished by increasing the penetration of the arcing contact.

The duration of the compression stroke should always be carefully evaluated to ensure that there is adequate gas flow throughout the range of minimum to maximum arcing time.

In most cases, depending on the circuit breaker design, the minimum arcing time is in the range of 6 to 12 milliseconds. Since the maximum arcing time is approximately equal to the minimum arcing time plus one additional major asymmetrical current loop, which has an approximate duration of 10 milliseconds, then the range of the maximum arcing time is 16 to 22 milliseconds.

What is significant about the arcing time duration is that since interruption can take place at either of these times, depending only on when a current zero is reached, then what is necessary is that the appropriate pressure be developed at that proper instant where interruption takes place.

It is rather obvious that at the maximum arcing time, the volume has gone through the maximum volume reduction and has had the maximum time exposure to the heating action of the arc and thus the gas pressure is expected to be higher.

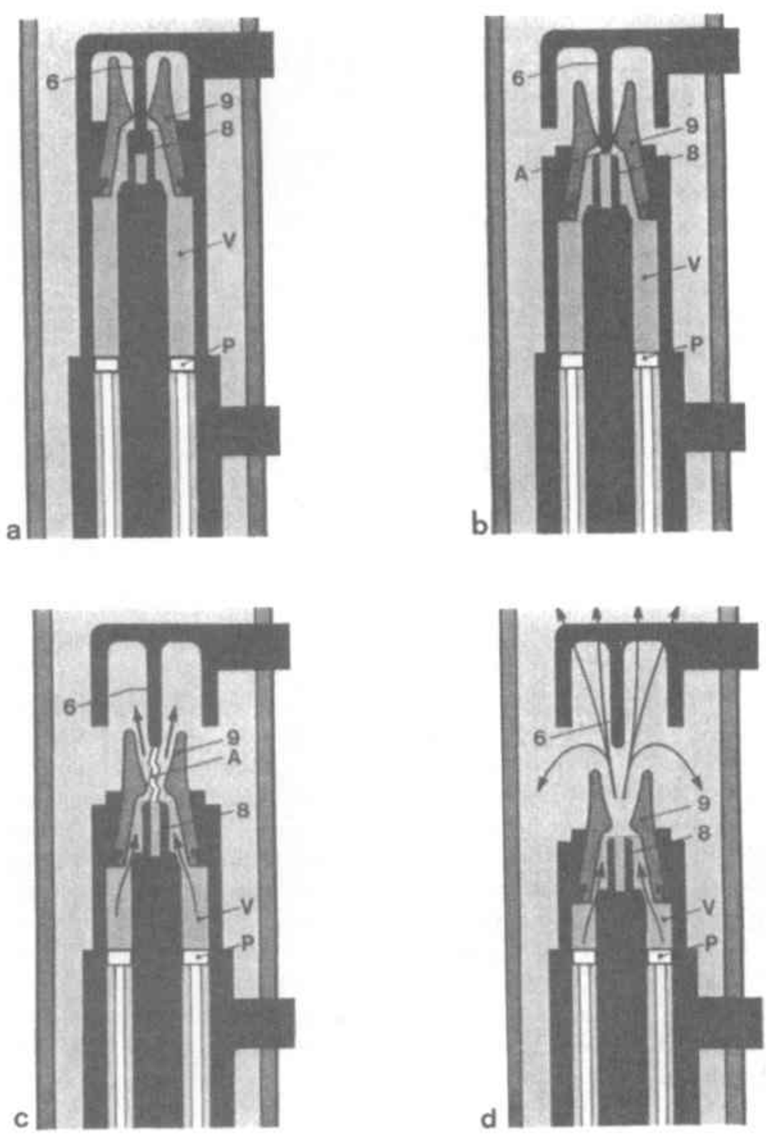

Figure 5.36 Puffer circuit breaker principle; (a) circuit breaker closed, (b) start of opening, main contacts separate, (c) arcing contacts separating gas flow starts, (d) interruption completed. A = Arc, V = Puffer Volume, P = Puffer Piston, 6 & 8 = Arcing Contacts, 9 = Interrupter Nozzle.

For the minimum arcing time condition, both the compression and the heating of the gas are minimal and therefore the pressure generated is relatively low.

It follows from the above discussion that the critical gas flow condition for a puffer interrupter is around the region of the minimum arcing time. However, it also points out that consideration must be given to the opening speed of the circuit breaker in relation to its opening stroke in order to assure that the assumed maximum arcing time is always less than the total travel time of the interrupter.

It was mentioned before that when interrupting large currents in a three phase fault, there is a tendency for the circuit breaker to slow down and even to stall somewhere along its opening stroke. This slowing down generally assures that the current zero corresponding to the maximum arcing time is reached before the circuit breaker reaches the end of its opening stroke. However, when interrupting a single phase fault that is not the case. That is, because during a single phase fault the energy input from the fault current is lower which represents a lower generated pressure and so the total force that is opposing the driving mechanism is much lower. Therefore it is quite important to carefully evaluate the single phase operation to assure that there is a sufficient overlap between the stroke and the puffing action and the maximum arcing time of the circuit breaker.

5.5.7.2 Self Blast Circuit Breakers

Self blast circuit breakers take advantage of the thermal energy released by the arc to heat the gas and to raise its pressure. In principle the self blast circuit breaker idea is quite similar to the concept of the explosion pot used by oil circuit breakers. The arc is drawn across a pair of contacts that are located inside of an arcing chamber and the heated high pressure gas is released alongside of the arc after the moving contact is withdrawn from the arcing chamber.

In some designs to enhance the interrupting performance, in the low current range, a puffer assist is added. In other designs a magnetic coil is also included [19]. The object of the coil is to provide a driving force that rotates the arc around the contacts providing additional cooling of the arc as it moves across the gas. In addition to cooling the arc the magnetic coil also helps to decrease the rate of erosion of the arcing contacts and thus it effectively extends the life of the interrupter. In some designs a choice has been made to combine all of these methods for enhancing the interruption process and in most of the cases this has proven to be a good choice. A cross-section of a self blast interrupter pole equipped with a magnetic coil is included in Figure 5.37.

5.5.8 Pressure Increase of SF_6 Produced by an Electric Arc

The pressure increase produced by an electric arc burning inside of a small sealed volume (constant volume) filled with SF_6 gas can be calculated with a reasonable degree of accuracy [20] using the curve given in Figure 5.38.

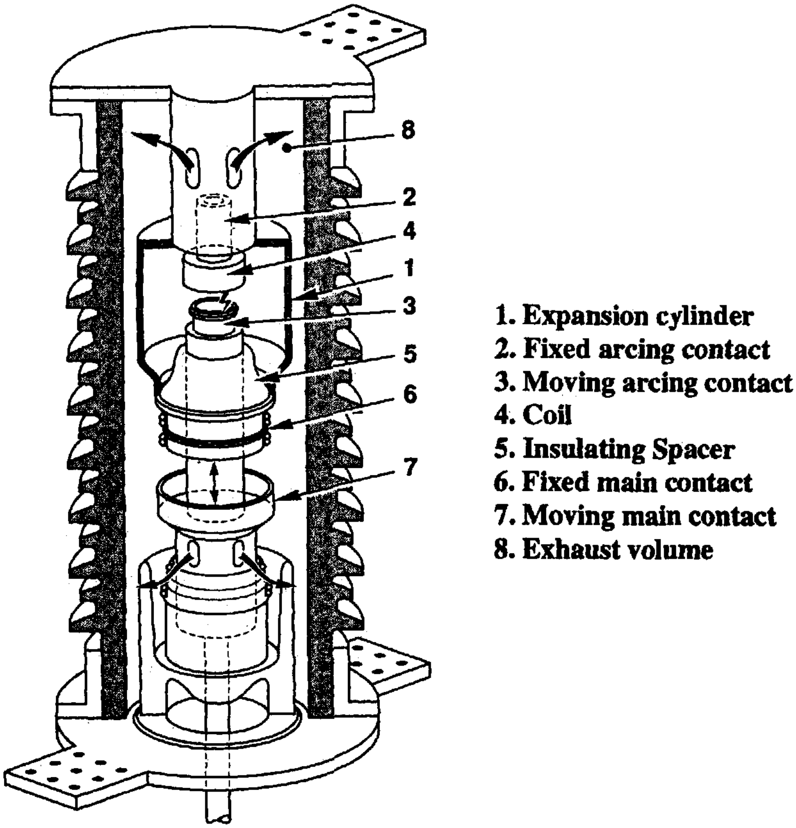

Figure 5.37 Outline of a self blast circuit breaker pole.

The curve was obtained by solving the Beattie-Bridgman equation, and by assuming a constant value of 0.8 Joules per gram-degree C for the heat capacity at constant volume (C_v). It is of course this assumption which will introduce some errors because the value of C_v increases with temperature. However the results can be corrected by multiplying the change by the ratio of the assumed C_v to the actual C_v. Values of C_v as a function of temperature are given in Figure 5.39.

To calculate the approximate increase in pressure produced by arcing the following procedure may be used.

1. Estimate the arc energy input to the volume. The energy input will be approximately equal to the product of the average arc voltage times the rms value of the current times the arc time duration.
   For a more accurate calculation the following expression may be used:

$$Q_a = \int_0^t E_a I_m \sin \omega t \, dt$$

where:

Q_a = Arc Energy input in Joules
E_a = Arc Voltage
$I_m \sin \omega t$ = Current being interrupted
t = arcing time

2. Find the value of the quotient of the arc energy input, divided by the volume, in cubic centimeters, of the container.

3. Find the gas density for a constant volume at normal gas filling conditions using the ideal gas law which says:

$$\rho = \frac{M \times p}{R \times T} \quad \text{in grams per cubic centimeter}$$

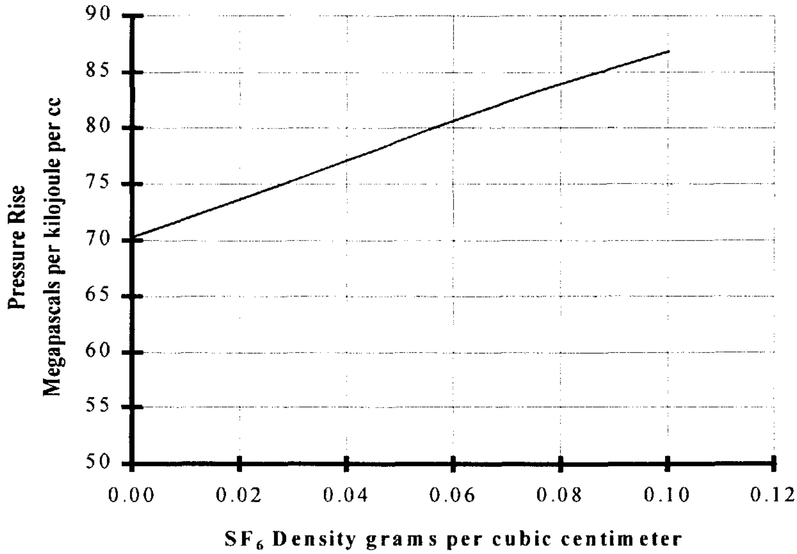

Figure 5.38 Pressure increase for a constant SF_6 volume produced by arcing.

where

M = molecular weight of SF_6 = 146 gm
P = absolute pressure in kiloPascal
R = gas constant = 80.5 c.c. - kiloPascal per mole - °K
T = temperature in degree Kelvin

4. Using the just calculated density extract the factor for the pressure rise fromFigure 5.38 and multiply it by the energy per unit volume obtained in line 1 above.

5.5.9 Parameters Influencing SF_6 Circuit Breaker Performance

Pressure, nozzle diameter, and rate of change of current were the parameters chosen before as the base for evaluating the recovery capabilities of air blast circuit breakers. To facilitate the comparisons between the two technologies the same parameters have now be chosen for SF_6 interrupters and the results are shown graphically in Figures 5.40, 5.41 and 5.42 [21].

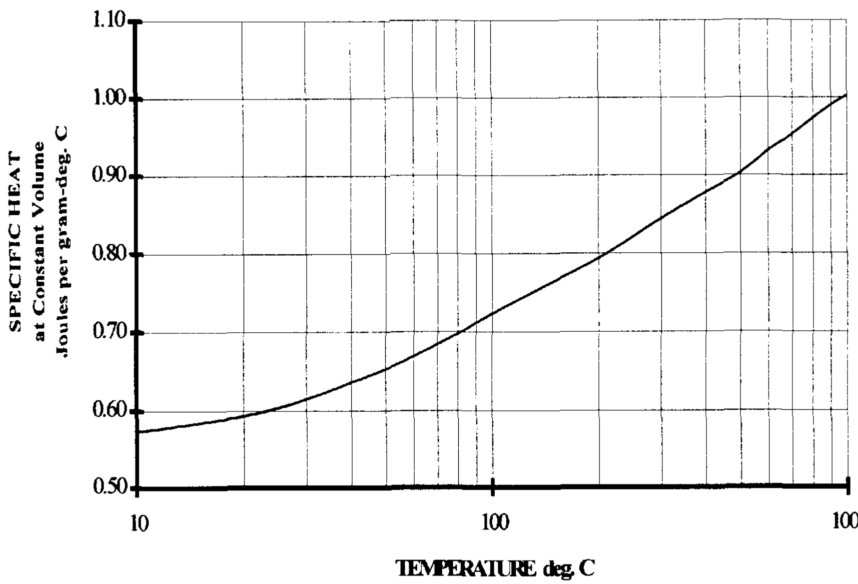

Figure 5.39 Coefficient of heat capacity C_V for SF6 at constant volume.

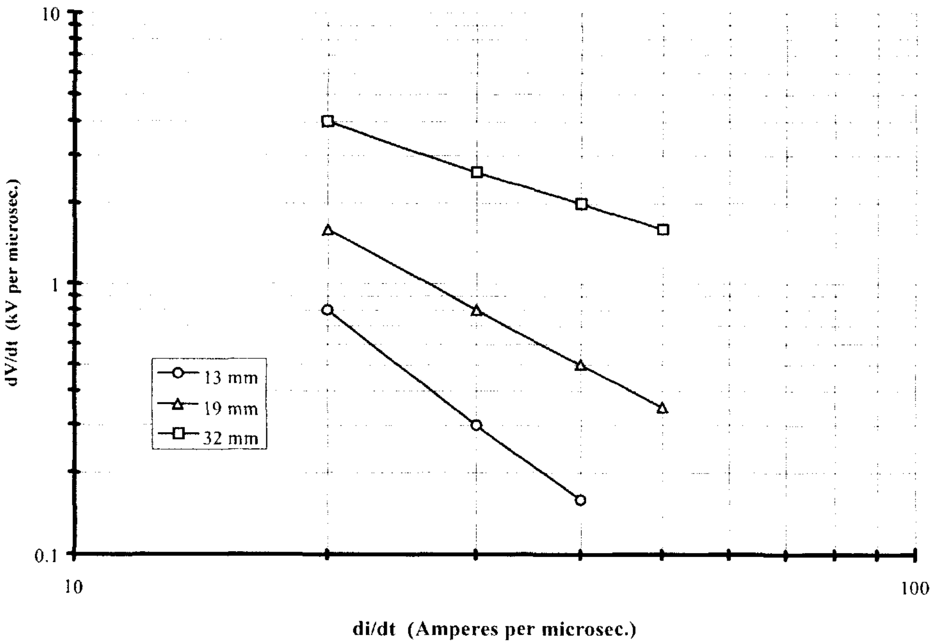

Figure 5.40 Interrupting relationship between current and voltage for various nozzle diameters.

Once again, the significance of the performance relationships which are shown in the above figures lies not in their absolute values but in the trends that they predict. In Figure 5.40, for example, it is easy to see what is intuitively clear, which is that in order to interrupt larger currents, a larger nozzle diameter is required. It can also be seen the effects of the nozzle diameter and current magnitude; the smaller the current, the lesser the influence of the nozzle diameter. The curve even suggests that there may be a converging point for the nozzle diameters, where, at a certain level of smaller currents, the recovery capabilities of the interrupter remains the same regardless of the nozzle size.

Figure 5.41 shows the dependency of the recovery voltage during the thermal recovery period in relation to the rate of change of current. It is important to note that the slope of each of the lines is remarkably close considering that they represent three independent sources of data extracted from references 7 and 21.

These curves indicate that the rate of recovery voltage in the thermal region is proportional to the maximum rate of change of current (at I=0) raised to the 2.40 power. The 2.40 exponent compares with the 2.0 exponent obtained with air blast interrupters.

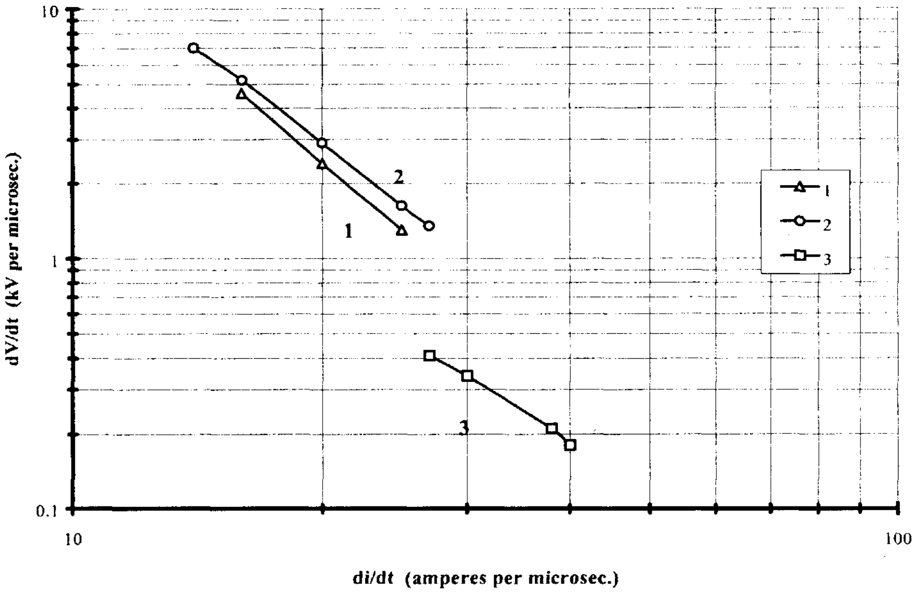

Figure 5.41 Comparison of interrupting capability of SF_6 using data from three independent sources.

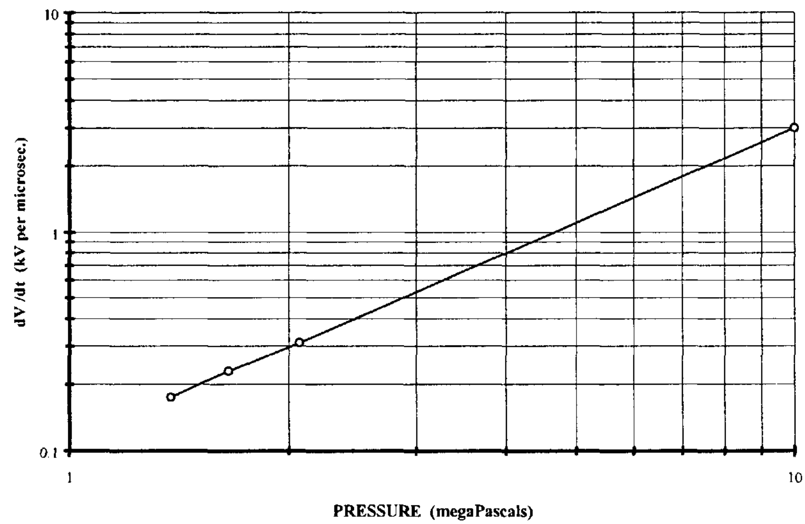

Figure 5.42 Dependency of the recovery voltage upon pressure for SF_6.

In Figure 5.42 we find a strong dependency of the recovery on the gas pressure as evidenced by the equation defining the relationship which indicates that the recovery is proportional to the pressure raised to the 1.4 power. In comparison the slope corresponding to the same relationship curves but with air as the interrupting medium is equal to 1.0.

The results observed for the dependency on the rate of change of current and on pressure confirm what we already know, which is that at the same current magnitude and at the same pressure, SF_6 is a better interrupting medium than air.

5.5.10 SF_6-Nitrogen Gas Mixture

Because of the strong dependence of SF_6 on pressure it has always been convenient to increase the pressure in order to improve the recovery characteristics of the interrupter. However, as it has been discussed before there are limitations imposed by the operating ambient temperature to avoid liquefaction of the gas.

To overcome the problem the possibility of mixing nitrogen (N_2) with SF_6 has been investigated. Although today the issue is only academic when referring to two pressure circuit breakers since they are not manufactured any longer, it has been demonstrated that the performance of a two pressure circuit breaker was improved, as shown in Figure 5.43, when at the same total pressure a mixture by pressure of 50% SF_6 and 50% N_2 was used [22], [23].

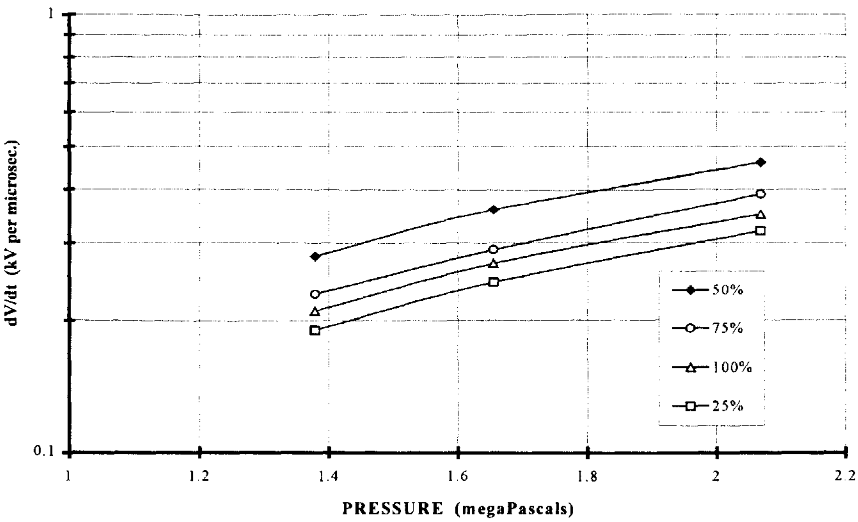

Figure 5.43 Interrupting capability for SF_6-N_2 mixtures.

For single pressure circuit breakers this has not been the case, and this is attributed to the fact that sufficient pressure can not be sustained due to the high flow rates of this lighter gas mixture. In two pressure circuit breakers maintaining the pressure differential high enough is not a problem because the high pressure is maintained in the high pressure reservoir by means of an external compressor.

From the point of view of dielectric withstand no significant difference is found with mixtures containing a high percentage of N_2. For example, with a 40% N_2 content the dielectric withstand is reduced by only about 10%.

5.6 VACUUM CIRCUIT BREAKERS

Vacuum interrupters take advantage of vacuum because of its exceptional dielectric characteristics and of its diffusion capabilities as an interrupting medium. It should be noted that the remarkable dielectric strength of vacuum is due to the absence of inelastic collisions between the gas molecules which means that there is not an avalanche mechanism to trigger the dielectric breakdown as is the case in gaseous mediums.

The pioneering work on the development of vacuum interrupters was carried out at the California Institute of Technology by R. Sorrensen and H. Mendelhall as reported in their 1926 paper [24].

Despite the early work it was not until the 1950s that the first commercially viable switching devices were introduced by the Jennings Company, and until 1962 when the General Electric Company introduced the first medium voltage power vacuum circuit breaker.

What prevented the earlier introduction of vacuum interrupters were technical difficulties that existed in areas such as the degassing of the contact materials, which is a process that is needed to prevent the deterioration of the initial vacuum due to the release of the gases that are normally trapped within the metals. Another problem was the lack of the proper technologies needed to effectively and reliability weld or braze the external ceramic envelopes to the metallic ends of the interrupters.

In the last 30 years these problems have been solved and that coupled with the development of highly sensitive instrumentation have substantially increased the reliability for properly sealing the interrupters to prevent vacuum leaks.

In the 1970s there were some attempts made to develop vacuum circuit breakers for applications at voltages greater than 72.5 kV. However, these designs were not suitable to compete with SF_6 circuit breakers and vacuum has been relegated primarily to applications in the range of 5 to 38 kV.

In the US vacuum is used most of the time for indoor and outdoor applications from 5 to 38 kV. At the same or similar voltages vacuum circuit breakers also have the larger share of the world market.

5.6.1 Current Interruption in Vacuum Circuit Breakers

The characteristics of a vacuum, or a low pressure arc, were presented in Chapter 1. In this section the current interrupting process that takes place in a vacuum interrupter will be described.

Current interruption, like in all circuit breakers, is initiated by the separation of a pair of contacts. At the time of contact part a molten metal bridge appears across the contacts. After the rupture of the bridge a diffuse arc column is formed and the arc is what is called a diffuse mode. This mode is characterized by the existence of a number of fast moving cathode spots, where each spot shares an equal portion of the total current. The current that is carried by the cathode spot depends on the contact material and for copper electrodes a current of about 100 amperes per spot has been observed. The arc will remain in the diffuse column mode until the current exceeds approximately 15 kA. As the magnitude of the current increases a single anode spot appears thus creating a new source of metal vapors which because of the thermal constant of the anode spot continues to produce vapors even after current zero. With the reversal of current, following the passage through zero and because of ion bombardment and a high residual temperature it becomes quite easy to reestablish a cathode spot at the place of the former anode. M. B. Schulman et al. [25] have reported on the sequence of the arc evolution and have observed that the development is sensitive to the method of initiation.

During normal interruption of an ac current, near current zero the arc column will be diffuse and will rapidly disappear in the absence of current. Since, during interruption and depending on the current magnitude, the arc may undergo the transition from the diffuse mode to the constricted mode and back again to the diffuse mode just prior to current zero it becomes clear that the longer the arc is in the diffuse mode, the easier it is to interrupt the current.

What it is important to realize from the above is the desirability of minimizing the heating of the contacts and maximizing the time during which the arc remains diffuse during the half current cycle. This objective can be accomplished by designing the contacts in such way that advantage can be taken of the interaction that exists between the current flowing through the arc and the magnetic field that is produced by the current flowing through the contacts or through a coil that may be assembled as an integral part of the interrupter [26]. Depending on the method used, the magnetic field may act in a transverse or in the axial direction with respect to the arc.

5.6.1.1 Transverse Field

To create a transverse or perpendicular field different designs of spiral contacts, such as those illustrated in Figure 5.44, have been used. In the diffuse mode the cathode spots move freely over the surface of the cathode electrode as if it was a solid disk.

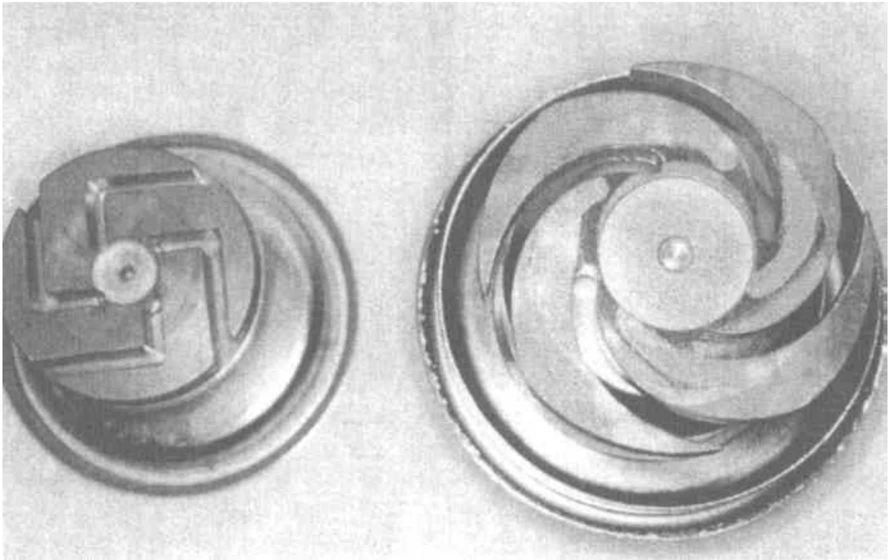

Figure 5.44 Two types of spiral contacts used in vacuum interrupters.

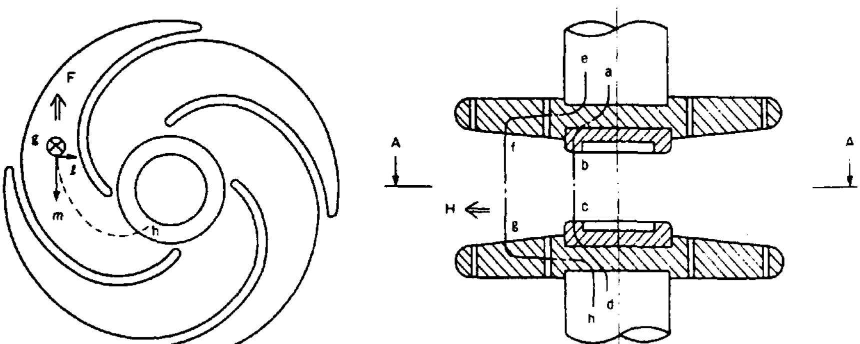

Figure 5.45 Magnetic forces in a transverse magnetic field.

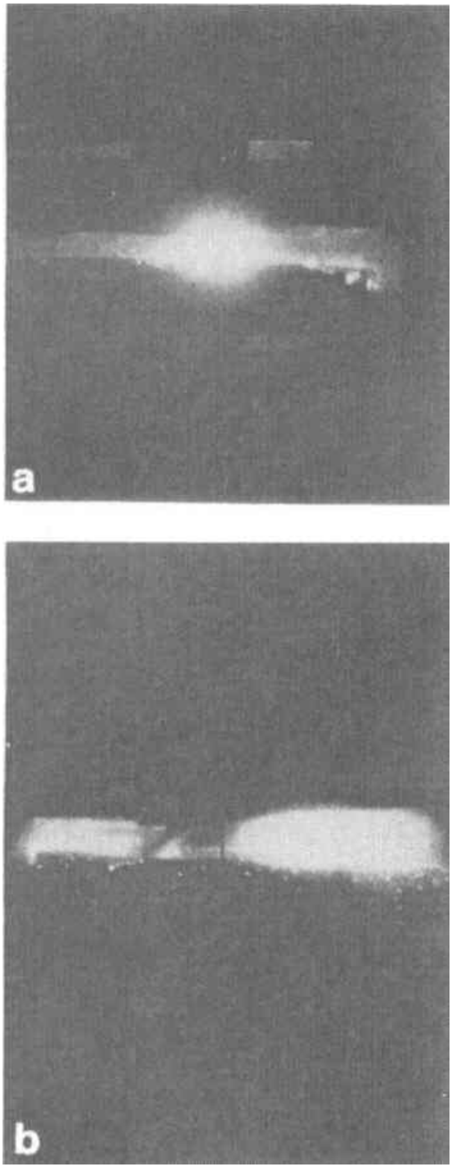

Figure 5.46 Vacuum arc under the influence of a transverse magnetic field: (a) constricted column (18.8 ka peak), (b) arc showing two parallel diffuse columns (Courtesy of Dr. M. B. Schulman, Cutler-Hammer, Horseheads, NY).

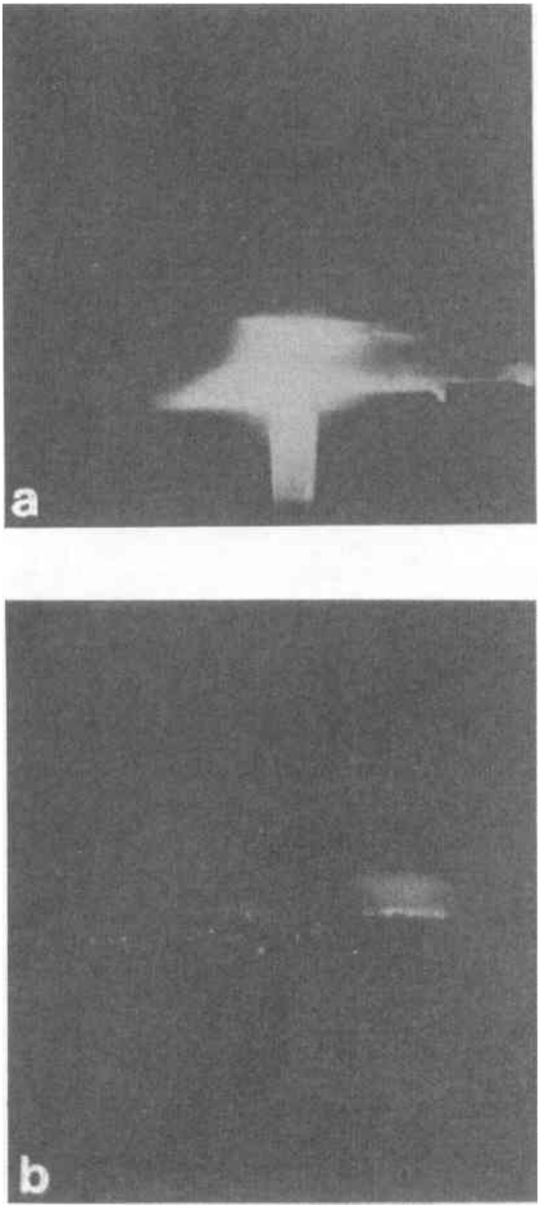

Figure 5.47 Vacuum arc under the influence of a transverse magnetic field: (a) jet column with wedge instability (26.8 ka peak), (b) 7 ka diffuse arc following a current peak of 18.8 ka. (Courtesy of Dr. M. B. Schulman, Cutler-Hammer, Horseheads, NY).

At higher currents and as the arc becomes coalescent the magnetic field produced by the current flowing through the contact spirals forces the arc to move along them [27] as a result of the magnetic forces that are exerted on the arc column as shown in Figure 5.45. As the arc rotates its roots also move along reducing the likelihood of forming stationary spots and reducing the localized heating of the electrodes and thus also reducing the emission of metallic vapors. When the end of the contact spirals is reached, the arc roots, due to the magnetic force exerted on the arc column are forced to jump the gap and to continue the rotation along the spirals of the contacts.

The effects of the field on the arc are illustrated in Figures 5.46 (a) and (b) and 5.47 (a) and (b) where the photographs of an arc in the diffuse and constricted modes are shown.

5.6.1.2 Axial Field

The axial magnetic field decreases the arc voltage and the power input from the arc by effectively confining the diffuse arc column to the space between the contact region as it can be seen in the photograph of a 101 kA peak diffuse arc shown in Figure 5.48.

An axial magnetic field acting on the arc column serves to promote the existence of a diffuse arc at higher current levels. The diffuse arc distributes the arc energy over the whole contact surface and consequently it prevents the occurrence of gross melting at the contacts. In the absence of the magnetic field, diffusion causes the arc to expand outwards from the space between the electrodes. However, when the axial magnetic field is present the ion trajectory becomes circumferential and a confining effect is produced.

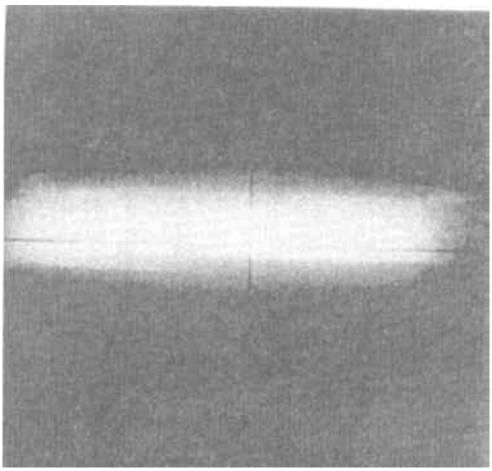

Figure 5.48 High current (101 kA peak) diffuse arc in an axial magnetic field. (Courtesy of Dr. M. B. Schulman, Cutler-Hammer, Horseheads, NY).

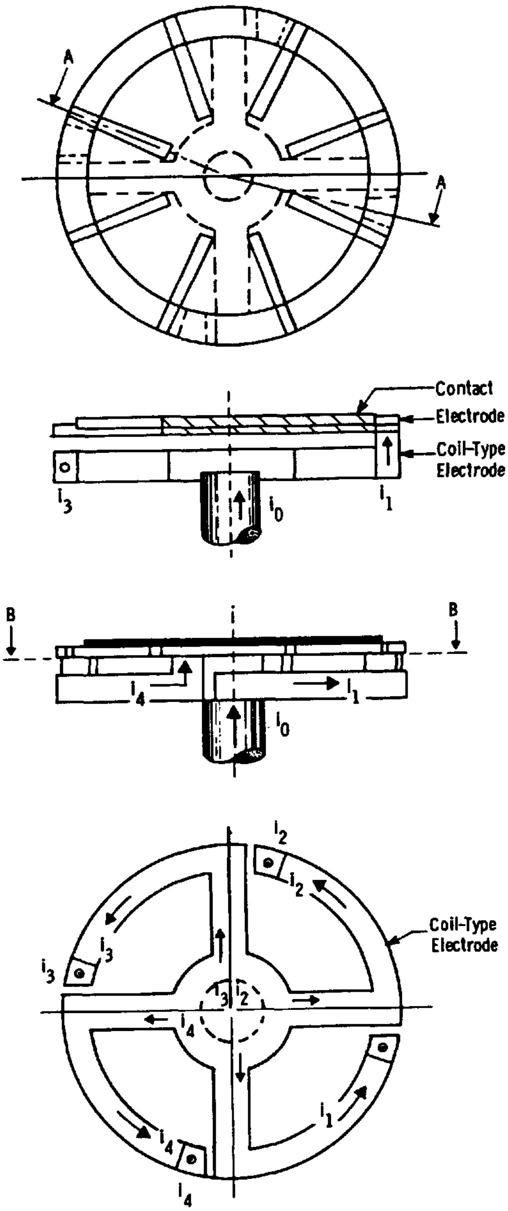

Figure 5.49 Illustration of a contact structure and direction of the force on the arc produced by an axial magnetic field.

For a reference on the effects of the axial magnetic fields upon the arc column and on the formation of the diffuse arc one can refer to the work published by M. B. Schulman et al. [28].

Axial magnetic fields can be produced by using either a coil that is located concentrically outside the envelope of the interrupter and that is energized by the current flowing through the circuit breaker [29], or by using specially designed contacts such as the one suggested by Yanabu et al. [30] and which is shown in Figure 5.49. Observing this figure, it can be seen the action of magnetic force on the arc column as the result of the interaction of the magnetic field set up by the current flowing through the arms of the coil electrode and the contact.

5.6.2 Vacuum Interrupter Construction

Vacuum interrupters are manufactured by either of two methods. The differences between methods are mainly in the procedures that are used to braze and to evacuate the interrupters.

In one of the methods, which is the one commonly known as the pinch-off method, the interrupters are evacuated individually in a pumping stand after they are completely assembled. An evacuation pipe is located at one end of the interrupter, generally adjacent to the fixed contact and after the required vacuum is obtained the tube is sealed by compression welding.

With the second method the interrupters are concurrently brazed and evacuated in specially designed ovens. The advantage of this method is that evacuation takes place at higher temperatures and therefore there is a greater degree of vacuum purity in the assembly.

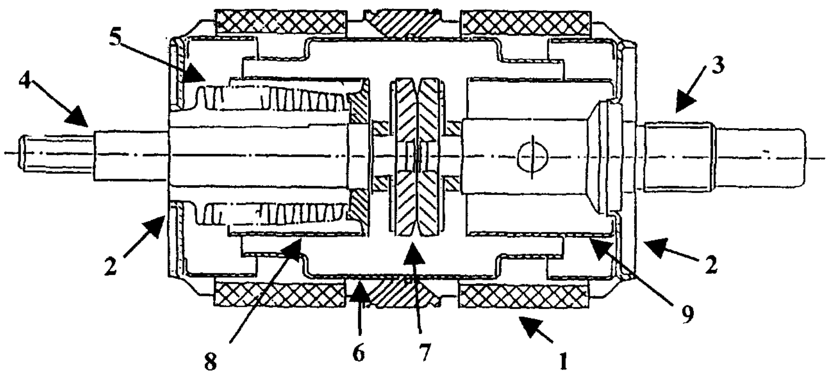

Figure 5.50 Vacuum interrupter construction.

The interrupter, as shown in Figure 5.50, consists of: (1) a ceramic insulating envelope that is sealed at both ends by (2) metallic (stainless steel) plates brazed to the ceramic body so that a high vacuum container is created. The operating ambient pressure inside of the evacuated chamber of a vacuum interrupter is generally between 10^{-6} and 10^{-8} torr.

Attached to one of the end plates is the (3) stationary contact, while at the other end the (4) moving contact is attached to the bottle by means of (5) metallic bellows. The bellows used may be either seamless or welded, however the seamless variety is usually the preferred type.

A metal vapor condensation shield (6) is located surrounding the set of contacts (7), either inside of the ceramic cylinder, or in series between two sections of the insulating container. The purpose of the shield is to provide a surface where the metal vapor condenses thus protecting the inside walls of the insulating cylinder so that they do not become conductive by virtue of the condensed metal vapor.

A second shield (8) is used to protect the belows from the condensing vapor to avoid the possibility of mechanical damage. In some designs there is a third shield (9) that is located at the junction of the stationary contact and the end plate of the interrupter. The purpose of this shield is to reduce the dielectric stresses in this region.

5.6.3 Vacuum Interrupter Contact Materials

Seemingly contradicting requirements are imposed upon the possible choices of materials that are to be used for contacts in a vacuum interrupter and therefore the choice of the contact material ends up being a compromise between the requirements of the interrupter and the properties of the materials that are finally chosen [31].

Among the most desirable properties of the contact material are the following:

1. A material that has a vapor pressure that is neither too low nor to high. A low vapor pressure means that the interrupter is more likely to chop the current since there is not enough vapor to maintain the arc at low values of current.
   A high vapor pressure, on the other hand, is not very conducive for interrupting high currents because there would still be a significant amount of vapor remaining at current zero, thus making interruption difficult.
2. A material that has a good electrical conductivity is desired in order to minimize the losses during continuous operation of the interrupter.
3. A high thermal conductivity is also desirable in order to reduce the temperature of the contacts and for obtaining rapid cooling of the electrodes following the interruption of the current.
4. Good dielectric properties are needed to assure rapid recovery capability.
5. High current interruption capabilities.

6. A material that has a low weld strength is needed because contacts in vacuum will invariable weld due to the pre-arcing that occurs when closing or to the localized heating of the micro contact areas when the short circuit current flows through the closed contacts. To facilitate the opening of the contacts easily fractured welds are a basic necessity.
7. Mechanical strength is needed in the material mainly to withstand the impact forces, especially during a closing operation.
8. Materials with low gas content and ease of outgassing are desirable since the contacts must be substantially gas free to avoid the release of any gases from the contacts during interruption and thus to prevent lowering the quality of the vacuum ambient.
9. To prevent the new cathode from becoming a good supplier of electrons a material with low thermionic emission characteristics is desirable.

From the above given list we can appreciate that there are no pure element materials that can meet all of these requirements. Refractory materials such as tungsten offer good dielectric strength, their welds are brittle and thus are easy to break. However, they are good thermionic emitters, they have a low vapor pressure and consequently their chopping current level is high and their interrupting capability is low.

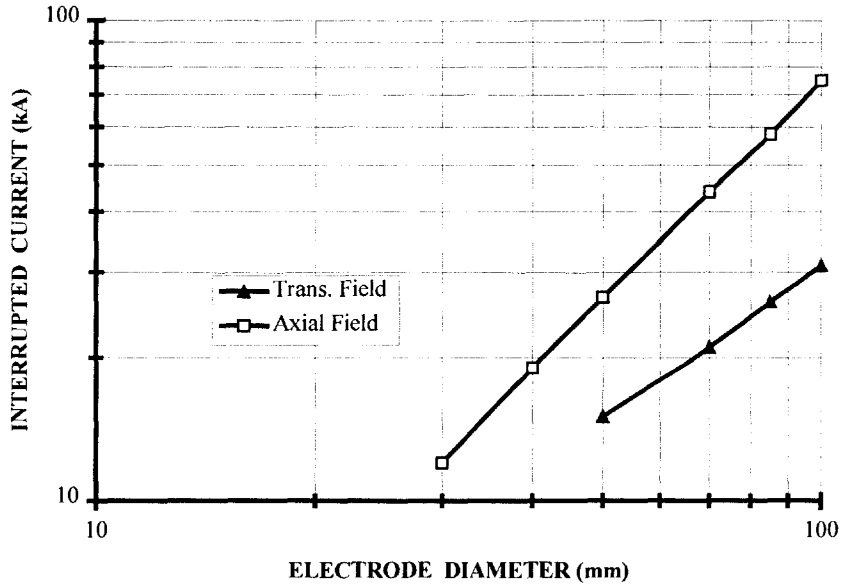

Figure 5.51 Comparison of interruption capability for vacuum interrupters as function of electrode diameter and magnetic field type.

On the other side of the spectrum copper appears to meet most of the requirements. Nevertheless its greatest disadvantage is that due to its ductility it has a tendency to form very strong welds which are the result of diffusion welding. This type of welding occurs, especially inside of a vacuum atmosphere, when two clean surfaces are pushed together and heated.

Since an acceptable compromise material can not be found among the pure elements the attention has been directed to investigate the use of synthered metals or other alloys.

A number of binary and ternary alloys have been studied, but from all of those that have been considered two alloys, one a Cu-Bi (copper-bismuth) and the other a Cu-Cr (copper-chrome) alloy, have prevailed and today are the most commonly used.

In the Cu-Bi alloy copper is the primary constituent material and the secondary material is bismuth the content of which is generally up to a maximum of 2%. For the Cu-Cr alloy there are different formulations but a typical composition is a 60% Cu to 40% Cr combination.

In general Cu-Bi contacts exhibit a weld strength about 7 times lower than Cu-Cr but they have a higher chopping current level than that of Cu-Cr. The typical chopping level for Cu-Bi contacts is in the range of 3 to 15 amperes with a median value of 7 amperes, while for Cu-Cr is only between 1 to 4 amperes with a median value of 2.7.

Other differences in performance between the materials are the higher rate of erosion that is observed in Cu-Bi contacts and the decrease in dielectric withstand capability that results by the cumulative process of the interrupting duties.

5.6.4 Interrupting Capability of Vacuum Interrupters

From the above discussions it is evident that the interrupting capability of a vacuum interrupter depends more than on anything else on the material and the size of the contacts and on the type of magnetic field produced around the contacts [32]. Larger electrodes in an axial field, as shown in Figure 5.51, have demonstrated that they have a better interrupting capability.

Another very important characteristic, related to the interrupting, or recovery capability, of vacuum interrupters is their apparent insensitivity to high rates of recovery voltage [33]. In ref. 7 it is shown that within a frequency range of 60 to 800 Hz, for a given frequency, the TRV has only a weak effect on the current magnitude. Furthermore it is widely recognized that the transient voltage recovery capability of vacuum interrupters is inherently superior to that of gas blast interrupters.

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6

MECHANICAL DESIGN

6.0 INTRODUCTION

The two most basic functions of a circuit breaker are to open and close its contacts on command. This at first sight implies a rather simple and trivial task; however, many of the characteristics involved in the process of opening, closing and maintaining the contacts closed can be quite demanding.

It is interesting to note that according to a CIGRE report [1] more than 90% of circuit breaker failures are attributed to mechanical causes. These findings confirm the fact that circuit breakers are primarily mechanical devices that are called upon to perform an electric function.

The majority of the time circuit breakers remain closed and simply act as electrical conductors, but in many occasions they do indeed perform their intended protective functions and when this happens, from the combined electrical and mechanical point of view, undoubtedly the contact structure is probably one of the most essential and critical components. A second and equally important component is the operating mechanism employed to produce the motion of the contacts.

These two components are closely linked to each other and in more ways than one they determine the success or failure of an interrupting device. Given the importance of these two components this chapter will be dedicated to the discussion of subjects relating to these components.

The most commonly used designs of operating mechanisms will be described in general terms, concentrating primarily in describing the operational sequences, rather than dealing with specific details of how to design a particular type of a mechanism.

The subject of electrical contacts will be treated in more detail so that a better understanding is gained on this area of design which tends to re-occur frequently, not only when dealing with the development of new circuit breakers but when evaluating circuit breaker performance or special applications.

6.1 CONTACT THEORY

Circuit breaker contacts must first be able to carry their assigned continuous current rating, without overheating or deteriorating, and must do so within reasonable limits of power consumption.

In addition, during short circuit conditions, they must be able to carry large currents for some specified periods of time, and again they must do so without deteriorating or arcing.

To meet these requirements it is indispensable that among other things the resistance of the contacts be kept as low as possible, that the contact area be maximized, that the materials are properly selected for the application at hand, that proper contact force be applied, that the optimum number of contacts be selected, that the contact cross section and the contact mass are properly sized, and that the minimum operating speed, both during closing and during opening, are sufficient to limit erosion of the contacts.

6.1.1 Contact Resistance

The resistance of a clean, ideal contact, where any influence due to oxide films is neglected and where it is assumed that a perfect point of contact is made at a spot of radius (r), is given by the following equation:

$$R = \frac{\rho}{2r}$$

where:

R = Contact resistance

ρ = Resistivity of contact material

r = Radius of contact spot

However, in actual practice, this is not the case and the real area of contact is never as simple as it has been assumed above. It should be recognized that no matter how carefully the contact surfaces are prepared, the microscopic interface between two separable contacts invariably will be a highly rough surface, having a physical contact area that is limited to only a few extremely small spots. Furthermore, whenever two surfaces touch they will do so at two micro points where, due to their small size, even the lightest contact pressure will cause them to undergo a plastic deformation that consequently changes the characteristics of the original contact point.

It is clear then that contact force and actual contact area are two important parameters that greatly influence the value of contact resistance. Another variable that also must be taken into consideration is the effects of thin films, mainly oxides that are deposited along the contact surfaces.

6.1.1.1 Contact Force

When a force is applied across the mating surfaces of a contact the small microscopic points where the surfaces are actually touching are plastically deformed and as a result of this deformation additional points of contact are established. The increase in the number of contact points serves to effectively decrease the value of the contact resistance.

The contact force F exerted by a pair of mating contacts can be approximated by the following equation [1]:

$$F = k\,H\,A_r$$

where:

H = Material hardness

A_r = Contact area

k = Constant between 0.1 and 0.3

The constant of proportionality k is first needed to account for the surface finishes of the contacts and secondly because, in reality, the hardness is not constant since there are highly localized stresses at the micro points of contact.

6.1.1.2 Contact Area

Even though it cannot be determined very accurately, the knowledge of the approximate areas of contact is essential for the proper understanding and design of electrical contacts. It is found that contact resistance is a function of the density of the points of contact and of the total area of true contact within the envelope of the two engaging full contact surfaces. In a well-distributed area the current will diffuse to fill all the available conducting zone, but in practical contacts this area is greatly limited because it is not possible to have such a degree of precision on the alignment, nor is it possible to attain and maintain such a high degree of smoothness.

In the earlier discussion, dealing with contact pressure, it was implied that the contact area is determined solely by the material hardness and by the force that is pushing the contacts together.

Since the original simplified equation for the contact resistance was given in terms of resistivity of the material and the radius of the contact point, it is then possible to substitute the term for the contact radius with the expression for the contact force, noting that:

$$A_r = \pi a^2$$

When this is done and the term R_F representing the film resistance is added the final expression for the total contact resistance R_T then becomes:

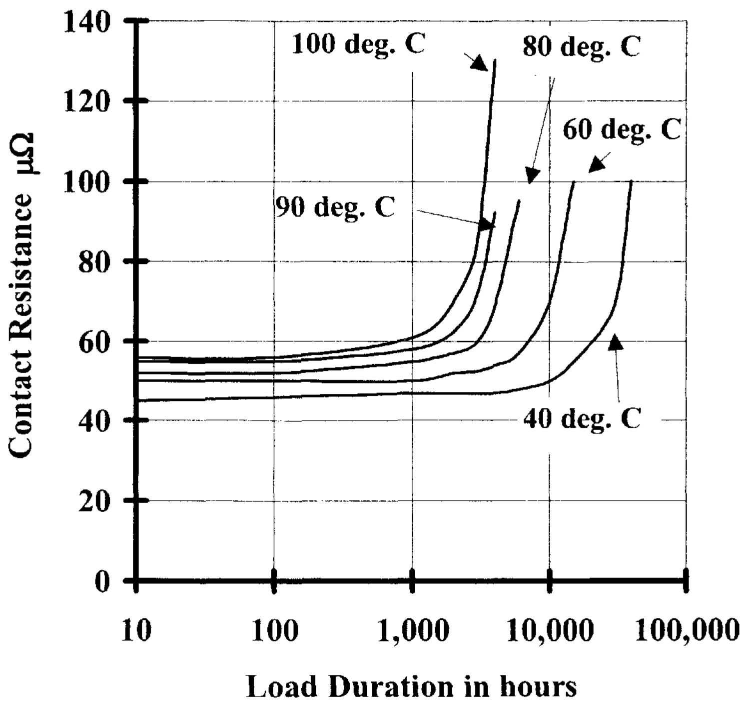


Figure 6.1 Resistance run-away condition as a function of time of carrying load currents for copper contacts that are immersed in oil at various temperatures (ref. 4 © IEEE).

$$R_T = \frac{\rho}{2}\sqrt{\frac{\pi k H}{F}} + R_F$$

6.1.2 Insulating Film Coatings on Contacts

A pure metal-to-metal contact surface can only be achieved in a vacuum, or in an inert gas atmosphere. In air the contact surfaces can oxidize and they become coated with a thin oxide film. According to Holm [2] a layer of 3 to 30 microns is formed on copper in a few seconds and almost instantly on aluminum, while it takes about two days to form on a silver or silver plated surface.

If the formed oxides are insulating, as is the case of CuO in copper contacts, then due to their build-up the contact spots will gradually reduce in size thus decreasing the contact area and increasing the contact resistance. This process as observed by Williamson [3] and by Lemelson [4] and as shown in Figure 6.1 is not very noticeable in its early stages but in its later stages it will suddenly get into a run away condition.

The formation of a sulfide coat on a silver contact surface also produces an increase in the contact resistance, this situation can develop on SF_6 circuit breakers after the contacts have been subjected to arcing and when there is no scraping or wiping motion between the contacts. However, in references 5 and 6 it is pointed out that the sulfide film on a silver surface is easily removed by slight friction and that it may even become decomposed by heat. The latter has been demonstrated experimentally and the results are shown in Figure 6.2. It can be seen in this figure that the resistance is reduced as a function of the temperature rise, which in turn was reached by passing 600 amperes through the interrupter.

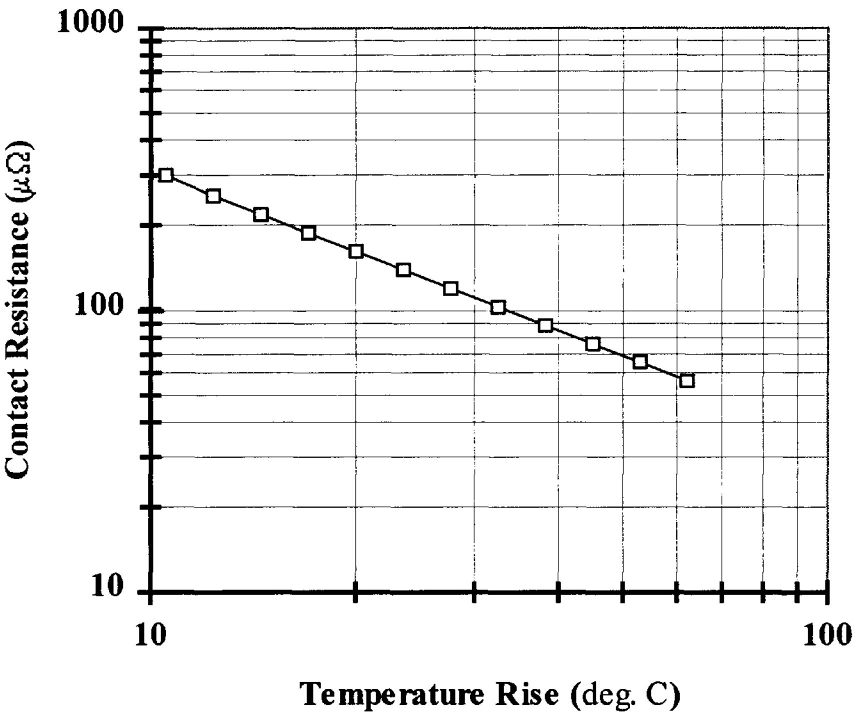


Figure 6.2 Change in contact resistance as a function of temperature rise at the contacts. Silver plated contacts exposed to sulfides resulting as by-products of arcing in SF_6.

6.1.3 Contact Fretting

Fretting is described as an accelerated form of oxidation that takes place across the contact surfaces and that is caused by any continuous cyclical motion of the contacts. Initially the junction points of the contact spots will seize and will eventually shear; however, this shear action does not increase the contact resistance because the particles are of pure metal. As the cycle repeats and the metal fatigue progresses then the metal layers are softened and separate allowing the oxide layer to grow until contact is lost.

The increase of contact resistance under these conditions has been observed as being a strong function of current, contact force and plating material.

To avoid this problem it is important then, when designing a contact interface, to consider using silver plating especially on aluminum bars.

6.1.4 Temperature at the Point of Contact

The following relationship between the voltage drop measured across the contact and its temperature can be established. It is based on the analogy that exists between the electric and the thermal fields and on the assumption that in the close proximity of a contact there is no heat loss by radiation.

$$\theta = \frac{V_C^2}{8\lambda\rho}$$

where:

θ = Temperature
λ = Thermal conductivity of contact material
ρ = Electric resistivity of contact material
V_C = Voltage drop across contact

This equation however is valid only within a certain limited range of temperatures. At higher temperatures the materials at the contact interfaces will begin to soften and thus can undergo a plastic deformation. At even higher temperatures the melting point of the material will be reached. In Table 6.1 below the softening and the melting temperatures together with their corresponding voltage drop are tabulated.

The significance of the above is that now we can determine for a specific material the maximum currents at which either softening or melting of the contacts would occur, and consequently the proper design to avoid the melting and welding of the contacts can be made.

The equations for the maximum softening and melting currents are:

TABLE 6.1
Softening and Melting Temperatures
for Contact Materials

	Resistivity ρ	Hardness H	Softening		Melting	
Contact Material	Ω*cm 10^{-6}	kg/cm^2 10^3	Temp. Kelvin	Voltage Drop mV	Temp. Kelvin	Voltage Drop mV
Au	2.2	2-7	373	80	1336	450
Ag	1.63	3-7	423	90	1233	350
Al	2.9	1.8-4	423	10	931	300
Zn	6.16	3-4	443	10	692	170
Cu	1.8	4-7	463	120	1356	430
Ni	9.0	7-20	793	220	1728	650
Pt	11.0	4-8	813	250	2046	700
Mo	4.8	18	1172	340	2883	960
W	5.5	12-40	1273	400	3653	1000

Softening current $I_s = \dfrac{2V_s}{\rho}\sqrt{\dfrac{F}{\pi H}}$ and

Melting current $I_m = \dfrac{2V_m}{\rho}\sqrt{\dfrac{F}{\pi H}}$

6.1.5 Short Time Heating of Copper

The maximum softening and melting currents as defined by the above equations are applicable to the point of contact and are useful primarily for determining the contact pressure needs. However when dealing with the condition where the contacts are required to carry a large current for a short period of time it is useful to define a relationship between time, current and temperature for different materials.

Below is given a general derivation for a general expression that can be used for determining the temperature rise in a contact.

First, it will be assumed that for very short times all the heat produced by the current is stored in the contact and is therefore effective in producing a rise in temperature.

Then the heat generated by the current i flowing into a contact of R ohms during a dt interval is:

$$Q = R\, i^2\, dt \quad \text{(Joules)}$$

and the heat required to raise the contact temperature by dθ degrees C is:

$Q = S\,V\,d\theta$ (Joules)

Since it was assumed that there is no heat dissipation, then it is possible to write:

$R\,i^2\,dt = S\,V\,d\theta$

where:

i = Current in amperes
t = Time in seconds
S = Specific heat of material in joules per m^3 per °C
θ = Temperature in °C
V = Contact volume in m^3
R = Contact resistance in ohms

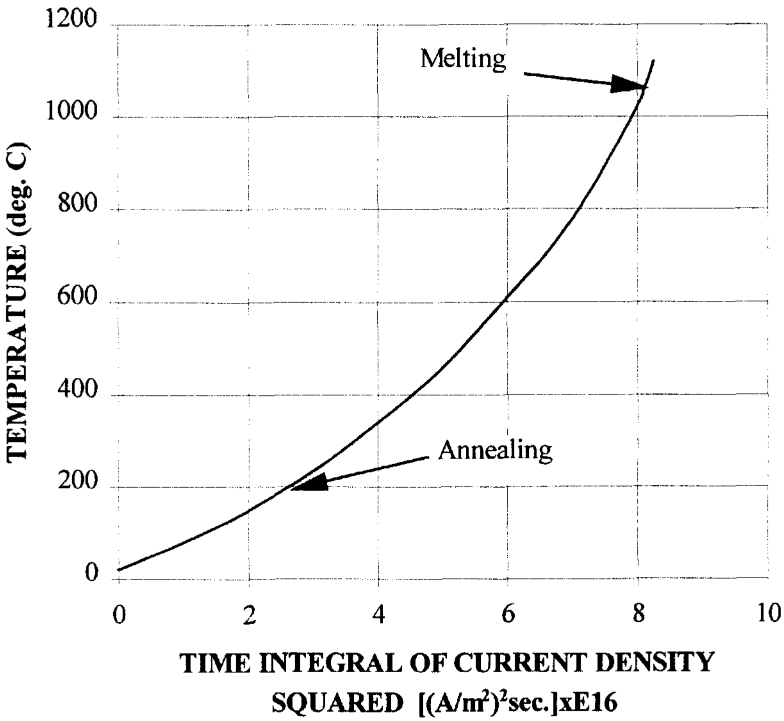


Figure 6.3 Short time heating of copper as function of the time integral of the current squared ($\theta = \int_0^t J^2\,dt$).

It can be shown that substituting the resistance of the contact with the specific resistivity of the material as a function of a standard ambient temperature which is assumed to be 20°C and by integrating the function the following equation is obtained:

$$\frac{1}{A^2}\int_0^t i^2 dt = 11.55 \times 10^{16} \log_{10} \frac{234 + \theta}{254}$$

By substituting the current density it is possible to re-write the equation as:

$$\theta = f\left(\int J^2 dt\right)$$

The heating of a copper contact of uniform cross section, with a current that starts to flow when the initial contact temperature is 20°C, is illustrated in Figure 6.3. Similar curves can be generated for other contact materials by using the proper constant for the new material under consideration.

Since the softening or melting temperatures for a given material are known, then it is possible to determine from the graph the integral of the current density, and furthermore since the current is constant we have:

$$\int J^2 dt = J^2 t$$

Therefore:

$$t = \frac{\int J^2 dt}{J^2}$$

6.1.6 Electromagnetic Forces on Contacts

As it has been described before, we know that there is a current constriction at the point of contact. We also know that this constriction is responsible for the contact resistance and consequently for the heat being generated at the contacts, but in addition to this the current constriction is also the source of electromagnetic forces acting upon the contact structures. In Figure 6.4 the current path of the current at the mating surface of the contact is shown. As it can be seen from the figure, as the current constricts into a transfer point there is a component of the current that flows in opposite directions and thus the net result is a repelling force trying to force apart the contacts.

According to Holm [2] the repulsion force is given by:

$$F_R = 10^{-7} I^2 \ln \frac{B}{a} \qquad \text{newton}$$

where:

B = Contact area
a = Actual area of contact point

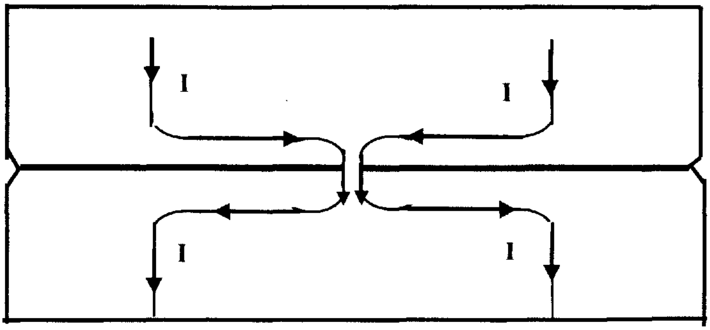


Figure 6.4 Current constriction at the actual point of contact.

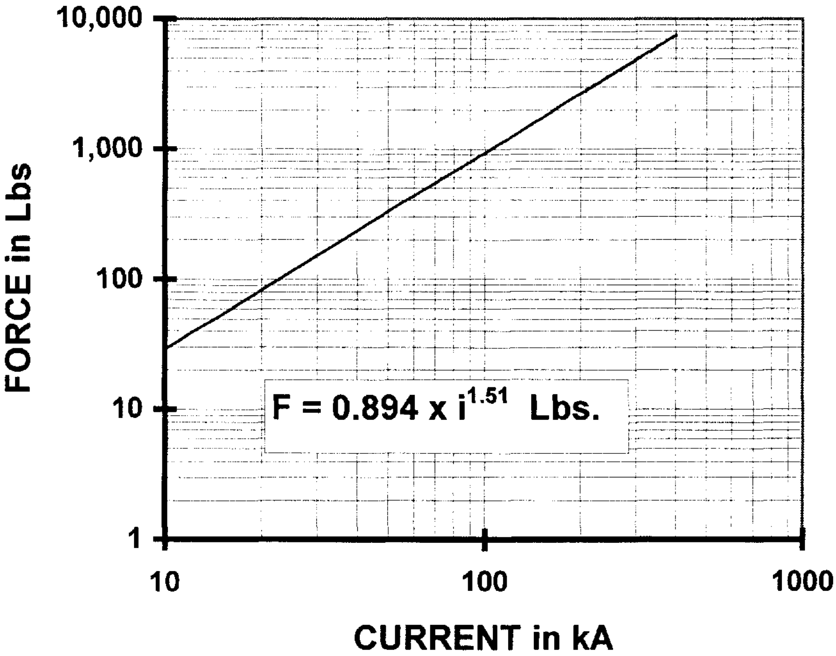


Figure 6.5 Measured blow-out force for 3 in. Cu-Cr butt contacts in vacuum.

It is difficult however to properly use this formula because of the difficulty in defining the actual contact area. For practical purposes some expressions that yield adequate results have been proposed. One such expression is given by Greenwood [7] as:

$$F_R = 0.112\left(\frac{I}{n}\right)^2 \qquad \text{lb. per finger}$$

Another practical relationship which was obtained experimentally with a 3 inch Cu-Cr butt type contact in vacuum is shown in Figure 6.5 and is given by the expression:

$$F_R = 0.885\left(\frac{I}{n}\right)^{1.51} \qquad \text{lb. per finger}$$

where:

I = Peak current in kA
n = Number of contacts

The differences on the force requirements obtained depending on which expression is used serve to point out the uncertainty of the variables involved and the probabilistic nature of the forces. In general the application of higher forces would yield a higher confidence level and a higher probability of withstanding the repulsion forces.

6.1.6.1 Force on Butt Contacts

The repulsion forces acting on butt contacts, such as those used in vacuum interrupters, can be calculated using any of the expressions given in the previous paragraph, considering the number of contacts n as being equal to 1. The magnitude of the repulsion forces must be counteracted by the operating mechanism, and therefore a proper determination of the force magnitude is essential for the design and application of the operating mechanism.

6.1.6.2 Force on Circular Cluster Contact

When a contact structure, such as the one shown in Figure 6.6 (a) and (b), is used, it can be shown that in addition to the repelling force there is another force. This additional force is due to the attraction between a set of two opposite fingers where current is flowing in the same direction on each contact (Figure 6.6 (a)). The attraction or blow-in force for a circular contact configuration can be calculated using the following equation:

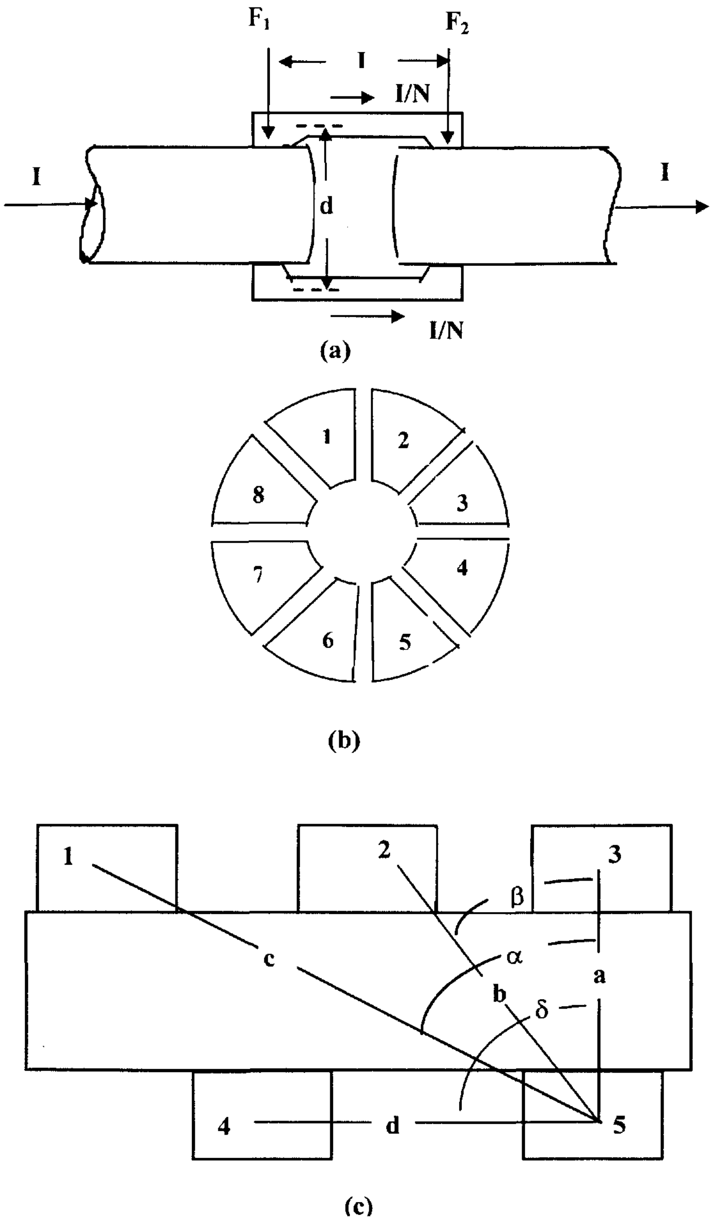


Figure 6.6 Diagram of blow-in forces relationships for circular and non-symmetrical contacts.

$$F_A = 0.102(n-1)\left(\frac{I}{n}\right)^2\left(\frac{l}{d}\right) \quad \text{newton}$$

6.1.6.3 Force on a Non-circular Non-symmetrical Cluster Contact

The following method can be used to calculate the blow-in force for each of any of the parallel contacts in the arrangement illustrated in Figure 6.6 (c). The forces are calculated assuming that the current divides equally among each contact, and although this is not totally accurate the results are close enough to provide an indication of the suitability of the design for a specific application.

$$F_{1-5} = 0.102\frac{l}{a}\left(\frac{I}{n}\right)^2 \cos\alpha \qquad \text{newton}$$

$$F_{2-5} = 0.102\frac{l}{b}\left(\frac{I}{n}\right)^2 \cos\beta \qquad \text{newton}$$

$$F_{3-5} = 0.102\frac{l}{c}\left(\frac{I}{n}\right)^2 \qquad \text{newton}$$

$$F_{4-5} = 0.102\frac{l}{d}\left(\frac{I}{n}\right)^2 \cos\delta \qquad \text{newton}$$

6.1.6.4 Total Force on Contacts

The total force acting on a contact therefore becomes:

$$F_T = F_S + F_A - F_R$$

where:

F_T = Total force per contact segment
F_S = Contact spring force
F_A = Blow-in, or attraction force per contact segment
F_R = Blow-out, or repulsion force per contact segment

In a properly designed contact it would be expected that $F_A \geq F_R$.

6.1.7 Contact Erosion

Contact erosion is the unavoidable consequence of current interruption and is caused primarily by the vaporization of the cathode and the anode electrodes. According to W. Wilson [8] the heating leading to the vaporization at the electrodes is the result of the accompanying voltage drops. He derived an equation for the vaporization rate in cubic centimeters of contact material lost per kA of current. In Figure 6.7 the results of tests reported in reference 9 have been reproduced. The graph presents the rate of erosion in air for various contact materials. The data are plotted in what is called "their order of excellence", that is from best to worst, best being the material exhibiting the least amount of erosion.

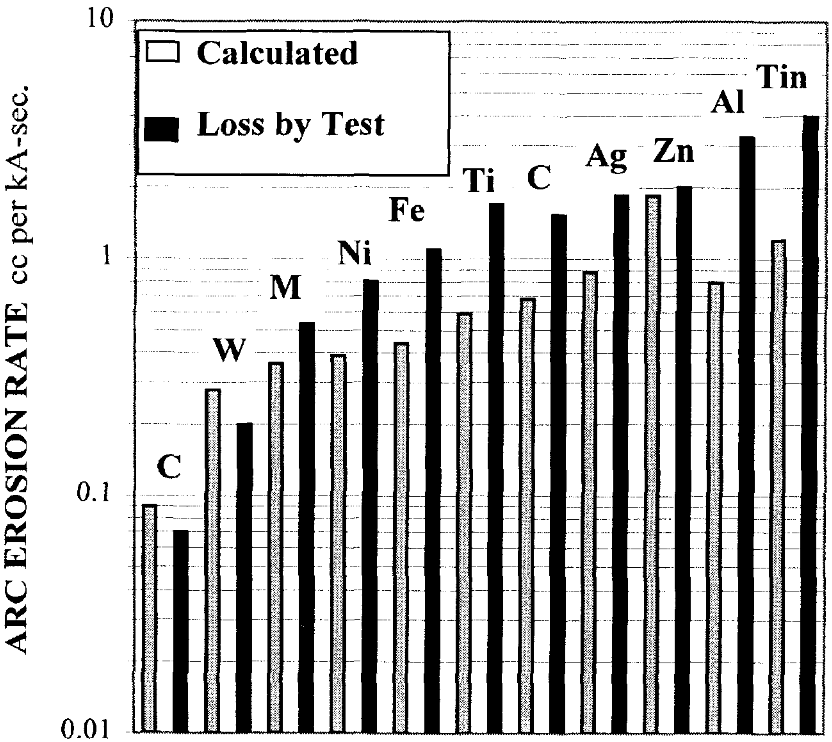


Figure 6.7 Contact material erosion due to arcing (data from ref. 8).

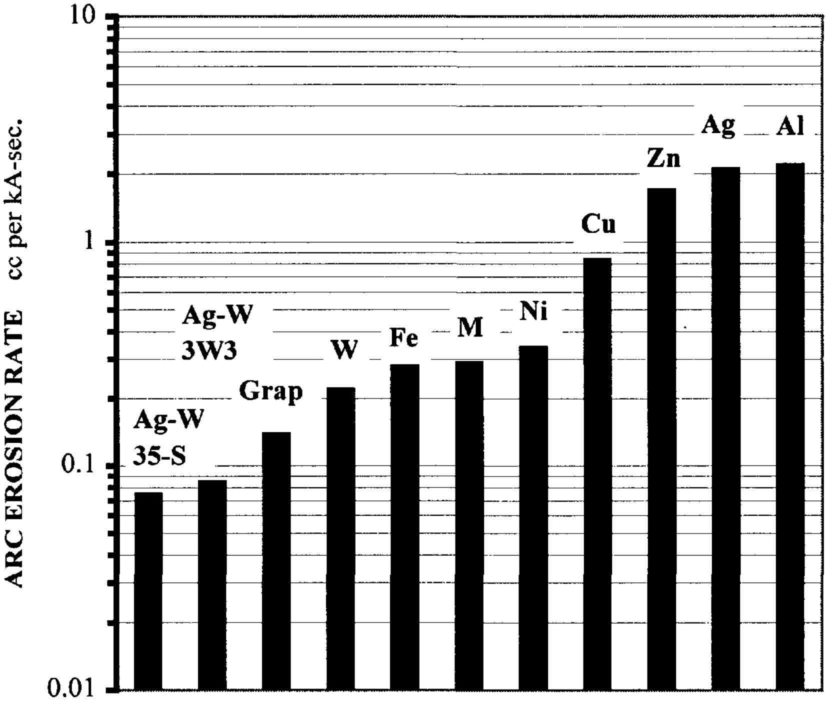


Figure 6.8 Measured materials rate of erosion due to arcing in SF_6.

In Figure 6.8 the rate of contact erosion in SF_6 based on a set of personal unpublished data is plotted. It is interesting to note that there is a reasonable degree of agreement between these values and those given by Wilson. As calculated and as "vaporized loss by test".

It seems therefore that the following equation can be used to obtain reasonable estimates for the rate of erosion of the contacts.

$$R = \frac{1000\left(E_C + E_A\right)}{\rho JH}$$

where:

R = Erosion rate, cc per kA-sec.
E_C = Cathode drop, volts
E_A = Anode drop, volts
J = Heat equivalent, 4.18 joules per calorie
H = Heat of vaporization, calories per gram
ρ = Density of contact material, grams per cc

6.2 MECHANICAL OPERATING CHARACTERISTICS

Opening and closing velocities, as well as stroke, or travel distance, are the most important operating characteristics of a circuit breaker. They are dictated primarily by the requirements imposed by the contacts. Opening and closing velocities are important to the contacts in order to avoid contact erosion as well as contact welding. Since contact stroke is synonymous with contact gap, circuit breaker stroke is primarily related to the ability of the circuit breaker to withstand the required operating dielectric stresses.

6.2.1 Circuit Breaker Opening Requirements

Two basic requirements for the total opening operation of a circuit breaker are the opening speed and the total travel distance of the contacts. The opening speed requirements are dictated by the need to assure that the parting of the contacts is done as rapidly as possible for two reasons; first, to limit contact erosion and second by the need to control the total fault duration which is dictated by the system coordination requirements. The total travel distance is not necessarily the distance needed to interrupt the current. This distance is generally dictated by the open gap space needed to withstand the normal dielectric stresses including any lighting impulse waves that may appear across the open contacts of a breaker that is connected to a system.

The need for carrying the continuous current and for withstanding a period of arcing sometimes makes it necessary to use two sets of contacts in parallel. One, the primary contact, which is always made of a high conductivity material such as copper, and the other, the arcing contact, made of synthetic arc resistance materials like copper or silver tungsten or molybdenum which have a much lower conductivity than those used for the primary contacts.

With a parallel set of contacts there is a finite time that is required to transfer the current from the main contact path to the arcing contact path. This commutating time lapse is due to the differences in the resistance and the inductance between the two electrical paths.

The significance of the commutation time can be appreciated when one considers that in the worst case commutation may not take place until the next current zero is reached, and during that time the arc continues to erode the copper from the main contacts. Arc erosion of the contacts not only limits the life of the contacts but it can also lead to dielectric failures by creating an ionized conducting path between phases or phase and ground. It is important to realize that commutation must be completed before the arcing contacts separate otherwise, the arc is likely to remain attached to the main contacts and in such case the circuit breaker will certainly fail to interrupt.

The commutation time can be calculated by solving the electrical equivalent circuit for the contact arrangement as given in Figure 6.9.

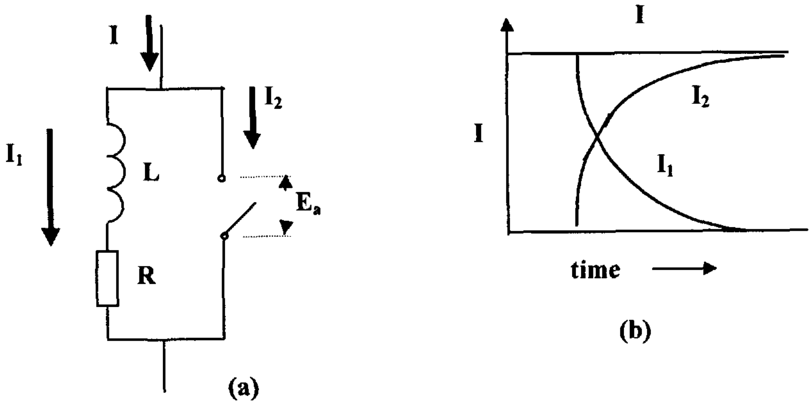


Figure 6.9 Equivalent circuit for determining the required arc commutation time between main and arcing contacts.

It can be shown that:

$$I = I_1 + I_2 = I_m \sin(\omega t + \phi) \quad \text{and}$$

$$I_1 = I - \frac{E_a}{R}\left(1 - e^{-\alpha t}\right)$$

where:

$$\alpha = \frac{R}{L}$$

I = System current
I_1 = Main contact current
I_2 = Arcing contact current
R = Arcing contact resistance
L = Loop inductance of arcing contact path

Commutation is completed at $t = t_1$ when $I_2 = I$

The commutation time is then obtained by solving the above equation for the time t_1:

$$t_1 = \frac{L}{R} \ln\left(\frac{1}{1 - \frac{IR}{E_a}}\right)$$

From the above it is observed that to have a successful commutation of current it requires that $E_a > IR$.

While the opening operation continues and as the contact gap increases, a critical contact position is reached. This new position represents the minimum contact opening where interruption may be accomplished at the next current zero. The remainder of the travel is needed only for dielectric and deceleration purposes.

Under no-load conditions and when measured over the majority of the travel distance, the opening and closing velocity of a circuit breakers is constant, as it is shown in Figure 6.10 (a) and (b) where actual measurements of the circuit breaker speeds are shown.

Although different type circuit breakers have different speed and travel requirements, the characteristic shape of the opening travel curve are very much similar in all cases. The average speed is usually calculated by measuring the slope of the travel curve over the region defined by the point of initial contact part to a point representing approximately three-fourths of the total travel distance.

The opening speed for vacuum circuit breakers is generally specified in the range of 1 to 2 meters per second, for SF_6 circuit breakers the range is on the order of 3 to 6 meters per second.

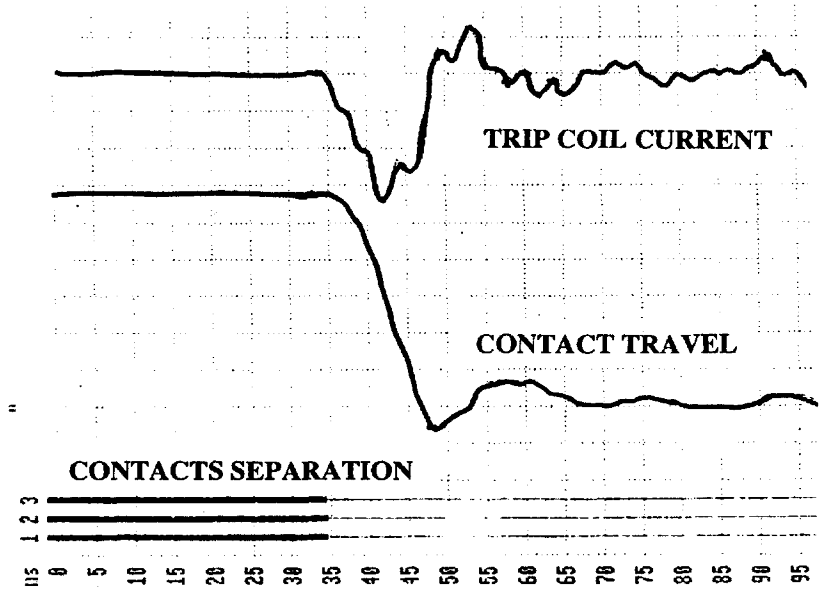


Figure 6.10 (a) Typical distance vs. time measurement of the opening operation of a circuit breaker.

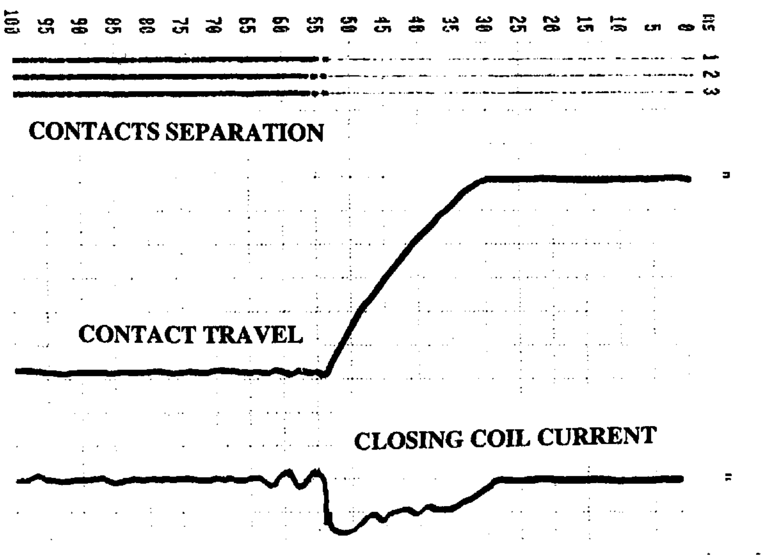


Figure 6.10 (b) Typical distance vs. time measurement of the closing operation of a circuit breaker.

For vacuum circuit breakers there is another, often overlooked, requisite for the initial opening velocity of the contacts which corresponds with the assumed point of the critical gap distance immediately after current has been interrupted. Considering that the typical recovery voltage of à vacuum interrupter is about 20 to 30 kV per millimeter then for those applications at 25 or 38 kV it is extremely important to assure that the actual gap is about 3 millimeters for an assumed 2 milliseconds of minimum arcing time. This translates into an opening velocity of at least 3 meters per second. Even though this is a relatively modest velocity in comparison to other circuit breakers the fact that butt contacts are used in vacuum interrupters means that a higher initial acceleration is needed since there is no contact motion prior to the actual beginning of the contact separation. In lieu of contact wipe or contact penetration, a certain amount of overtravel, or contact spring wipe, is provided primarily for compensation of contact erosion. A second objective of the design is to provide the means for creating a hammer or impact blow that is applied to the end of the moving contact and which is needed to break the contact weld. This impact force is utilized as a convenient source of kinetic energy to deliver a high rate of initial acceleration to the contacts. However, because of the mechanics at the time of impact, to avoid a discontinuity in the opening motion it is usually recommended that the mass of the mechanism moving parts be equal to at least twice the mass of the moving contact.

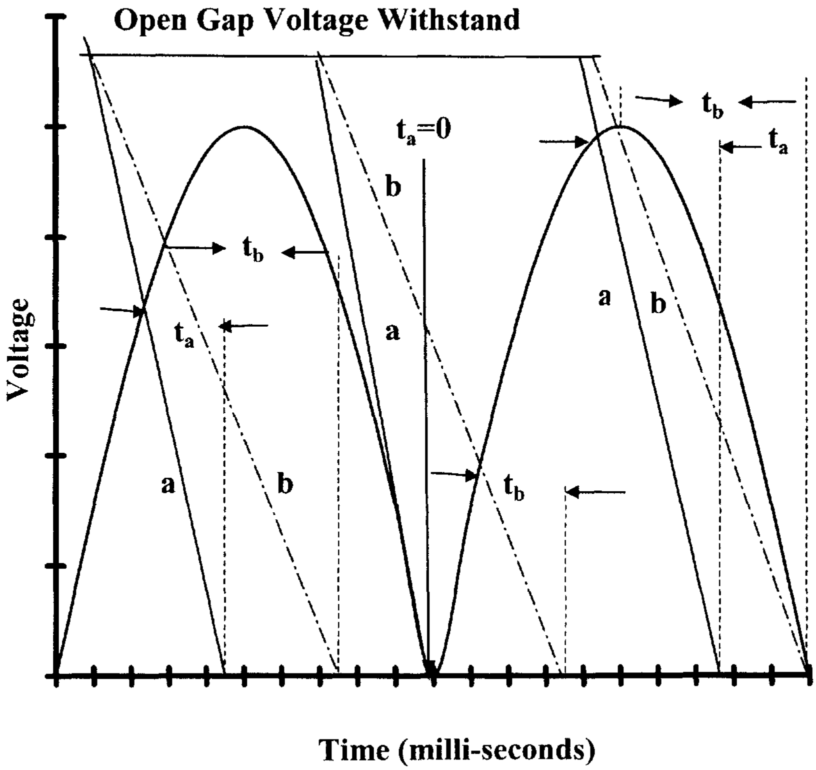


Figure 6.11 Prestrike during closing relationship between closing velocity and system voltage.

6.2.2 Closing Speed Requirements

During a closing operation and as the contacts approach each other, a point is reached where the gap equals the minimum flashover distance and therefore an electric arc is initiated. As the distance between the contacts continues to diminish the arc gradually shortens until finally the contacts engage and the arc disappears. Therefore as we have seen not only when opening but also during closing an arc can appear across a pair of contacts.

Depending upon the voltage, the interrupting medium and the design of each particular circuit breaker, the contact flashover characteristics vary very widely. For illustration purposes, let us assume two characteristic slopes as shown in Figure 6.11 (slopes *a* and *b*). When these slopes are superimposed on the plot of the absolute values of a sinusoidal wave that represent the system voltage, it shows that depending on the instantaneous relation between the contact gap and the system voltage the arc is initiated at the point of intersection of these two curves.

The elapsed time between the flashover point and the time where the contacts engage represents the total arcing time, which is shown as t_a and t_b corresponding to slopes a and b respectively. It also can be seen in this figure that the arcing time decreases as the slope of the flashover characteristics increases, which suggests what should be obvious, that increasing the closing velocity decreases the arc duration.

Increasing the closing velocity not only decreases the arcing time but it also decreases the magnitude of the current at the instant of contact engagement. Assuming that the electromagnetic repulsion forces are a function of the peak current squared, then as shown by P. Barkan [9] the work done by the mechanism against the electromagnetic repulsion is:

$$\varepsilon = \int_0^T I_m{}^2\left(\sin^2 \omega t\right)V dt$$

The dimensionless solution of this equation is given as:

$$\frac{\varepsilon}{2kI_m{}^2S} = 1 - \left(\frac{V}{2\omega S}\right)\sin\left(\frac{2\omega s}{V}\right)$$

where:

ε = Work done against electromagnetic force

k $\approx$ 0.112 = Constant of proportionality for electromagnetic force

I_m = Peak current at contact touch

S = Contact travel

V = Contact velocity

ω = 377 radians for 60 Hz currents

The benefits of a high closing speed are then a reduction in the mechanism energy requirements and a reduction of the contact erosion.

6.3 OPERATING MECHANISMS

The primary function of a circuit breaker mechanism is to provide the means for opening and closing the contacts. At first this seems to be a rather simple and straightforward requirement but, when one considers that most circuit breakers once they have been placed in service will remain in the closed position for long periods of time and yet in the few occasions when they are called upon to open or close they must do so reliably, without any added delays or sluggishness, then it is realized that the demands on the mechanisms are not as simple as first thought.

It is important then to pay special attention to such things as the type of grease used, the maximum stresses at the latch points and bearings, the stiffness of the whole system and most of all to the energy output of the mechanism.

Just as there are different types of circuit breakers, so are there different types of operating mechanisms, but what is common to all is that they store potential energy in some elastic medium which is charged from a low power source over a longer period of time.

Considering the methods that are used for energy storage, the types of mechanisms that are installed in today's circuit breakers are identified as being spring, pneumatic or hydraulic. Recently a new type of mechanism that is based on the use of a permanent magnet has also been introduced for vacuum circuit breaker applications.

From the mechanical point of view operating mechanisms are either of the cam or the four bar linkage type.

6.3.1 Cam Versus Linkage

Cams are generally used in conjunction with spring stored energy mechanisms and these cam-spring driven mechanisms are mostly used to operate medium voltage vacuum interrupters.

Cam drives are flexible, in the sense that they can be tailored to provide a wide variety of motions, they are small and compact. However, the cam is subjected to very high stresses at the points of contact, and furthermore the cam follower must be properly constrained, so that it faithfully follows the cam's contour, either by a spring which raises the stress level on the cam, or by a grooved slot where the backlash may cause problems at high speeds. For those interested in further information for the design of a spring operated cam-follower system Barkan's paper [10] is highly recommended.

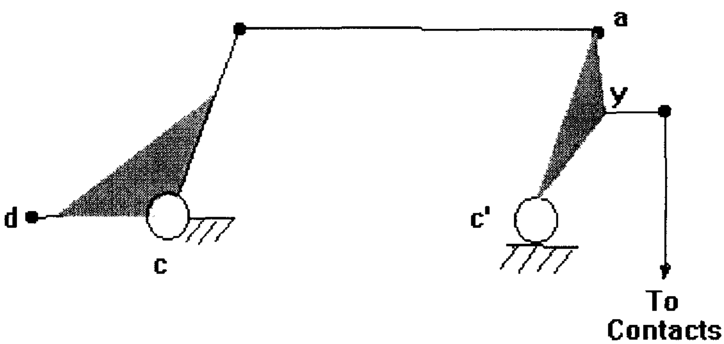


Figure 6.12 Schematic diagram of a four bar linkage arrangement.

Linkages, in most cases, have some decided advantages over cams; for one they are more forgiving in terms of fabrication accuracy because small variations on their lengths do not significantly influence their motion. In general the analysis of a four bar linkage system is a relatively simpler task and it is not that difficult to determine the force at any point in the system.

Since the mechanism must deliver as much work as it receives, then when friction is neglected, the force at any point multiplied by the velocity in the same direction of the force at that point must be equal to the force at some other point times the velocity at that same point, or in other words the forces are inversely proportional to their velocities.

Four bar linkages such as the one shown schematically in Figure 6.12 are practically synonymous with pneumatic and hydraulic energy storage mechanisms.

6.3.2 Weld Break and Contact Bounce

Contact bounce and contact welding are two conditions which are usually uniquely associated with vacuum circuit breakers.

We already know that vacuum contacts weld upon closing and that therefore it is necessary to break the weld before the contacts can be opened. Breaking the weld is accomplished by an impact, or hammer blow force, which is applied preferably directly to the contacts. To provide this force it is a common practice to make use of the kinetic energy that is acquired by the opening linkages as they travel over the compressed length of the wipe springs.

To assure that the proper impact force will be available the velocity at the time of contact separation can be used as a guideline.

$$V < \frac{M_1 \frac{dx_1}{dt} + M_2 \frac{dx_2}{dt}}{M_1 + M_2}$$

where:

M_1 = Contact's mass

M_2 = Mechanism's mass (moving parts)

x_1, x_2 = Displacement

Contact bounce can have serious effects on the voltage transients generated during closing and it may cause damage to equipment connected to the circuit breaker, although protective measures can be taken to reduce the magnitude of the transients it is also advisable to design the circuit breaker so that the bounce is at least reduced, if not eliminated.

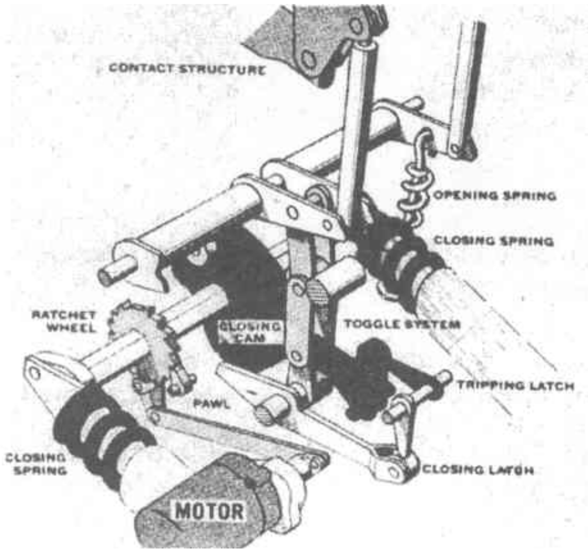


Figure 6.13 Simplified drawing of a spring stored energy mechanism.

Suppression of bounce requires that a close interaction be established between the energy dissipation at the contact interface and the energy storage of the supporting structure of the interrupter and its contacts. If means are provided for the rapid dissipation of the stored energy in the supporting structure, the effect of the bounce can be minimized.

6.3.3 Spring Mechanisms

A simplified drawing depicting a typical spring type operating mechanism is shown in Figure 6.13. This type of mechanism is commonly found in some outdoor medium voltage and in practically all of the indoor medium voltage circuit breakers. However, it is not uncommon to find these mechanisms also on outdoor circuit breakers up to 38 kV and in a few cases they even have been used on 72.5 kV rated circuit breakers.

As its name suggests the energy of this mechanism is stored on the closing springs. The stored energy is available for closing the circuit breaker upon command following the release of a closing latch.

The spring mechanism, in its simplest form, consists of a charging motor and a charging ratchet, a closing cam, closing springs, opening springs and a toggle linkage. The charging motor and ratchet assembly provides automatic recharging of the closing springs immediately following the closing contact sequence.

The charged springs are held in position by the closing latch, which prevents the closing cam from rotating. To release the spring energy either an electrically operated solenoid closing coil or a manual closing lever is operated. Following the activation of the closing solenoid a secondary closing latch is released while the primary latch rotates downward due to the force being exerted by the charged closing springs, and thus the rotation of the closing cam which is connected to the operating rods is allowed. As the cam rotates it straightens the toggle linkage (refer to Figure 6.13), which in turn rotates the main operating shaft thus driving the contacts that are connected to the shaft by means of insulating rods.

The straightening of the toggle links loads the trip latch as they go over-center. The trip latch then holds the circuit breaker in the closed position. In addition to closing the contacts the closing springs supply enough energy to charge the opening springs.

Opening of the contacts can be initiated electrically or manually; however, the manual operation is generally provided only for maintenance purposes. When the tripping command is given the trip latch is released freeing the trip roller carrier. The force produced by the over-center toggle linkage rotates the trip roller carrier forward, and as the first toggle link rotates about its pivot it releases the support that was provided to the second and third links. The opening springs, which are connected to the main operating shaft, provide the necessary energy to open the contacts of the circuit breaker.

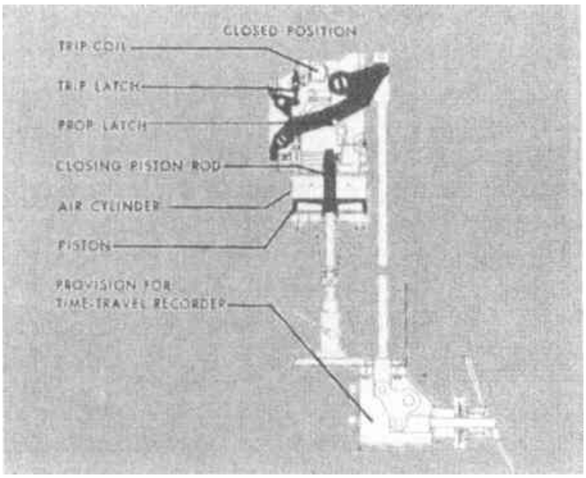


Figure 6.14 Illustration of a pneumatic mechanism.

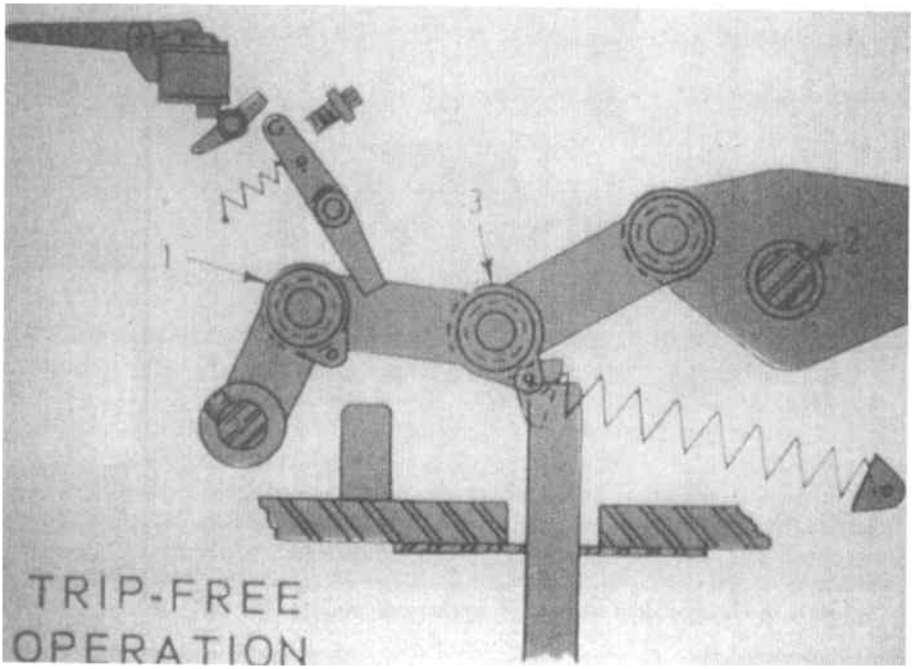


Figure 6.15 Toggle linkages arrangement to satisfy trip free requirements.

6.3.4 Pneumatic Mechanisms

Pneumatic mechanisms are a logical choice for air blast circuit breakers, and that is so because pressurized air is already used for insulating and interrupting; however, pneumatic mechanisms are not limited to air blast breakers, they also have been used to operate oil and SF_6 circuit breakers.

Those mechanisms, which are used with air blast circuit breakers, usually open and close pneumatically and in some cases there is only a pneumatic rather than a solid link connection between the mechanism and the contacts.

Other pneumatic mechanisms, such as the one that is illustrated in Figure 6.14, use an air piston to drive the closing linkage and to charge a set of opening springs. This mechanism, which has been used in connection with oil and SF_6 circuit breakers, has a separate air reservoir where sufficient air is stored at high pressure for at least 5 operations without the need of recharging in between operations.

To close the circuit breaker, high-pressure air is applied to the underside of the piston by opening a three-way valve. The piston then moves upwards transmitting the closing force through a toggle arrangement to the linkage which is connected to the contacts by means of an insulating push-rod, as shown in Figure 6.15. The toggle arrangement is used to fulfill the trip free capability required by some standards. In addition to closing the contacts the mechanism charges a set of opening springs and once the contacts are closed a trip latch is engaged to hold the breaker in the closed position.

Opening is achieved by energizing a trip solenoid which in turn releases the trip latch thus allowing the discharge of the opening springs which forces the contacts to the open position.

Another variation of a pneumatic mechanism is one where the pneumatic force is used to do both the closing and the opening operation. The direction being controlled by the activation of either of the independent opening or closing three-way valves.

6.3.5 Hydraulic Mechanisms

Hydraulic mechanisms are in reality only a variation of the pneumatic operator; the energy, in most cases, is stored in a nitrogen gas accumulator and the incompressible hydraulic fluid becomes a fluid operating link that is interposed between the accumulator and a linkage system that is no different than that used in conjunction with pneumatic mechanisms.

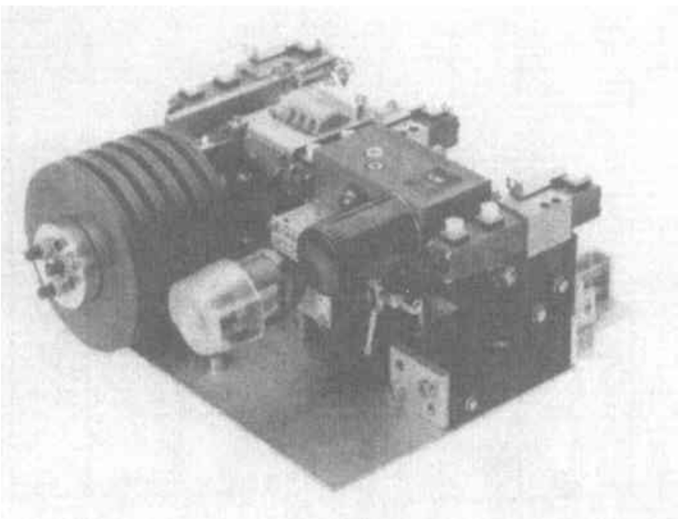
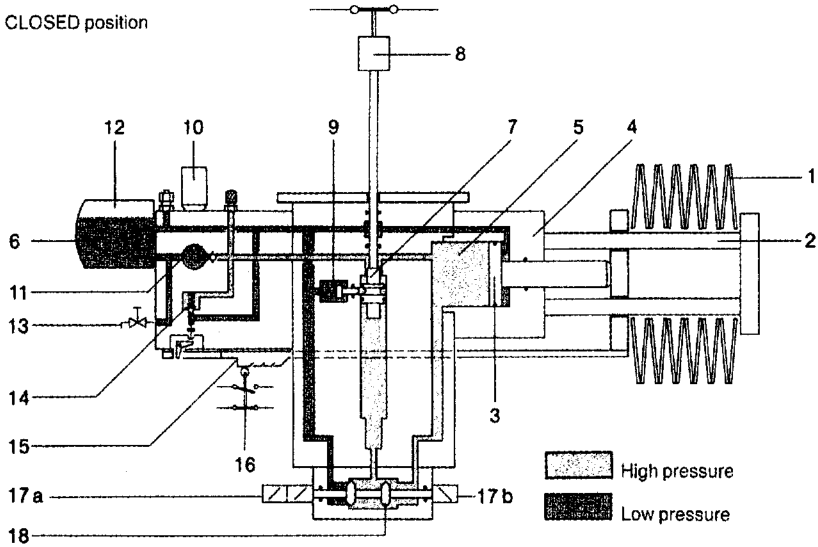


Figure 6.16 Photograph of a hydraulic mechanism used by ABB T&D Co.



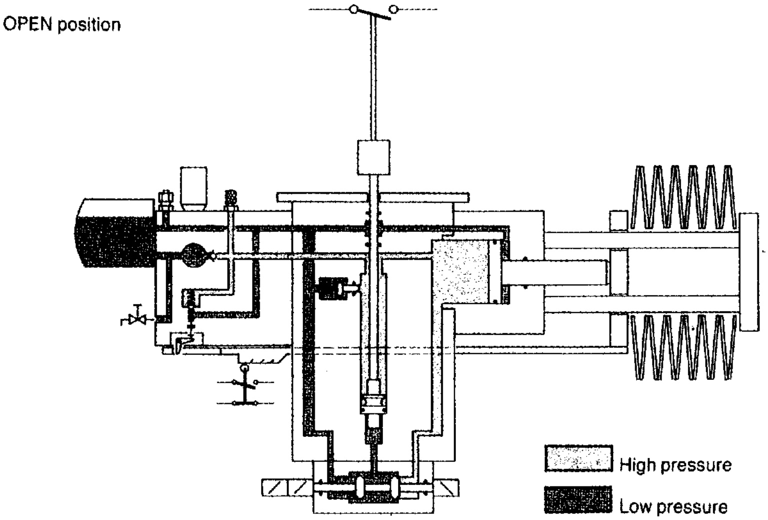


Figure 6.17 Functional operating diagram of the mechanism shown in Figure 6.16.

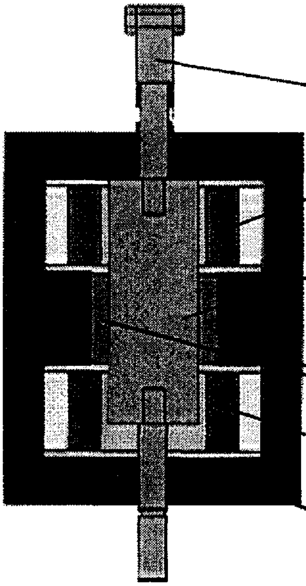


Figure 6.18 Schematic of magnetic mechanism.

In a variation of the energy's storage method, the nitrogen accumulator is replaced by a disk spring assembly, which acts as a mechanical accumulator. A mechanism of this type is shown in Figure 6.16. It offers significant advantages; it is smaller, there is no chance for gas leaks from the accumulator, and the effects of the ambient temperature upon the stored energy are eliminated.

The operation of this mechanism can be described as follows (note that the numerical references to components correspond to those shown in Figure 6.17).

A supply of hydraulic oil is filtered and stored in a low-pressure reservoir (12), from where it is compressed by the oil pump (11). The high-pressure oil is then stored in a reservoir (5). The piston (3), which is located inside of the high-pressure storage, is connected to the spring column (1). The springs are supported by the tie bolts (2). A control link (15) checks on the charge of the spring column and activates the auxiliary switch contacts (16) that control the pump's motor (10) as required to maintain the appropriate pressure.

With the circuit breaker in the closed position the operating piston (7), which is connected to the conventional circuit breaker linkages (8), has high pressure applied to both of its faces. To open the breaker the opening solenoid (17a) is energized causing the changeover valve to switch positions and connect the underside of the operating piston to low pressure (6), thus causing the piston to move to the open position. Closing is the reverse of the opening and is initiated by energizing the closing solenoid (17b) and by admitting high pressure to the underside of the operating piston. Item (4) is a storage cylinder, (9) is a mechanical interlock, (13) is an oil drain valve and (14) is a pressure release valve.

6.3.6 Magnetic Mechanism

Recently a new type of mechanism has been introduced for use specifically on vacuum circuit breakers. Its application at the moment would be limited to the medium voltage class in the rating range of 15 kV to 38 kV and up to 40 kA.

The mechanism can be described as a magnetically actuated device and is shown schematically on Figure 6.18. Mechanically it is a rather simple device since it only has a single moving part, a drive rod that is connected to an armature which in turn is surrounded by a pair of permanent magnets and by an operating coil at each end.

As described in its sales literature the mechanism is a bi-stable magnetic actuator where the switchover of the armature to the relevant limit position is effected by the magnetic field of two electrically excited coil.

The permanent magnets provide the necessary holding force at either of the two end positions of the armature. To change positions a capacitor is discharged on the respective coil producing a bucking magnetic field. Once the holding force of the magnets is exceeded then the operating rod is free to change position (Figure 6.19). One of the advantages of this concept is that the higher force is produced towards the end of the stroke which is the time when it is needed to provide the bias force required by the butt contact structure.

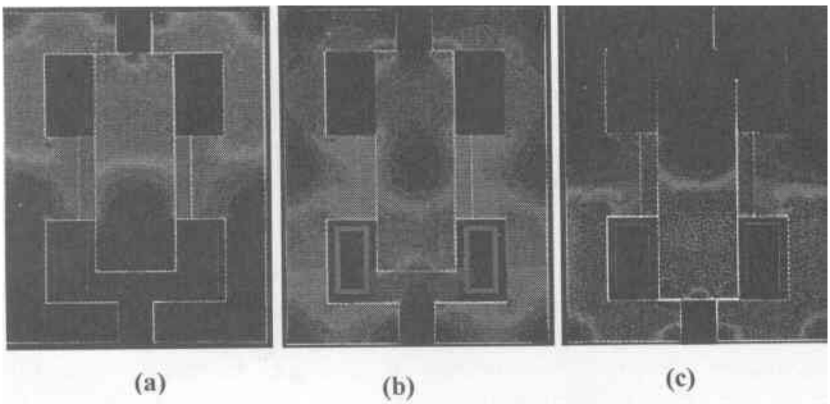


Figure 6.19 (a) Latch on upper position. (b) Current build-up on lower coil. (c) Latch on lower position.

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7

DIELECTRIC DESIGN

7.0 INTRODUCTION

Dielectric withstand capability and reliability are factors of utmost importance for the design of all circuit breakers. A circuit breaker must be able to withstand the stresses produced not only by the steady state operating voltage but also those resulting from transient overvoltages caused by lightning or system switching operations. Additionally the insulating components must be designed to withstand equally well mechanical and electrical stresses.

Furthermore, the insulation characteristics of the different components within the circuit breaker should be coordinated so that in the event of an excessive overvoltage, a flashover will occur externally through a line-to-ground path rather than internally across the open contacts. Moreover, the external flashover should occur across self-healing insulating paths that are in most cases through air or SF_6.

The aim of this chapter is to provide a basic review of dielectric theory, to show how to employ these concepts in the design and application of circuit breakers and to review the significance of dielectric measurements that are made on solid insulation.

It is also considered that a review of the properties of insulation and the properties of materials commonly used would be a valuable tool for use in future designs and therefore a section will be dedicated to cover this subject.

It should be noted that for this review it is not necessary to consider the different types of circuit breakers separately because their major paths to ground and between phases are similar for all circuit breakers.

In the closed position the line-to-ground path is through the external porcelain columns or the entrance bushings, the operating rod and the insulating medium, and in the open position through the insulating medium across the open gaps.

7.1 FUNDAMENTALS OF DIELECTRIC THEORY

Materials that are used in electric applications fall into the categories of conducting, insulating or dielectric, and semiconductors. In conducting materials electric charges are free to move through the material, while on insulators they are not. It is worth noting that there are no perfect insulators; however, the conducting capabilities of these materials are so limited that for all practical purposes they behave as if they were perfect insulators.

Based primarily on observed statistical data most of the concepts about dielectrics and insulating materials have been known for more than a century. The modern view of electromagnetic theory considers that in dielectric materials bound electron charges instead of free electrons are responsible for producing current flow. Consequently, the type of current flow that can be observed in an insulator is more of a displacement rather than a conductive type.

When very high electric fields are applied across dielectric materials large numbers of electrons may be suddenly excited to energies within the conduction band. As a result the current through the dielectric by motion of these electrons increases dramatically. Sometimes localized melting, burning or vaporization produces irreversible degradation and perhaps even failure of the material.

To produce the interaction and motion of the charges within the material there needs to be a force, which in this case is the result of an electric field or electric potential. The interchangeable use of electric field or electric potential is permissible considering that the electric fields and potentials are obtained by dividing the force and potential energy, respectively, by the charge. They are measured in units of newton per coulomb or volts per meter for the electric field and joule per coulomb or simply volts for the electric potential.

7.1.1 Electric Fields

Before Faraday the force acting between charged particles was considered to be a direct and instantaneous interaction between the two particles. Today's theories consider the electric field as a vector function in space that is used to determine the force acting on a charge at that position. In other words if a charge is positioned somewhere and the space around it is affected in a way that if another charge is brought to this region it will experience a force acting on it, the change in the surrounding space produced by the charge at rest is then called the electric field and any other charge is considered to interact with the field and not with the charge that gives rise to it [1].

The effect of the field can be related to its strength and it can be represented by the following expression:

$$E = 9 \times 10^9 \frac{q_1}{d^2} \qquad \text{newtons/coulomb}$$

A collection of charges that are fixed in place will produce an electric field and this field is equal to the summation of the individual fields produced by each charge.

Relating to the electric field is the dielectric stress E that is imposed on an insulating material. The electric stress is the force acting on a unit charge located on the dielectric and is related to the kinetic energy that is acquired by the charged particles. Quantitatively E is equal to the voltage gradient and is expressed in units of volts/meter.

Based on Gauss's Law there are three important properties that should be remembered:

1. When on a static condition the electric field inside of a conductor is always equal to zero.
2. The electric field is always perpendicular to the surface outside of a conductor.
3. All the excess positive or negative charge in a conductor must be on its surface.

The above listed properties are applicable only to conductors since inside a non-conductor (dielectric) which does not have free electrons an electric field can exist. Furthermore, the electric field outside is not necessarily normal to the surface of a non-conductor.

It must be noted that electric forces are given in terms of newtons (N), electric potential energies are in joules (J) and electric charge is given in coulombs (C). Since electric fields and potentials are obtained by dividing the force and the potential energy by the charge then they are measured in units of newtons per coulomb and joules per coulomb respectively. But a volt is defined as a joule per coulomb, therefore the electric potential can also be referred to simply as voltage. However, a note of caution is needed to remember that electric potential is not the same as electric potential energy. The potential energy is the electric field and is a vector while the electric potential is a scalar quantity and therefore it has no direction.

7.1.1.1 Electric Field Lines

Electric field lines provide a convenient way for graphically representing an electric field (Figure 7.1). Field lines however do not exist in space; they are simply a device that has been created to help in our thinking about force fields.

Whatever the number of field lines that are chosen to represent the electric field around a point charge Q, the same number must be associated with a body that carries the same net charge (Q). For example, in the case of a charged sphere the pattern of field lines outside the sphere is identical to the field lines around a point charge of the same magnitude.

The following are some basic rules that apply to electric field lines:

1. The field lines indicate the direction of the electric field, the field being tangent to the field lines at any point.

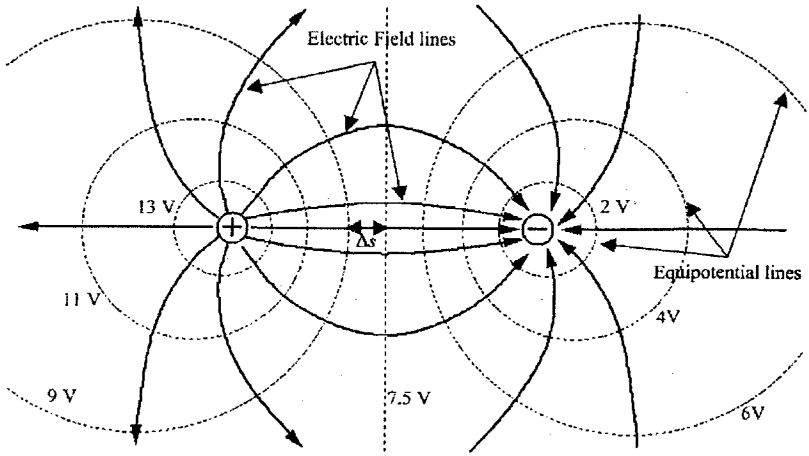


Figure 7.1 Equipotential lines and electric field lines.

2. Electric field lines leave positive charges and enter at the negative charge.
3. The number of lines entering or leaving a charge is proportional to the magnitude of the charge.
4. The magnitude of the electric field is proportional to the number of lines crossing a unit area perpendicular to the lines.
5. The spacing between field lines represents the field strength. The lines are closer together where the field is stronger and they are far apart where the field is weak.

7.1.1.2 Equipotential Lines and Surfaces

Electric potential can be represented graphically by plotting equipotential lines or equipotential surfaces for two-dimensional or for three-dimensional fields, respectively. An equipotential surface is one where all points are at the same potential and consequently where the potential difference between them is zero and no work is required to move a charge from one point to another.

Equipotential lines and surfaces are always perpendicular to the electric field; this fact simplifies the task of locating the equipotential when the electric field lines are known or vice versa.

Another way of describing equipotential lines is in terms of potential energy. If the potential energy does not change, then the kinetic energy also does not change. No change in kinetic energy implies that the velocity of a charge would not change and these regions of constant potential energy are then known as equipotential.

In Figure 7.1 the electric field lines and the equipotential lines are shown. For illustration purposes let us use this figure to calculate the electric field at the center of the interval Δs.

Since the electric field between two points of different potential is equal to:

$$E = -\frac{\Delta V}{\Delta s}$$

where ΔV is the potential difference in volts and Δs is the distance in meters.

Assume that Δs in Figure 7.1 is 15 mm (0.015 m). Then the potential difference across the distance is:

$$E = -\frac{7.5 - 9.0}{0.015} = 100 \quad \text{volts/meter}$$

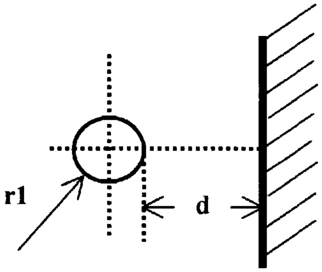
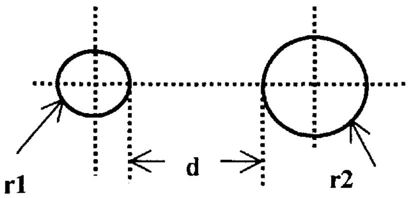
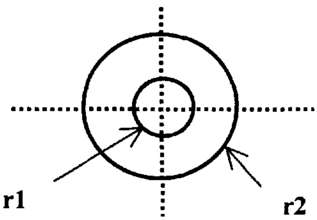
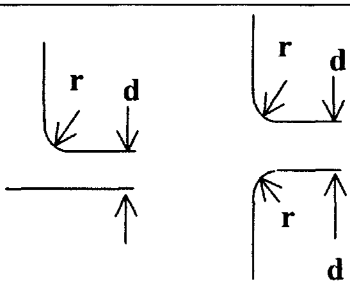
7.1.1.3 Manual Calculations and Field Factors

In many applications it is not necessary to have a very accurate field analysis. Relatively complex geometries can be approximated by simple geometric equivalents; such as a sphere to sphere, sphere to plane, rod to plane, edge to plane, edge to edge, etc., and approximate values for the electric field can be obtained using simplified relationships. The simplified approach is possible since in most cases electrode configurations that are found in the high voltage fields of circuit breakers are essentially solids of rotation. Rotational objects having a perpendicular plane of symmetry with respect to one axis of rotation or to two parallel axes of rotation can always be reduced to a special case of long parallel electrodes. If these long electrodes are again considered rotational electrodes, then they can be referred to two parallel planes.

Using simple equations the field strength can be approximated in the perpendicular plane of symmetry to the axis of rotation. These calculations generally are valid for non-uniform fields where the ratio of the electrode distance to the electrode radii are not too great, generally in the order of 5 to 6 times their radii. Applicable values for a utilization function for the typical geometries shown in Table 7.1 have been calculated and are shown below in graphical form in Figures 7.2, 7.3, 7.4 and 7.5.

Applying the given utilization factors the field strength can be calculated using the following relationship:

Table 7.1
Equivalent Geometric Shapes

	Sphere to Plane Figure 7.2 Cylinder to Plane Figure 7.3
	Sphere to Sphere Figure 7.2 Parallel Cylinders Figure 7.3
	Concentric Cylinders Figure 7.4
	Edge to Plane Figure 7.5 Edge to Edge Figure 7.5

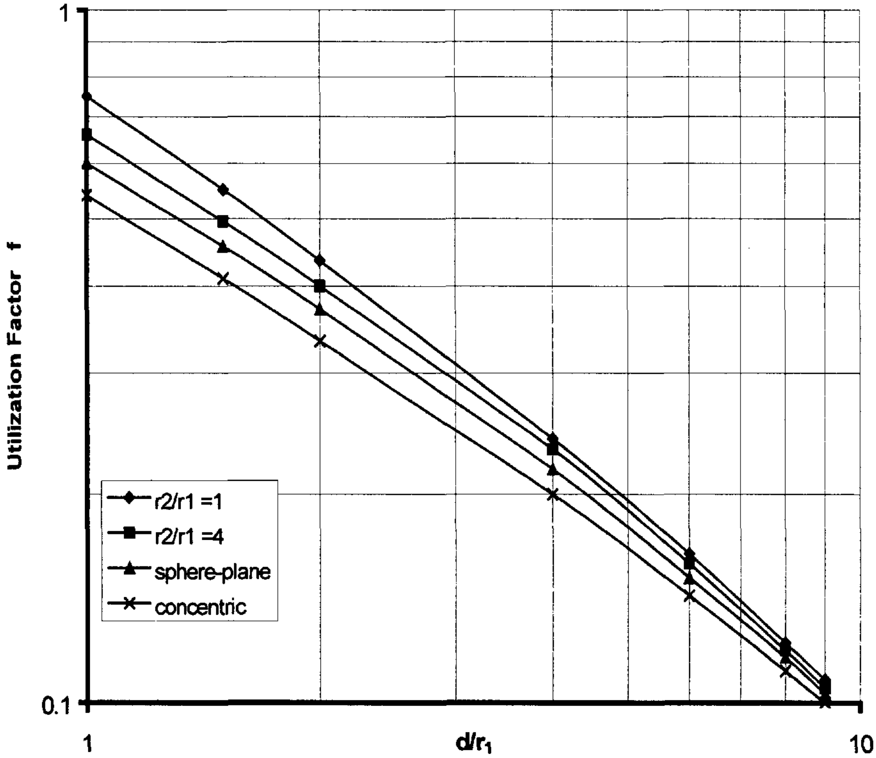


Figure 7.2 Utilization factor for spheres.

$$V = E_{MAX} fd$$

where:

V = Applied voltage
E_{MAX} = Spark-over voltage
f = Utilization factor
d = Electrode gap distance

In most instances it possible to use an experimental value of the flashover voltage to substitute for E_{MAX} and the result will represent the voltage capability for the geometry under consideration.

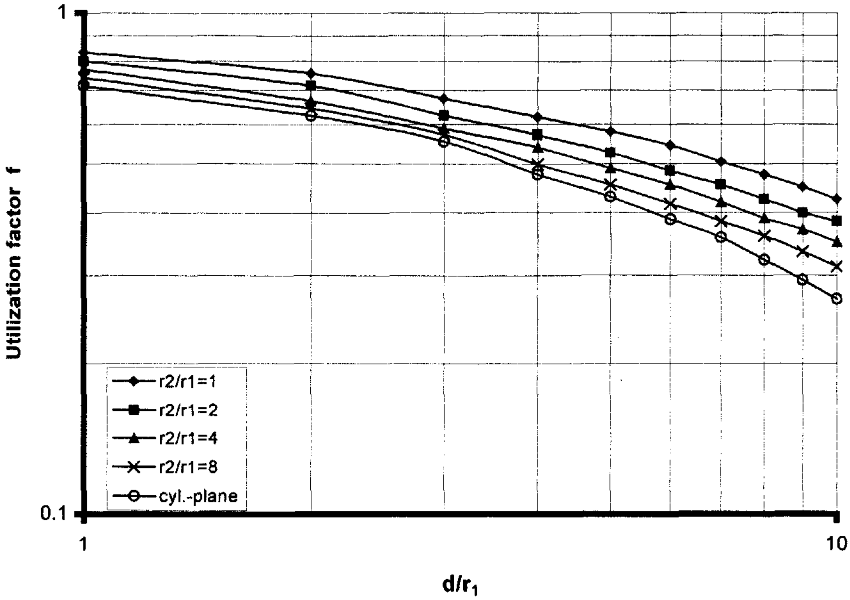


Figure 7.3 Utilization factor for parallel cylinders.

7.1.1.4 Electrolytic Tanks and Analog Paper Methods

Two well-known analog methods for plotting electric fields are the electrolytic tank and the analog paper method.

To plot an electric field using the electrolytic method, an electric field is established by placing electrodes in a shallow pan of water. Electric equipotential lines then are mapped out for various distributions of charge by probing points in the pan of water with a voltmeter. The relationship between electric equipotential lines and electric field lines (they are always perpendicular) is used to map the electric field for each charge distribution.

The conducting paper method is somewhat similar in procedure to the electrolytic tank method, the difference being that a conductive paper is used instead of a water tank. The electrode shapes are drawn into the conducting paper using a conducting, silver-based paint and the equipotential lines are measured using a voltmeter.

7.1.1.5 Computer Aided Methods

More precise, two-dimensional and three-dimensional field strength calculations and electric field plots can be produced using any of a large number of electromagnetic simulation software programs now readily available for this purpose.

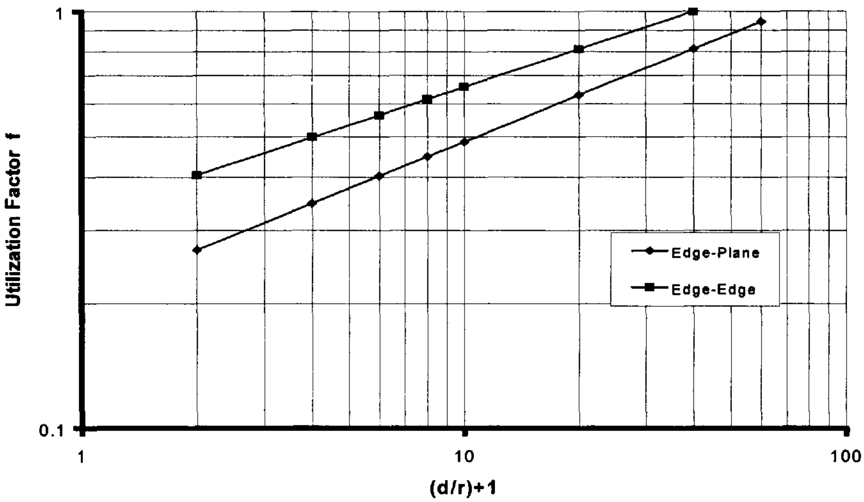


Figure 7.4 Utilization factor for concentric cylinders.

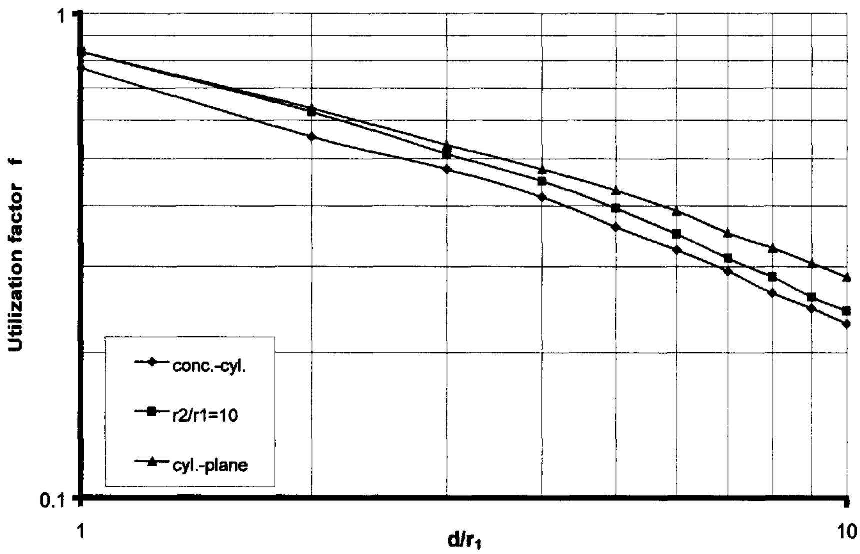


Figure 7.5 Utilization factor for edges.

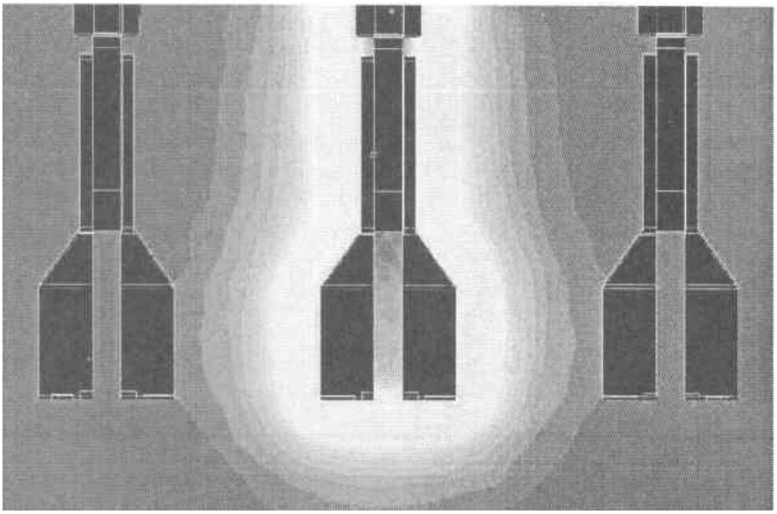


Figure 7.6 Computer simulation of electric field.

Regardless of the techniques used the digital computation provides a solution for the Maxwell equations and by properly choosing the boundary conditions, the grid size, and by increasing the number of charges it is possible to increase the sensitivity of the analysis. Expected accuracy with these methods is the order of ±2%. An example of a computer calculated field plot is shown in Figure 7.6.

7.1.1.6 Design Factors to Consider

Dielectric calculations should only be used as guidance for design purposes. Calculations will serve to establish sufficient margins of safety. Absolute compliance to calculated values can not be expected from a piece of equipment because there are a number of factors that may influence the ultimate withstand capability of the equipment. Notable factors affecting withstand capability are:

- The effects of surface finish of the electrodes [2]. Surface irregularities and projections in the cathode are especially significant as localized high field intensities that result in enhanced emission and ionization that may result in a significant lowering of the breakdown voltage. In general it is advisable to have a surface finish of better than 10 μm. This condition merits special consideration when the electrodes are the circuit breaker contacts since mechanical operations and current interruption significantly alter the contact finish.
- Contamination by metallic particles which are left between the electrodes where they can acquire a charge and then move to a place where they can cause a breakdown that is initiated by the enhanced fields at the particles. In

some cases to avoid this condition it is advisable to use some form of a particle trap [3].

7.2 TYPES OF INSULATION

Insulating mediums or materials are used in circuit breakers to provide mechanical support of structures and at the same time to provide electric isolation between the conducting parts and ground. They are also used to provide isolation between the open contact gaps and in all cases the insulating medium across the gaps also constitutes the interrupting medium of the device.

In high voltage circuit breakers fluid insulating mediums are generally used in combination with solid materials. Gases, primarily air or SF_6, liquids, in particular mineral oil, and vacuum have been used for the dual purposes of isolation and interruption. The type of solid materials used in circuit breakers depends primarily on its intended application; porcelain, epoxy, and silicone rubber are used for entrance bushings. Reinforced epoxy is used for interrupting chambers and a number of inorganic materials are used as barriers, support insulators and insulating links.

7.2.1 Gaseous Insulation General Principles

Although there are a number of pure gases or gas mixtures that exhibit good insulating capabilities the most commonly used gases that have been used in circuit breakers are air and SF_6. These gases in the past were utilized both as an interrupting medium and as an insulating medium. However, in modern circuit breakers, for this dual role, only SF_6 is used and this is due primarily to its excellent properties as a current interrupting and as an insulating medium.

Regardless of the gas used there are some similarities in the behavior of gases when used for insulation purposes. Among these are the dependence of their dielectric strength upon pressure, temperature, gap length, and field uniformity.

Table 7.2
Coefficients α, β, and τ
for Various Gases

GASES	WEIGHT Gm/Mole	COEFICIENTS		
		α	β	τ
Argon	39.95	0.856	0.901	4.31
Nitrogen	28.01	0.854	0.829	76.3
Air	28.8	0.899	0.878	75.4
SF_6	146.1	0.995	1.01	214

From these factors the ones that may be considered to be the most significant are pressure and gap length. Generally the breakdown voltage for gases is given as a function of gap length for several pressures.

It has been shown however [4] that for a sealed volume the breakdown voltage is constant for temperatures lower than –50°C and greater than 800°C and that the voltage breakdown depends on the density rather than the pressure or the temperature alone. For this reason it appears that it would be desirable to have an expression that allows the calculation of the breakdown voltage as a function of the gas density. Such an equation has been derived [5] and is given below.

$$V = \left(\frac{P}{RT}\right)^{\alpha} \times d^{\beta} \times \tau$$

where

V = Breakdown voltage (kV)
P = Pressure (absolute) in atmospheres
R = Constant = 0.08205 liter-atm/mole-°K
T = Temperature in °K
d = Gap length in mm
α, β, and τ = Empirical coefficients

The coefficients α, β, and τ are independent of gap length and pressure and vary only as a function of the gas used. These values have been obtained from available equidistant and isobar curves that have been plotted using known breakdown data and are tabulated in Table 7.2.

7.2.2 Paschen's Law

As it has been stated the breakdown voltage of a gas in a uniform field is a function of the product of the relative gas density (δ) and the gap or electrode separation. If the gas temperature is constant, then the breakdown voltage becomes a function of the product of pressure and gap distance.

This relationship is what is commonly known as Paschen's Law. The theoretical shape of the curve is shown schematically in Figure 7.7. Paschen's law is valid only for uniform field conditions and all gases fail to obey this law at some point. The failure of Paschen's law generally occurs at stress levels on the order of 10–20 MV/meter and at gas pressures above 10 atmospheres. These deviations are caused by distortions of the electric field produced by field emission often caused by electrode surface or contamination conditions.

From a design point of view the usefulness of this law may be viewed as being rather limited, but nevertheless it does provide some guidance as to what to expect from a design.

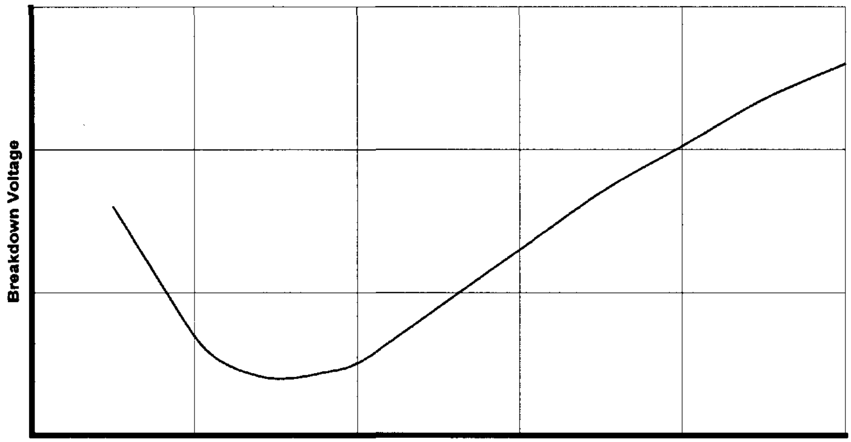


Figure 7.7 Typical shape representation of Paschen's Law.

For applications using gaseous insulation the design should be based on characteristics that insure that such design will lie in the region located to the right of the minimum point in the curve shown in Figure 7.7.

The breakdown voltage may be calculated for a simple uniform field in SF_6, where Pashen's law is still valid, and only for the region in the range of $100 \le pd \ge 2000$ mm kPa using the following equation:

$$V_S = C \times pd + Y$$

where:

V_S = Breakdown voltage in kV
C = Constant = 87.8 V/mm kPa
p = Pressure in kPa
d = Gap length in mm

The value for the constant C is the critical value for ratio of the electric field to the pressure where the net ionization is zero [6].

7.2.3 Factors Influencing Dielectric Strength

It was mentioned earlier that there are a number of factors that can influence the expected dielectric performance of a given design. Among these there are two which deserve special mention.

1. Electrode conditioning
2. Voltage waveform

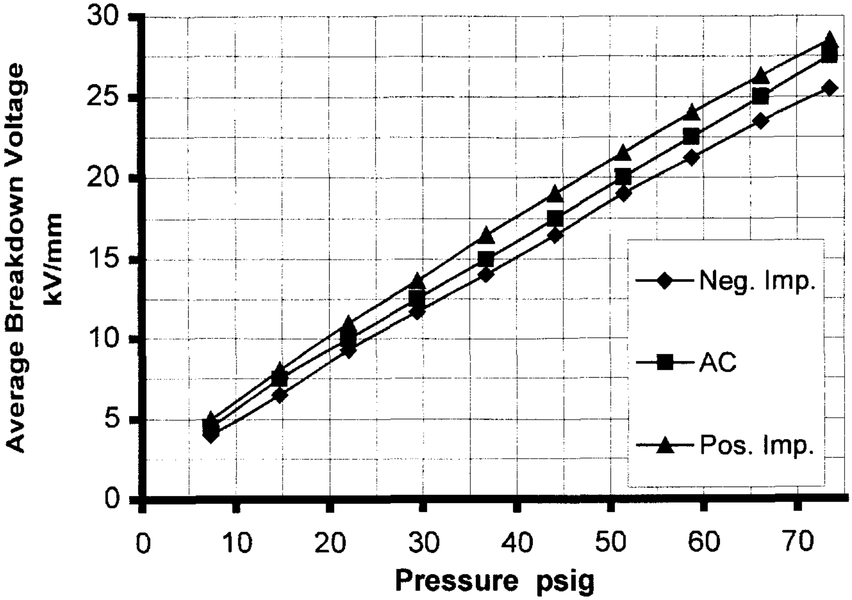


Figure 7.8 Average breakdown voltage in SF_6 as a function of waveform.

7.2.3.1 Electrode Conditioning

Although the mechanics of electrode conditioning are not fully understood, its effects have been extensively observed. At lower pressures the breakdown voltage appears to be independent of how many breakdowns have occurred previously across the gap. But at higher pressures and at fields of about 10 MV/m, which coincidentally are similar to where Paschen's Law does not hold, the breakdown voltage can increase as a function of successive flashovers until a relatively constant value is reached.

For a designer this condition poses somewhat of a dilemma. Circuit breakers are seldom if ever preconditioned prior to installation and since the equipment is designed to avoid discharges during operation then spark conditioning does not happen. On the other hand the values of breakdown voltage that are available for reference are conditioned values. Consequently, when using these references care should be exercised and sufficient margin must be provided to account for this conditioning effect.

7.2.3.2 Voltage Waveform

In non-uniform fields it is observed that there is a variation on the breakdown voltage level that is related to the waveform of the applied voltage. Lightning impulses reach higher breakdown levels followed by switching impulse and then by the power frequency voltage (see Figure 7.8). There is also a difference in the impulse voltages; those of the negative polarity are lower than positive polarity voltages. In general it is found that the difference in the breakdown voltage levels between these waveforms are about 10% from each other. It is also worth noting that no difference in breakdown voltage levels is found between dc and ac sources.

It should be noted that due to the above described properties achieving the 60 Hz withstand capability in a SF_6 circuit breaker does not present a problem. Once the minimum impulse capability is met then the circuit breaker is inherently over-designed for its power frequency withstand.

7.3 AIR INSULATION

Today pressurized air is no longer used for electrical isolation. However, it is unavoidable to depend on air under normal atmospheric conditions to provide external insulation for circuit breaker components, such as for entrance bushings, standoff insulators and operating rods.

A family of curves for the breakdown values of air at different gaps and pressures and for two electrode configurations is given in Figures 7.9 and 7.10. This is done to provide a source of reference for those older and now obsolete air blast circuit breakers that use pressurized air as the insulating medium and that still are in service.

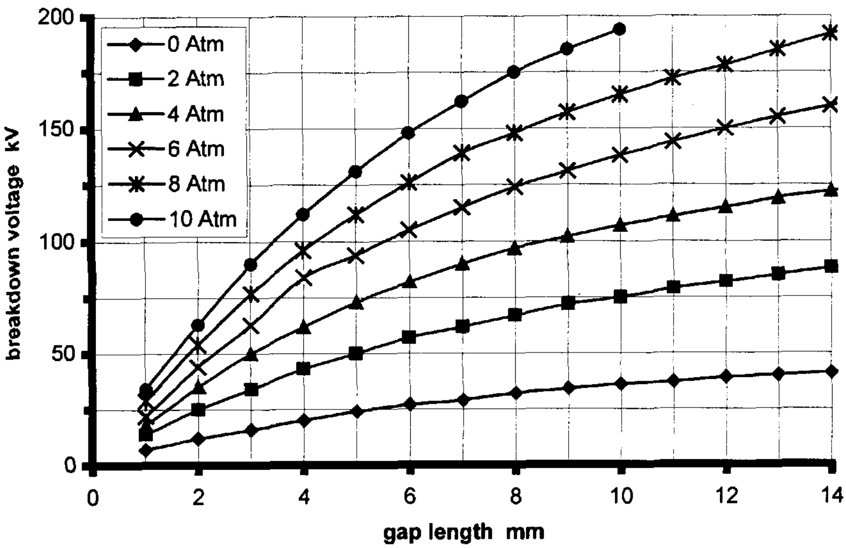


Figure 7.9 Breakdown voltage in air spherical electrodes.

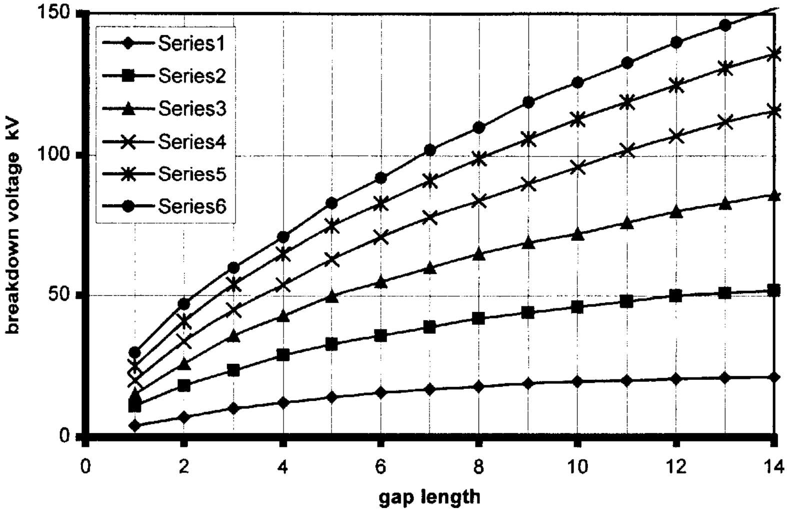


Figure 7.10 Breakdown voltage in air for simulated breaker contacts.

For those interested in making a comparison between air and SF_6 the data in Figures 7.9 and 7.10 and those shown in Figures 7.11 and 7.12 were obtained using the same test conditions and electrode configuration thus making direct comparison of the data possible.

7.4 SF_6 INSULATION

The aim of this section is to review the dielectric properties of SF_6 to provide a compilation of available data and to introduce a simplified general case approach to the design of switching equipment using SF_6 as the insulating medium.

The qualitative general principles for dielectric behavior of gases are all applicable to SF_6 and it is only the differences in the quantitative properties that have to be taken into account.

A very important characteristic is that the dielectric strength of SF_6 is approximately 2.5 times that of air under the same conditions of temperature and pressure. It is also important to know that SF_6 maintains its high dielectric strength even when it is mixed with other gases [7], [8].

Typical measured values for the voltage breakdown of SF_6 are shown graphically in Figures 7.11 and 7.12. The differences in the breakdown voltage level between Figures 7.11 and 7.12 are the result of the geometry of the electrodes that were utilized for the measurements. In Figure 7.11 a sphere to sphere configuration is used. For Figure 7.12 the electrode shape is one representative of a simple contact structure.

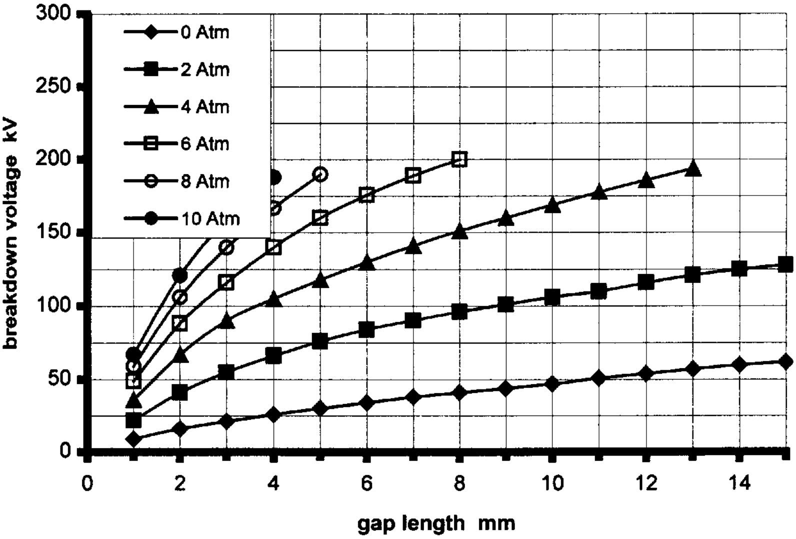


Figure 7.11 SF_6 breakdown voltage spherical electrodes.

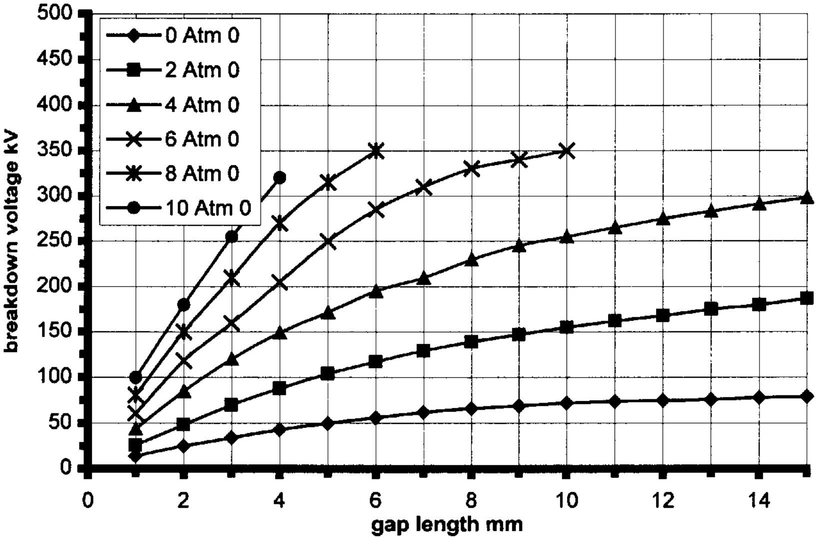


Figure 7.12 SF_6 breakdown voltage for simulated breaker contacts.

Obviously these observed differences serve to emphasize the fact that absolute values for breakdown voltages are only relative to the configuration used to acquire the data, and that the value of these published values should serve only as a guidance for a "ball park" design.

7.4.1 Simplified Design Approach

It is often desirable to have some method by which a quick approximation can be made for design purposes. Based on an empirical formula, on accumulated design experience and on available published data it is possible to define an approximated impulse breakdown voltage for a number of equivalent geometric configurations.

The breakdown voltage can be obtained by solving the following equation:

$$E_C = \frac{V}{(P)^n f d}$$

where:

E_C = Breakdown voltage gradient constant (kV per inch per psia)
V = Impulse breakdown voltage (kV)
P = Absolute SF_6 pressure (psia)
d = Gap length (inches)
f = Utilization factor (see Section 7.1.2.1)
n = Pressure exponent = 0.86 (empirical constant)

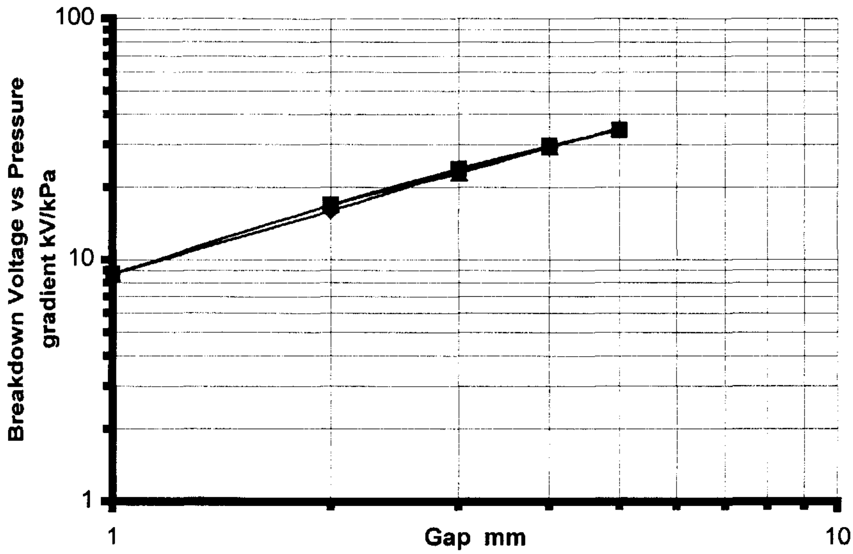


Figure 7.13 Pressure exponent n.

Table 7.3
Critical Breakdown Values for Metals

OFHC Cu	Al	Ni	Nb	Mo	Cr	St. Steel
48 kV/m	30 kV/m	68 kV/m	52 kV/m	54 kV/m	53 kV/m	59 kV/m

The values of the two constants E_C and n have been derived from the available voltage breakdown data shown in Figure 7.11.

For the breakdown gradient a value of 19 kV/inch/psia or 7.45 kV/mm/bar is recommended for negative polarity voltages and 21 kV/inch/psia or 8.25 kV/mm/bar for positive polarity (1 bar = .1 kPa = 14.5 psi). These are conservative values, which have proven to provide satisfactory results for many designs.

The exponent n is calculated from Figure 7.13 which is plotted using the data shown in Figure 7.11. The value 0.86 was obtained by calculating the slope of the breakdown voltage-pressure gradient in relation to the gap distance.

7.5 VACUUM INSULATION

Voltage breakdown across a gap in vacuum is the result of electron emission rather than the avalanche mechanism found in the breakdown of gases. Small changes in voltage will, in general, produce large changes in emission. This is especially so as the breakdown voltage level of the gap is approached. The electrical breakdown in vacuum can be regarded as a process that is primarily dominated by the electric field at the cathode.

Gap distance. The breakdown voltage in vacuum is proportional to the gap distance; however, it has been observed that the voltage gradient for gaps in the order of 1 to 2 mm is in the range of 50 to 100 kV per mm, depending on the contact material. With contact gaps larger than 2 mm the gradient decrease to values in the range of 20 to 30 kV per mm.

Vacuum pressure. It is also noted that for the small gaps (< 2 mm) and for pressures below 10^{-4} Torr and up to 10^{-7} Torr the breakdown level is independent of the pressure. For larger gaps and for pressures above 10^{-4} Torr the breakdown level does vary with pressure and it falls off rather sharply. In view of this characteristic the operating pressure range for available vacuum interrupters is in the range of 10^{-3} to 10^{-8} Torr.

Electrode material. It was mentioned that the type of electrode material has an influence in the breakdown voltage level. Available data [9] show that there is a small variation of critical field corresponding to the breakdown of a given cathode material as a function of the type of material.

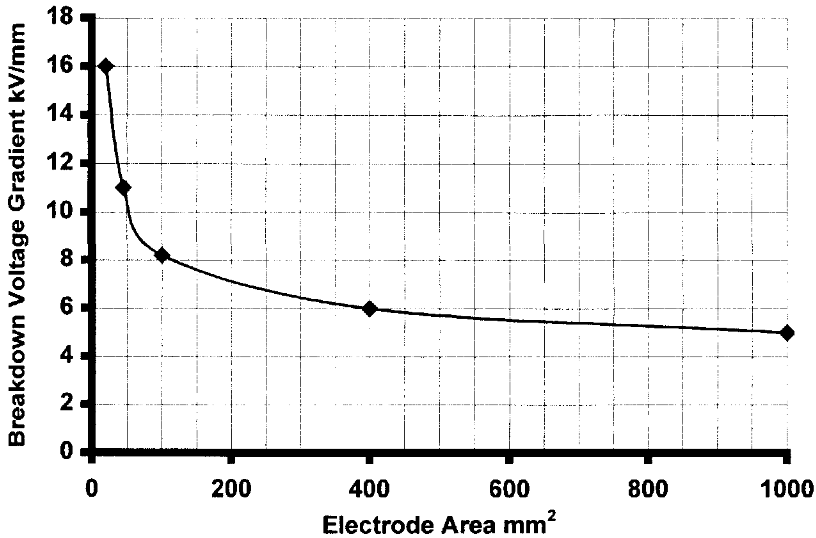


Figure 7.14 Breakdown voltage in vacuum as a function of electrode area.

It also shows that for larger electrode areas it is essentially constant for each type of metal. Typical values for the critical breakdown for various metals are given in Table 7.3.

Electrode geometry and area. The influence of the electrode geometry upon the breakdown voltage in vacuum is not as important as in gases, but the electrode's area, at least for gap distances shorter than 1 mm as shown in Figure 7.14, is shown to have a significant influence [10].

Conditioning. The effects of conditioning are similar to those observed in high-pressure gases. Repetitive sparking across the electrodes generally will produce a final value having a greater than two-fold increment over the pre-conditioning breakdown voltage level.

7.6 SOLID INSULATION

Solid insulating materials are used extensively in a circuit breaker. These materials are needed for structural support as stand-off insulators and bushings, as mechanical links and operating rods to transmit the motion from the mechanism to the contacts or simply as barriers to improve the withstand capabilities of a particular design.

The selection of a particular material should always be based in the choice of the optimum characteristics of the material for the intended application. Nevertheless in most instances some degree of compromise is always necessary when selecting these materials due primarily to the extensive number of compounds and the diversity of characteristics that are available. The best compromise must be one where as a minimum the properties listed below will be taken into consideration.

Mechanical. Tensile, compressive, shear, impact and fatigue strength. Porosity, moisture absorption. Material hardness and brittleness.

Electrical. Volume and surface insulation resistance, dielectric strength, dielectric absorption, power loss, power factor, arc resistance, surface tracking, ionization resistance.

Chemical. Stability of compound. Resistance to acids, alkyls, oils, sunlight, ozone. Flash and fire point, combustibility; compatibility with arced by-products, more specifically with SF_6.

Thermal. Specific heat, coefficient of expansion, softening, melting, boiling and freezing temperature limits. Thermal resistance, thermal stability.

7.6.1 Solid Insulation: Basic Concepts

To provide a basic understanding about the behavior of insulating materials basic concepts related to insulators in general and to solid insulators in particular are briefly reviewed. Since insulating materials are not truly perfect insulators there is always some current flow across the material. However, the conductivity is so low that this current can be neglected. The current flow through insulation is called leakage current and is composed of absorption, displacement and conduction currents. The absorption and conduction currents are quite low and therefore current flow in an insulator is largely by displacement.

7.6.1.1 Dielectric Circuit

A basic dielectric circuit represents an elementary conception of a circuit composed of a dielectric material which is subjected to an electric stress produced by a source of voltage. The circuit takes into account the normal properties of the dielectric material at voltage stresses that are below the rupturing strength of the material.

Since the total insulation resistance of a solid material is the combination of the volume insulation and the surface insulation resistance, one approach is to represent these insulation resistances as two parallel branches. One represents the permittance and the absorption losses or volume resistance. This branch is composed of a capacitor in series with a resistor. The second branch has only a resistor that represents the leakage losses.

The volume resistance is dependent upon the volume resistivity of the material and is generally expressed in terms of mega-ohm-centimeters. For most practical purposes this resistance is negligible when compared to the surface resistance. However, if the volume resistivity is less than 10^8 mega-ohm-centimeters and when the insulator is placed in an atmosphere with a humidity of less than 25% a greater share of the leakage current will flow through the material. Surface insulation resistance depends on conduction through a thin film of moisture sometimes enhanced by dust or foreign material collected on the surface of the insulating material. When the volume resistance is ignored, since as it was said before it is normally negligible, it is possible to simplify the circuit to that which is shown in Figure 7.15 (a), where the series resistor is omitted.

7.6.2 Dielectric Loss

In a dielectric, when acted by a changing electric field, the dielectric loss is the time rate at which electric energy is transformed into heat. Absorption and leakage currents constitute the primary sources of dielectric loss, absorption being the most significant component in most insulating materials.

The dielectric losses in a material are all related to the dissipation factor, the power factor, and the permittivity or dielectric constant.

7.6.2.1 Dielectric Constant

The dielectric constant or permittivity is that property of a material that determines the amount of electrical energy stored in an insulator when an electrical field is applied across.

The following are typical dielectric constants for some commonly used materials:

Vacuum	1.0
Pure Teflon	2.1
Epoxy glass (G10)	5.2
Paper phenolic	4.6 - 6.0
Polycarbonate	3.0
Nylon	4.0
Ceramic	9.0 - 10.0

7.6.2.2 Dissipation Factor

The insulation dissipation factor, also known as tan δ, is the measurement of the resistive losses. It corresponds to the tangent of the dielectric loss angle, see Figure 7.15 (b), which can be expressed as the ratio of the equivalent series resistance to an equivalent capacitive reactance. It can also be defined as the ratio of the real power generated by the losses in a dielectric divided by the total voltage applied to the dielectric times the magnitude of the current that is flowing through it.

The dissipation factor measurement leads to conclusions regarding the general dielectric condition of the insulator and can be used to determine the amount of deterioration of the insulating component material. The tan δ measurements are generally considered to be a primary quality control measure.

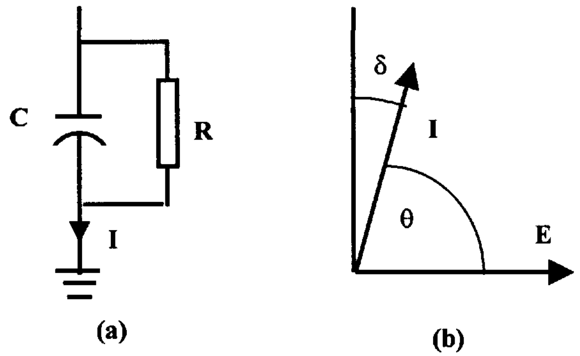


Figure 7.15 Dielectric circuit and insulation phase relations of current.

7.6.2.3 Thermal Deterioration

Changes in temperature can lead over a period of time to deterioration and failure of an insulating material. This situation arises when the heat input into the insulator exceeds the heat being lost to the ambient. The heat input is a function of the dielectric constant and the dissipation factor. Numerically the power generated at the insulator is equal to:

$$W = 2\pi f E^2 \varepsilon \tan \delta$$

where:

W = Watts per cm^3
f = Power frequency
E = Applied volts rms.
ε = Dielectric constant
δ = Loss angle

Since both the dielectric constant and the dissipation factor increase with temperature, then the dielectric losses become a function of the ambient or surrounding temperature. Other factors such as partial discharges and moisture can also produce a change in the dissipation factor thus increasing the losses of the material. It should be noted that the above are applicable only to insulation other than porcelain.

7.6.3 Layered Insulation

In some applications it may be impractical to provide a homogeneous insulation. An alternate solution is to insert solid insulating material into the space, thus creating a composite or laminated dielectric structure. The layers in this structure are normally comprised of materials that have a different dielectric constant and therefore the final assembly may be regarded as being made up of a number of capacitors in series. Each layer of insulation would represent a capacitor.

In such cases the voltage stresses applied to any of the layers in a uniform electric field normal to the layer are directly proportional to the thickness and inversely proportional to the dielectric constant of the material. This relationship is one that must be carefully evaluated whenever this approach is taken in a design. Laminating insulation in some cases can improve the overall dielectric strength. However, proper selection and placement of the insulation are important in order to avoid a situation where instead of improving the withstand capability the opposite result is achieved. An insulating material with a low dielectric constant placed so that the air gap is maximized will be a correct solution.

7.6.4 Partial Discharges

Partial discharges are small electrical discharges that take place in a gas filled void or on the dielectric surface of a solid or liquid insulation system. The discharges are basically small arcs that only partially bridge the gap between phase-to-ground and phase-to-phase insulation. For surface discharges the partial discharge inception voltage, which is the voltage level where the first discharges are detected, depends mainly on the sharpness of the conductors. For voids it depends on the geometry of the void, the gas pressure and the thickness of the void.

Gaps or voids within the material may be the result of thermal or mechanical aging or simply a material defect. In any case the partial discharge serves to provide an early warning of an imminent equipment failure. The ultimate failure is the result of the cumulative heating effect caused by the discharges. This can lead to the formation of deeper pits within the voids of the material that will eventually puncture the insulator. In other instances it may take the form of insulation tracking across the surfaces that may have been made conductive by chemical attack and by the deposit of carbon, which is usually one of the by-products of organic materials which have been subjected to arcing.

The type and rate of deterioration of the insulation and the time until breakdown takes place depend mainly on: (a) the chemical and thermal stability of the material, (b) the thickness of the material, (c) the presence of contamination, (d) the applied voltage stress and (e) the ambient temperature and humidity.

The deteriorating effects of partial discharges are primarily dependent on the material being subjected to the partial discharge. Porcelain, ceramics and glass are practically immune to partial discharges. Some filled epoxy resins are moderately resistant, while oil impregnated paper, for example, deteriorates very rapidly.

Ideally there should be no discharges in a circuit breaker since the life of insulating materials decreases exponentially with increasing voltage above the discharge inception voltage [11]. However, to expect zero discharges is not practical and it is generally acceptable to accept a maximum limit for partial discharges. Experience has shown that a discharge of less than 10 pico-coulombs at 0.75% of line-to-ground voltage is acceptable.

7.6.5 Insulating Materials

The choice of materials available to provide dielectric isolation in a design is quite extensive and as it was said before the choice comes down to the best possible compromise.

Porcelain and some types of polymers are used extensively. Polymers are especially suitable since their properties can be tailored to meet specific needs. There are literally thousands of plastics available and a large number of these are suitable for applications as electrical insulators. In actual practice though only a relatively few are found consistently on most circuit breakers.

Following is a brief description of the generic groups of materials and in Table 7.4 a list of a few often-used materials and their properties is provided as a source of reference.

7.6.5.1 Porcelain

Porcelain can be considered to be a classic and traditional material that has been used since the early stages of circuit breaker history and still is the preferred choice in many applications.

Porcelain is generally used for entrance bushings and for support and stand-off insulators. It offers excellent mechanical compressible strength and it is impervious to tracking.

Porcelain is a ceramic material that is made by mixing in approximately equal proportions kaolin, also known as china clay, feldspar, whose chemical composition is $K_2O + Al_2O_3 + 2SiO_2 + 2H_2O$, and quartz. Porcelains for high dielectric strength applications are generally casted, they are then dried, finished to dimensions, glazed and fired.

The imperviousness of porcelain to tracking is not obtained by the application of the glazing, but by the vitrification of the material itself. The glazing constitutes only a coating to enhance the finish but it also serves to prevent accumulation of dirt.

7.6.5.2 Polymer Concrete

This is a material that started to be developed in the 1970's and was then known as Polycer. The first products developed were a composite of epoxy and pulverized ceramic.

More recently it has been reformulated into a composite material, which uses an epoxy resin and selected earth materials, including sand. This material is now beginning to be used more frequently in the medium voltage applications as a direct replacement for porcelain.

It offers comparable mechanical and electric characteristics to porcelain with the added advantage that metallic inserts can be molded directly into the final design. It also offers a greater resistance to shattering than porcelain.

Table 7.4
Insulation Materials Properties

	Porcelain	Polyurethane	Polyester	Polycarbonate	Epoxies		PTFE	Phenolic
					Bisphenol A	Cycloaliphatic		
Tensile strength psi × 10^3	3.0 8.0	4.0 9.0	16.0 23.0	9.0 10.5	4.0 13.0	10.0 20.0	3.35	5.0 7.0
Compressive Strength psi × 10^3	30.0 80.0		22.0 25.0	12.5	15.0 18.0	15.0 18.0		36.0 70.0
Flexural strength psi × 10^3	9.0 15.0	.6 1.0	24.0 33.0	11.0 15.0	13.3 21.0	15.0 32.0	no break	9.0 11.0
Deflection Temp. degree F		145	302 354	280	115 550	200 450	250	350
Dielectric strength volts / mil	250 400	450 500	300 400	380 400	300 500	420 440	500 600	400
dielectric constant	5.7 7.0	6.7 7.5	.6	3.02	3.5 4.5	3.9 4.5	2.1	4.9 6.5
dissipation constant tan δ	.017 .025	.05 .06	018	.0021	.002 .02	.003	.0005	.025 .10
volume resistivity ohm-cm	10^{14}	10^{11}	10^{14}	10^{16}	10^{13} 10^{17}	10^{15}	$>10^{18}$	10^{11} 10^{13}
Arc Tracking ASTM D495			80 40	100 120	45 120	150 180	>300	184

7.6.5.3 Polyester Molding Compounds

These are used in a variety of functions in a circuit breaker, from interrupter chambers to phase barriers and standoff insulators. Polyester resins are rather unique because unlike others plastics they contain substantial amounts of several materials which are used as additives to yield specific properties. Alumina oxide trihydrate fillers for example are used to improve resistance to tracking, silica powder is added to decrease the thermal expansion coefficient so that a better match to that of the conductor is achieved.

Polyesters are available as either thermosetting or thermoplastic compounds; thermosets come as either Bulk Molding Compounds (BMC) which are a mixture of polyester resin, short glass fibers (1/4 to 1/2 in. long), filler, catalyst and any other required additive, or as Sheet Molding Compounds (SMC) where the sheets are basically similar in composition to BMC except that they contain longer (up to 2 in.) glass fibers.

Glass polyester products are available in three grades.

GPO-1. This is an economy grade that has good electrical and mechanical properties. It offers a higher compressible and flexural strength than the other two grades but it has a lower dielectric strength.

GPO-2. This is similar to GPO-1 but utilizes a flame-retardant resin. Of the three types this material has the lowest arc resistance characteristic.

GPO-3. This is the material most commonly used in circuit breakers. It offers a flame retardant, high dielectric strength, and high arc and tracking resistance.

7.6.5.4 Polycarbonates

Polycarbonates are used specially for phase barriers in medium voltage applications, and in some non-critical situations on high voltage assemblies. Toughness, heat and flame resistance and dimensional stability characterize polycarbonates. Their electrical characteristics are excellent and they are relatively unaffected by temperature or humidity.

7.6.5.5 Epoxy Resins

Epoxies have a wide range of applications in circuit breaker designs. Epoxies have extremely good electrical, thermal and chemical resistance characteristics. Molded parts are hard and rigid with excellent dimensional stability although they tend to be brittle. The combination of mechanical strength and outstanding electrical characteristics makes them suitable to be utilized not only as insulating members but also as electrically stressed structural parts.

A widely used epoxy resin is based on the reaction of ephichlorohydrin with bisphenol-A. For applications requiring resistance to arc tracking and weathering cycloaliphatic resins are preferred.

7.6.5.6 Fluoroplastics

Of this family of plastics, polytetrafluoroethylene (PTFE), or more commonly known by its trade name Teflon (Du Pont), is widely used for gas-blast nozzles. The material is characterized for its chemical inertness and its high stability at high as well as low temperatures. Dielectric strength and surface arc resistance are very high and they do not vary with temperature or thermal aging. In addition it has a low dielectric constant and dissipation factor. Both remain stable over a wide range of frequencies and environmental conditions.

7.6.5.7 Phenolics

Phenolic compounds are widely used in a variety of applications. They are used primarily in compounds containing either organic or inorganic reinforcing fibers and fillers. The phenolic resins are also used as bonding and impregnating materials. Low cost, superior heat resistance, high heat deflection temperatures, good electric properties as well as water and chemical resistance characterize them.

7.6.5.8 Others

Other materials such as polyurethane and silicone-rubber are being used for specific purposes. Polyurethane can be found as an external coating to increase surface flashover. A number of vacuum interrupters utilize this approach to meet BIL requirements. Silicone-rubber is increasingly gaining acceptance for use as housings for outdoor bushings. Among its advantages are its lighter weight, less susceptibility to seismic or damage caused by vandalism and its reduced maintenance as a result not needing to be washed periodically.

A variety of insulating papers specifically designed for application as insulators and often called "transformer paper" are used mainly in entrance bushings.

7.6.6 Solid Insulation Design Guidelines

When evaluating a material for insulation purposes the first thing to be considered is the short- and the long-time dielectric withstand capabilities of the material. The short-time dielectric strength is associated to the withstand capability under lightning and switching impulses while the long-time capability relates to the ability of the materials to maintain their integrity when subjected to the continuous stress produced by the rated maximum operating voltage during the lifetime of the equipment, which in most cases is assumed to be 40 years.

Short-time capabilities are basically defined by the breakdown strength of the material, which are usually given in terms of kV per mil and by the surface resistivity. In general the breakdown voltage of the material is not a problem since most materials offer a breakdown value greater than 300 volts per mil or about 15 kV per millimeter. The surface resistivity can be widely influenced by the ambient and is difficult to define a value for any specific material. In most cases it is acceptable to use a fixed stress gradient value. Experience has shown that under ideal conditions a stress gradient of 500 to 600 volts per millimeter can be used.

However for high humidity conditions the acceptable stress gradient should be reduced to 300 volts per millimeter.

For applications where a spacer-electrode geometry is used and provided that the insulator has a higher breakdown voltage than the gas, the external flash-over voltage across the insulator should be the same as the inherent breakdown voltage of the gas across the electrodes in the absence of the insulator. In practice, however, the breakdown voltage across the insulators is reduced. This reduction is often attributed to imperfections at the points of contact and possible contamination on the surface of the insulators. Typical reduced values are between 0.5 and 0.9 of the open gap breakdown voltage. It is also found that a smooth cylindrical spacer generally offers a higher breakdown capability. For indoor applications in air at atmospheric pressure the recommended maximum voltage gradient is 100 volts per millimeter. For outdoor application the gradient is reduced to between 10 to 20 volts per millimeter depending upon the ambient conditions.

Long-time dielectric failures are caused mainly by thermal instability and by tracking and erosion. Tracking corresponds to the condition where a conducting path is created along the surface of an organic material insulator. It occurs when a conducting film is formed along that surface when atmospheric moisture is trapped by dust or any other pollutants that have been deposited on the surface of the insulator. The moisture itself plus any electrolytes originating from the contamination materials usually combine to form a vehicle for the conduction of leakage currents. The flow of these currents produces a heating effect which serves to evaporate the moisture; as this takes place the resistance increases locally and therefore a higher voltage appears across these areas leading to possible small discharges. The discharges can cause localized heating that can eventually produce a material degradation. This degradation can be progressive and as a limit it may cause a complete flashover of the insulator.

Materials that carbonize as a result of the heating will create tacking. Those that will decompose in the form of a volatile element will erode. Cycloaliphatic epoxy resins, nylons, Teflon, and polyethylene are among those materials that erode while bisphenol epoxies, polycarbonates and paper-based phenolics are among those which track.

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8

A COMPARISON OF HIGH VOLTAGE CIRCUIT BREAKER STANDARDS

8.0 INTRODUCTION

The preferred ratings, the performance parameters and the testing requirements of circuit breakers are well-established subjects that are covered by a number of applicable standards. Standards are living documents and as such they have evolved over a long period of time. This evolution process undoubtedly will continue. The future changes in the standards can be expected, not only because of changes in the circuit breaker technology but due to advances in associated technologies. Better, faster, more advanced and more accurate relaying and instrumentation packages using digital equipment are now replacing old electro-magnetic-analog devices. As a consequence some of the old established system operating practices are also undergoing a period of evolution.

In this chapter the most current internationally recognized standards which are represented by the American National Standards Institute (ANSI) and the International Electrotechnical Commission (IEC) will be reviewed. The review will include a discussion of ratings and performance parameters for each standard. Particular emphasis will be placed on the differences that exist between these standards. Where possible a clarification as to the intent and the origin of the ratings will be offered.

To have a basic understanding of the standardization process it is always beneficial to have some familiarity with the organizations involved in the creation of those standards and, thus, a summary that includes their historical background, their internal organization and their established process procedures will be offered.

A number of significant changes in the ANSI documents have taken place recently. These changes will be discussed and the prior, now obsolete, standards still will be discussed, if for no other reason, to provide a source of reference for those users that have equipment in service which may have been designed to those old standards.

The section in the standards dealing with power testing of circuit breakers deserves special attention and therefore the next chapter will be dedicated completely to this subject.

8.1 RECOGNIZED STANDARDS ORGANIZATIONS

The two most recognized and influential circuit breaker standards in the world are supported by the American National Standards Institute (ANSI) and the International Electrotechnical Commission (IEC).

ANSI is the choice document in the US, and in places around the world where the US has had a strong influence in the development of their electric industry. All other countries that are outside of the sphere of US influence invoke IEC standards. Today practically all of the high voltage circuit breakers being sold worldwide are built to meet the IEC standards.

There are a number of differences between these standards, the most fundamental being the constituency that participated in the development of these documents. ANSI documents are developed under a policy of open participation, meaning that the process is open to all persons who are materially affected by the activity. IEC on the other hand is restricted to participation only by delegates of the member countries.

The format of these two standards is significantly different, and to some extent there are noticeable differences in the technical requirements, but these differences are not so radical to the point of being non-reconcilable. The differences have more to do with local established practices than with fundamental theory and if there is something to be said about experience, then both standards have demonstrated to be more than adequate for covering the needs of the industry. The most significant specific differences will be discussed in the appropriate sections as the generic requirements are reviewed.

A current issue that commands a great deal of attention is that of harmonization between these two standards. The need for having a single standard is becoming increasingly more important. This is so, not only because of agreements reached by the World Trade Organization and the growing globalization of trade, but also because today most, if not all, of the major basic development of high voltage SF_6 circuit breakers is being done outside of the US. Furthermore, all of the major suppliers of this type of equipment are owned by European or Japanese multinational corporations.

8.1.1 ANSI/IEEE/NEMA

The first report on standardization rules in the electrical field can be traced to 1899 when it was prepared by the American Institute of Electrical Engineers (AIEE), now IEEE. In the years that followed, other organizations such as the Electric Power Club, which in 1926 merged with the Associated Manufacturers of Electrical Supplies to become what is now NEMA, became interested in the process of standardization.

Today, most US standards are approved by the American National Standards Institute (ANSI) but they are written and maintained by a number of developers that may consist of professional societies (i.e. IEEE), trade organizations (i.e. NEMA) and other organizations (i.e. Accredited Standards Committee, ASC).

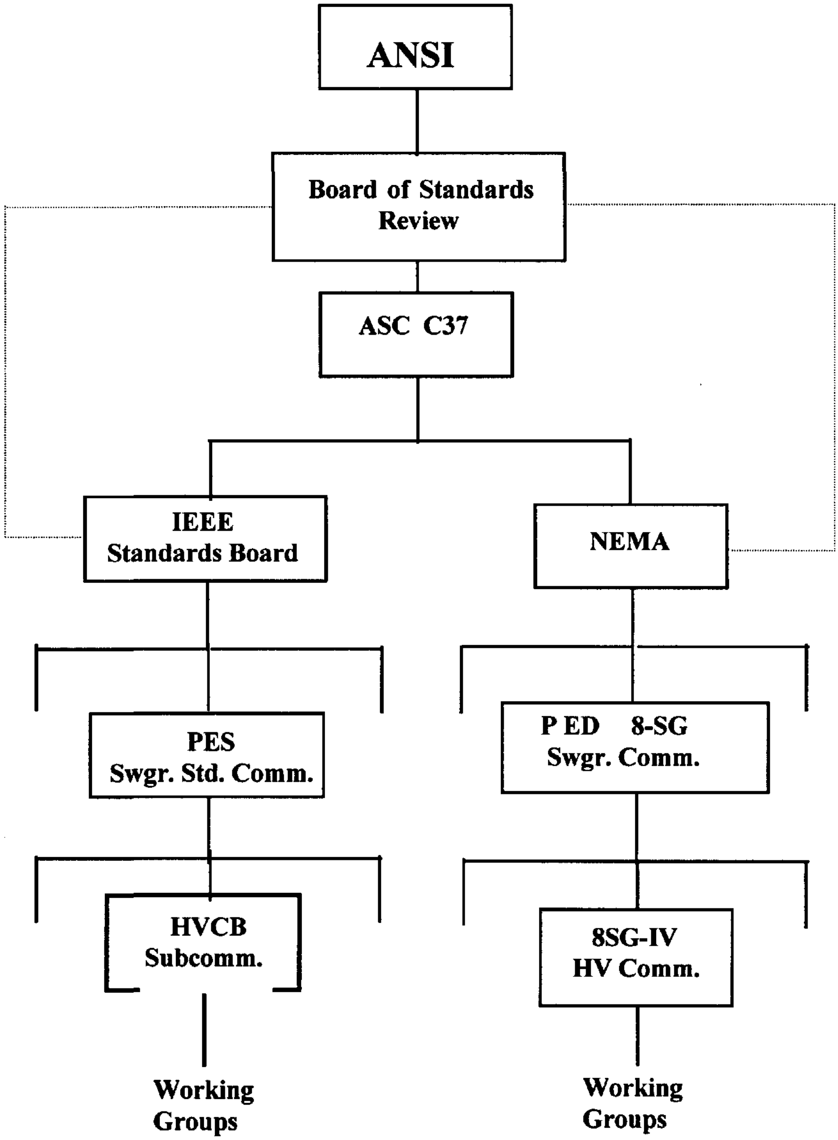

Figure 8.1 Basic flow chart of standards development ANSI/IEEE and NEMA groups dealing with high voltage circuit breaker standards.

High voltage circuit breakers and switchgear standards are, for the most part, developed through the combined and/or separate effort of IEEE and NEMA.

Both IEEE and NEMA participate as co-secretariats of the C37 section of the Accredited Standards Committee (ASC C37). This committee serves as the administrator or the clearinghouse through which the proposed standards are submitted to ANSI for publication as an American National Standard. It is the Accredited Standards Committee who assigns the industry's well-known and readily identifiable series C37 numbers to the ANSI/IEEE/NEMA circuit breakers standard.

In today's scheme, NEMA is responsible for the development of standards that are related to ratings, construction and conformance testing. IEEE responsibility is to develop all other technical standards related to requirements, performance, and testing including design, production, and field testing.

8.1.1.1 American National Standards Institute (ANSI)

ANSI is a private, non-profit organization that acts as a coordinating body for all volunteer standards writing organizations in the US with the aim of developing global standards that reflect US interests. ANSI itself does not develop standards, as an organization it provides the criteria and the process for approving a consensus document.

ANSI is the US member of non-treaty international standards organizations. Some others are the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). As a member ANSI coordinates the activities involved in the US participation in these groups.

The ANSI Board of Directors delegates approval of standards as ANSI to the Board of Standards Review (BSR). Approval and withdrawal of an American National Standard requires verification by ANSI that the requirements for due process have been met.

Due process means that any person (organization, company, government agency, individual, etc.) with any material interest has a right to participate by a) expressing a position and the basis for that position, b) by having that position considered, and c) by appealing if adversely affected.

8.1.1.2 IEEE Standards Association

IEEE is an accredited organization under ANSI procedures and as such it is entitled to submit approved standards to ANSI's BSR for recognition. The IEEE through the Standards Association, which is one of six entities within the IEEE organization, produces standards, recommended practices and guides.

The development process for a document begins with a Sponsor, which in the case of switchgear in general and circuit breakers in particular is the Switchgear Standards Committee. This committee is one of several technical committees that function under the auspices of the Technical Council of the Power Engineering Society and is subdivided into subcommittees, one of which is the High Voltage Circuit Breaker Subcommittee. The membership of the technical committees, subcommittees and working groups of the IEEE consists of voluntary individuals that represent users, manufacturers and interested groups, in a reasonably well balanced proportion.

Once the need for the initiation of a new standards project is determined a Project Authorization Request (PAR) must be submitted to IEEE SA. The PAR is the official document that authorizes the work and is approved by the IEEE Standards Board based on the review and recommendations of the New Standards Committee (NesCom). Once the work is completed and a draft standard is available then the balloting process may begin among the members of a balloting group. The balloting group consists of a number of individuals that represent interested parties, with no domination by any one group or company. What is important here is that the group must be balanced in order to comply with the principles of the standards process.

A successful ballot is achieved whenever consensus is reached. Consensus means agreement of the majority, and according to IEEE rules consensus is defined as having a minimum 75% return of ballots from the balloting group and a 75% approval rate from that 75% return group. One additional requirement is that there can not be more than 30% abstentions in the returned ballots.

After a successful ballot has been achieved then the IEEE Standards Board can approve the standard if its Review Committee (RevCom) so recommends.

8.1.1.3 National Electrical Manufacturers Association (NEMA)

NEMA is a private organization made up of manufacturers of electrical equipment. It is composed of nine divisions representing major categories in the electrical manufacturing industry, and within each division there is a number of product-specific sections. Number 8 of this group is the Power Equipment Division. Among the sections belonging to this division is the Switchgear section, which is generally referred as 8-SG. It is in this section where standards related to high voltage circuit breakers are developed. In most instances these standards are initiated at the request and following the recommendations of the IEEE Switchgear Committee.

8.1.1.4 Accredited Standards Committee C37 Power Switchgear

The Accredited Standards Committee, as its name implies, is an ANSI accredited standards developer. Although the scope of the organization includes the development of standards, which the committee has done in the past, its role is now to provide a forum for the participation of all those interested parties that are not members of either IEEE or NEMA and yet they have an interest on the process. This step is necessary to meet the due process requirements if ANSI approval is being sought.

Membership in this committee includes representation from three standing organizations: IEEE, NEMA and Edison Electric Institute (EEI). In addition committee membership also includes appropriate interested organizations such as

Underwriters Laboratories (UL), STLNA (Short–circuit Testing Laboratories of North America) and any interested government agencies.

8.1.2 International Electrotechnical Commission (IEC)

IEC, as an organization, dates back to the early 1900's. It was founded by a resolution of the International Electrical Congress held in St. Louis (USA) in 1904. Its membership consists of national delegates from member countries that are recognized in the form of national committees. Presently there are fifty-three full members, nine associate and four affiliate members.

Each national committee or full member nation has a single vote. This is one important point to emphasize, because it shows IEC as being a truly international organization where the decisions are approved at the country levels and each country member has only one vote. This represents a major philosophical difference between IEC and ANSI, since ANSI is a national organization where each individual has one vote.

The United States National Committee (USNC) serves as the ANSI sponsored US delegation to the IEC. Within this delegation there are a number of technical advisory groups (TAGs) that are called upon to support the individuals who act in the role of technical adviser (TA). It should be noted that both IEEE and NEMA at the organization and at the member level are heavily involved and have a strong influence within the USNC delegations. As a result most of the USNC members are also members of either or both IEEE and NEMA.

The supreme authority of the IEC is the Council, which is the general assembly of the national committees. Reporting to the Council there are a number of Committees, one of which is the Committee of Action (CA). It is this committee who is responsible for the management of all the IEC standards work. The CA has under its jurisdiction almost one hundred technical committees, one of which is the Technical Committee 17 (TC 17).

The Technical Committee 17 prepares IEC high voltage circuit breaker standards. More specifically, the scope of TC 17 is to prepare international standards regarding specifications for circuit breakers, switches, contactors, starters, disconnectors, busbar and any switchgear assemblies. Subcommittee 17A (SC 17A) is responsible for the current applicable standards IEC 60694 Common Clauses for High-Voltage Switchgear and Controlgear standards and IEC 62271-100 (formerly 60056) High-Voltage Alternating Current Circuit Breakers.

The stages for the development process of a new standard begins with the submission of a proposal for a new work item (NWP). A national committee, technical committee, a subcommittee or any liaison organization may submit these proposals. Approval of the proposal requires an affirmative vote from more than 50% and expert participation from 25% or a minimum of four participating members. If approved the document proceeds to a preparatory stage where a working draft (WD) is developed. From there it advances as a committee draft (CD) which is circulated within the committee for comments.

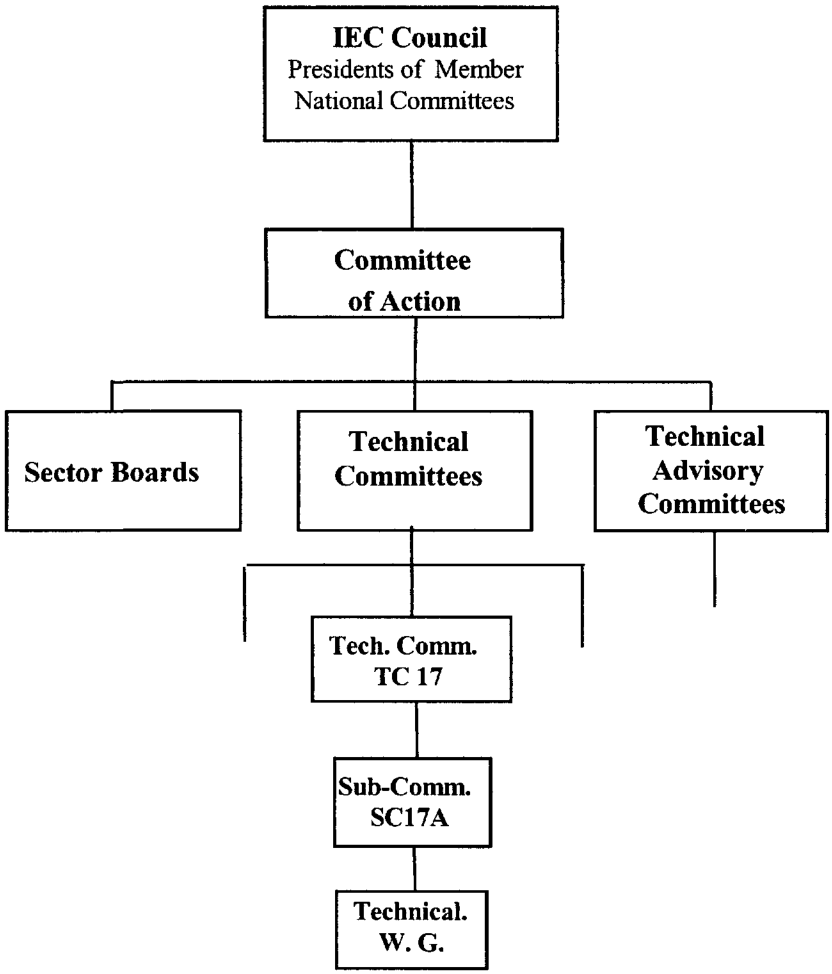

Figure 8.2 Organizational chart of IEC Technical Group 17 dealing with high voltage circuit breaker standards.

The next stage is the issue of a Committee Draft for Vote (CDV). This is the last stage where technical comments may be made. From here, if approved by at least two-thirds of participating members and if there is less than 25% negative votes of the total of voting members, the document advances to the Final Draft International Standard (FDIS). At this stage only affirmative or negative ballots may be cast. Balloting at this stage includes all national bodies and the acceptance criteria are the same as the one for CDV's. The organizational relationship of TC 17 within IEC is illustrated in the accompanying Figure 8.2.

8.2 CIRCUIT BREAKER STANDARDS AND RATINGS COMPARISONS

The core or primary ANSI high voltage circuit breaker standards are ANSI/NEMA C37.06 AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis--Preferred Ratings and Related Required Capabilities, ANSI/IEEE C37.04 IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis, and ANSI/IEEE C37.09 IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis. There are additional documents in the C37 series but these are either complementary documents to the above listed standards or applications guides.

The basic IEC standards are IEC 60694 Common Clauses for High-Voltage Switchgear and Controlgear Standards and IEC 62271-100 High-Voltage Alternating Current Circuit Breakers. The common clauses standard defines and establishes the general requirements that are applicable to all types of high-voltage switching equipment.

IEC 62271-100 is more specific on the requirements and establishes those which differ from the ones that are specified on IEC 60694.

The circuit breaker ratings assigned by the applicable standards are considered to be the minimum designated limits of performance that are expected to be met by the device when operated within specified operating conditions.

The rating structures, in addition to including the fundamental voltage and current parameters, list other additional requirements which are derived from the above listed basic parameters, and which in the ANSI documents are identified as related required capabilities.

ANSI C37.06 contains a number of tables where a list of Preferred Ratings is included. These ratings are just that, "preferred", because they are the ones more commonly specified by users and are simply those which have been selected by NEMA strictly for convenience, and in order to have what could be said to be an "off the shelf" product. The fact that there is a listing of preferred ratings does not exclude the possibility of offering other specific ratings provided that all the technical performance requirements and the related capabilities specified in the appropriate standard (C37.04) are met. The preferred ratings are grouped separately for indoor and outdoor circuit breakers

In the IEC the rating parameters are listed separately; there is not an all-inclusive table of preferred ratings and no generic differentiation between indoor and outdoor circuit breaker is made, except were more specific requirements for either are applicable.

8.2.1 Normal Operating Conditions

ANSI considers as normal or usual operating condition ambient temperatures which do not exceed plus 40°C and which are not below minus 30°C, and altitudes which do not exceed 3300 ft or 1000 m. ANSI does not differentiate service conditions between indoor or outdoor applications.

IEC does differentiate indoor or outdoor applications. It specifies the altitude limit at 1000 m and the maximum ambient temperature as plus 40°C for both applications; however, it additionally specifies that the average of the maximum temperature over a 24 hour period does not exceed 35°C.

For the lower temperature limits there are two options given for each application. For indoor, there is a minus 5°C limit for a class "minus 5 indoor" and a minus 25°C for a class "minus 25 indoor." For outdoor applications there is a class "minus 25" and a class "minus 40." Limits of 1 mm, 10 mm and 20 mm for icing accumulation and 34 m/sec for wind velocity are recognized by IEC. In ANSI the corresponding values are 20 mm of ice and 40 m/sec for wind. ANSI requires a minimum withstand for seismic for all circuit breakers while IEC considers it a special condition.

8.2.2 Rated Power Frequency

This seemingly simple rating that relates only to the frequency of the ac power system has a significant influence when related to other circuit breaker ratings.

The power frequency rating is a significant factor during current interruption, because for many types of circuit breakers, the rate of change of current at the zero crossing is a more meaningful parameter than the given rms or peak current values.

In all cases, when evaluating the interrupting performance of a circuit breaker, it should be remembered that a 60 Hz current is generally more difficult to interrupt than a 50 Hz current of the same magnitude. Both ANSI and IEC recognize 50 Hz and 60 Hz applications.

8.3 VOLTAGE RELATED RATINGS

8.3.1 Maximum Operating Voltage

Whether called rated maximum operating voltage (ANSI) or rated voltage (IEC), this rating sets the upper limit of the system voltage for which the circuit breaker application is intended.

The selection of the maximum operating voltage magnitudes is based primarily on current local practices. Originally ANSI arrived at the maximum operating voltage rating by increasing the normal operating voltage by approximately 5% for all breakers below 362 kV and by 10% for all other circuit breakers above 362 kV.

The practice of using the nominal operating voltage has been discontinued primarily because it has become common practice in other related standards [1],

[2] for apparatus that are used in conjunction with circuit breakers to refer only to the maximum rated voltage.

The IEC rated voltage values are specified in IEC 60694. For rated voltages below 100 kV there are two series of values shown, series I represent the most common values used in Europe while series II is based on the ratings in use in the USA and Canada.

In Table 8.1, the preferred values that are specified in each of the two standards are shown. For circuit breakers above 100kV the ratings that existed until 1997 are shown as the pre-harmonization ratings. Between 1997 and 1999 both, ANSI and IEC were revised to harmonize these ratings. The revised values are shown as post-harmonization ratings. Voltage ratings of 100, 300 and 420 kV are prescribed in the IEC due to the practices in Europe and since these ratings are not common in the US they are not listed by ANSI.

Table 8.1
ANSI and IEC Rated Operating Voltages
(Voltages shown in kV)

For voltages 72.5 kV and below										
IEC	Series I	3.6	7.2	12	17.5	24	----	36	52	72.5
	Series II	4.76	8.25	15	15.5	25.8	----	38	48.3	72.5
ANSI		4.76	8.25	15	15.5 *	25.8 *	27 ***	38 **	48.3 *	72.5 *

For voltages above 72.5 kV (Pre-Harmonization)										
IEC	100	123	145	170	245	300	362	420	525	765
ANSI	----	121	145	169	242	----	362	----	550	800

(Post-Harmonization 1999)										
IEC	100	123	145	170	245	300	362	420	550	800
ANSI	----	123	145	170	245	----	362	----	550	800

* These ratings are applicable to outdoor circuit breakers only.
** This rating applies to indoor and outdoor circuit breakers.
*** This rating was added in 1997 for indoor circuit breakers only.

8.3.2 Rated Voltage Range Factor K

The rated voltage range factor was defined by ANSI as the ratio of the rated maximum voltage to the lower limit of the range of operating voltage in which the required symmetrical and asymmetrical interrupting capabilities vary in inverse proportion to the operating voltage. This rating was unique to ANSI. It represented a carryover from earlier standards that were based on older technologies such as oil and air magnetic circuit breakers where, as we know, a reduced voltage results in an increase in the current interrupting capability. Another reason that was given for the adoption of the K factor rating was the convenience of grouping a certain range of voltages under a common denominator, which in this case was chosen to be a constant MVA, where MVA is equal to: $\sqrt{3}$ × Rated Maximum Voltage × Rated Symmetrical Current.

With the advent of modern technologies, namely vacuum and SF_6, this is no longer applicable. This fact was recognized for outdoor oil-less circuit breakers, and the rated range factor for this type of circuit breaker was eliminated more than twenty years ago. The latest versions of the C37 standards series have obsoleted this requirement, and basically for those accustomed to the old K factor it has now become K=1. For older SF_6 and vacuum circuit breakers it can safely be assumed that the maximum interrupting capability at the minimum operating voltage represents the true capability of these circuit breakers. However, before a decision is made to apply those older circuit breakers with the newer rules it is recommended that the manufacturer be consulted.

8.3.3 Rated Dielectric Strength

The minimum rated dielectric strength capability of a circuit breaker is specified by the standards in the form of a series of prescribed voltage values. These values represent electric stresses that are produced by power frequency overvoltages or overvoltages resulting from switching operations, and by surge voltages that are caused by lightning strikes.

8.3.3.1 Power Frequency Dielectric

The power frequency dielectric withstand capability is one of the earliest parameters that was established as a rating for a circuit breaker. AIEE standards as early as 1919 specified a one minute 60 Hz dry test. The selected voltage value used as the basis of this rating was chosen as being equal to 2.25 times rated voltage plus 2000 volts. In addition to the dry test, a 10-second wet test, which still is required for outdoor equipment, was included. The voltage magnitude chosen for this test was 2 times rated voltage plus 1000 volts. The criterion used for determining the voltage requirements still is approximately the same as before.

In the IEC, at least one of the power frequency dielectric capabilities corresponding to the rated maximum voltages specified in series II is basically the same as in ANSI. Several insulation levels are listed to take into account variations in application criteria such as grounded vs. ungrounded or type of arresters being used.

In all cases there is an additional requirement for a withstand capability across the open isolating gap which is 10% higher than the normal value across non-isolating gaps. This requirement is applicable only when the contact gap is designed to meet the requirements of an isolating gap. There is not a comparable requirement in ANSI.

At voltages above 72.5 kV some of the IEC requirements are lower than the ANSI requirements. For circuit breakers rated 242 kV and below IEC does not have a 10-second wet test requirement as ANSI does.

In general power frequency overvoltages that occur in an electric system are much lower than the power frequency (50 Hz or 60 Hz) withstand values that are required by the standards. Consequently, it can only be concluded that these higher margins where adopted in lieu of switching surge tests, which at the time were not specified and consequently were not performed. It should also be noted that generally the basic impulse level (BIL) withstand capability defines the worst case condition, and when the design of a circuit breaker meets the BIL then that circuit breaker is inherently over-designed for the corresponding standard specified power frequency withstand requirement.

8.3.3.2 Lightning Impulse Withstand

These requirements are imposed in recognition of the fact that overvoltages produced in an electric system by lightning strikes are one of the primary causes for system outages and for dielectric failures of the equipment. The magnitude and the waveform of the voltage surge, at some point on a line, depends on the insulation level of the line and on the distance between the point of origin of the strike and the point on the line which is under consideration. This suggests that it is not only difficult to establish a definite upper limit for these overvoltages, but that it would be impractical to expect that high voltage equipment, including circuit breakers, should be designed so that they are capable of withstanding the upper limits of the overvoltages produced by lightning strikes. Therefore the specified impulse levels are lower than the levels that can be expected in the electrical system in the event of a lightning strike, whether it is a direct strike to the station, or the more likely event, which is a stroke to the transmission line that is feeding the station. This is in contrast with the requirement for the power frequency withstand ratings where the margins are very conservative and are well above the normal frequency overvoltages that may be expected.

The objective of specifying an impulse withstand level, even though it is lower than what can be seen by the system, is to define the upper capability limit for a circuit breaker and to define the level of voltage coordination that must be provided.

The basic impulse level (BIL) that is specified in reality only reflects the insulation coordination practices used in the design of electric systems, and which are influenced primarily by the insulation limits and the protection requirements of power transformers and other apparatus in the system. Economic considerations also play an important role in the selection. In most cases the circuit breaker must rely solely on the protection that is offered by surge protection that is located at a remote location from the circuit breaker and close to the transformers. This issue arises because as a common practice surge arresters at the line terminals of the circuit breaker are generally omitted. In reference [3] C. Wagner et al. have described a study they conducted to determine the insulation level to be recommended for a 500 kV circuit breaker. The study, as reported, was done by equating the savings obtained by increasing the insulation levels against the additional cost of installing additional surge arresters if the insulation levels were to be lowered. The findings, in the particular case that was studied, suggested that a 1300 kV level was needed for the 500 kV transformers in the installation, however, a level of 1550 kV was chosen as the most economic solution for the associated circuit breakers and disconnect switches. Other studies have shown that in some cases, for a similar installation, an 1800 kV BIL would be needed. The findings of the two evaluations, then, further suggested that two values may be required, but having two designs to meet the different levels is not the optimum solution from a manufacturing point of view and consequently only the higher value was adopted by ANSI as the standard rated value.

For indoor and outdoor circuit breakers ANSI specifies only one BIL value for each circuit breaker rating with the exception of breakers rated 25.8 and 38 kV where two BIL values are given. The lower value is intended for applications on a grounded wye distribution system equipped with surge arresters. For circuit breakers rated 72.5 kV and above that are to be used on Gas Insulated Substations (GIS) ANSI specifies two BIL levels.

IEC, in contrast, specifies two BIL ratings for all voltage classes except for 48.3 and 72.5 kV, and for all circuit breakers rated above 100 kV, except for the 245 kV rating where three values are specified. For series II rated circuit breakers at least one of the BIL ratings matches the values specified in ANSI.

The comparative values for circuit breakers rated 72.5 kV and above are shown in Table 8.2. From this table it can be seen that for circuit breakers having operating voltage ratings of 123, 145 and 170 kV the requirements listed by both standards are the same. For circuit breakers rated 245 kV and above there are differences, but in all cases the requirements are overlapping.

It can also be observed that up to 169 kV ratings the per unit ratio between the impulse voltage and the maximum voltage of the breaker is basically a constant of approximately 4.5 p.u. However, as the rated operating voltage rating of the circuit breaker increases the BIL level is decreased. C. Wagner [4] attributes this decrease to the grounding practices, since at these higher voltage levels all systems are effectively grounded. Another reason is attributed to the types and characteristics of the surge arresters that are generally used in these applications.

The preceding comparison shows the variability of the requirements and serves to reaffirm the fact that these arbitrary values, as they are presently specified, are generally adequate whenever proper coordination practices and procedures are followed. This fact is corroborated by the reliable operating history of the equipment that has been built in accordance with one or the other standard.

For all practical purposes the dielectric requirements whether specified in ANSI or IEC will be adequate for the corresponding application at a chosen operating voltage.

Table 8.2
BIL Comparison
ANSI and IEC

ANSI					IEC	
Rated Voltage kV	p.u. of rated voltage	BIL kV	2 μsec. Chopped Wave	3 μsec. Chopped Wave (1)	BIL kV	Rated Voltage kV
72.5	4.8	350 300	452	402	325	72.5
123 (old 121)	4.55	550 450	710	632	550 450	123
145	4.5	650 550	838	748	650 550	145
170 (old 169)	4.45	750 650	968	862	750 650	170
245 (old 242)	3.7	900 750	1160	1040	1050 950 850	245
362	3.58	1300 900 1050	1680	1500	1175 1050	362
550	3.26	1800 1300 1550	2320	2070	1550 1425	550
800	2.56	2050 1800	2640		2100 1800	800

8.3.3.3 Chopped Wave Withstand

This dielectric requirement is specified only in ANSI and it has been a part of these standards since 1960. This requirement was added in recognition of the fact that the voltage at the terminals of a surge arrester has a characteristically flat top appearance, but at some distance from the arrester, the voltage is somewhat higher. This characteristic had already been taken into account by transformer standards where a 3 μsec chopped wave requirement was specified.

An additional reason for establishing the chopped wave requirement, based primarily on economic reasons, was to eliminate the need for installation of surge arresters at the line side of the breaker. This action allows the use of rod gaps in conjunction to the arresters, which are used at the transformer terminals.

The 3 μsec rating is given as 1.15 times the corresponding BIL. This value happens to be the same as that of the transformers and it assumes that the separation distance between the arrester and the circuit breaker terminals is similar as that between the transformer and the arrester.

The 2 μsec peak wave is given as 1.29 times the corresponding BIL of the circuit breaker. The higher voltage is intended to account for the additional separation from the circuit breaker terminals to the arresters in comparison to the transformer arrester combination.

In the 2000 issue of C37.06 the requirement for the 3 μsec chopped wave was eliminated. This action was taken because it is well known that the dielectric capabilities for SF_6 and vacuum are basically flat with respect to time and the 2 μsec fully demonstrates the circuit breaker capabilities.

8.3.3.4 Basic Lightning Impulse Tests

The tests are made under dry conditions using both a positive and a negative impulse wave. The standard lightning impulse wave is defined as a 1.2 x 50 microseconds wave.

The waveform and the points used for defining the wave [5] are shown in Figure 8.3 (a). The 1.2 μsec value represents the front time of the wave and is defined as 1.67 times the time interval t_f that encompasses the 30 and 90% points of the voltage magnitude when these two points are joined by a straight line. The 50 μsec represents the tail of the wave and is defined as the point where the voltage has declined to half of its value.

The time is measured from a point t = 0 which is defined by the intercept of the straight line between the 30 and 90% values and the horizontal axis that represents time.

In Figure 8.3 (b) a chopped wave is illustrated, the front of the wave is defined in the same manner as above, but the time shown as t_c, which represents the chopping time, is defined as the time from the wave origin to the point of the chopping initiation.

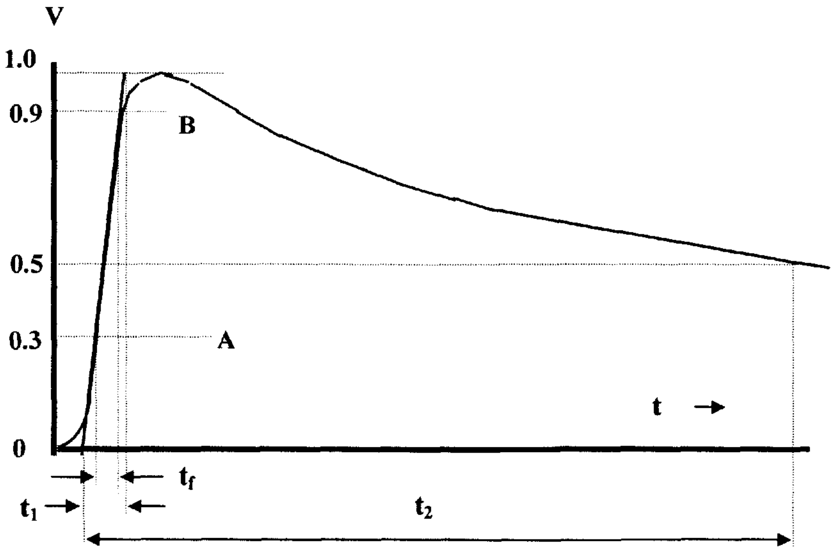

Figure 8.3 (a) Standard 1.2 x 50 impulse wave.

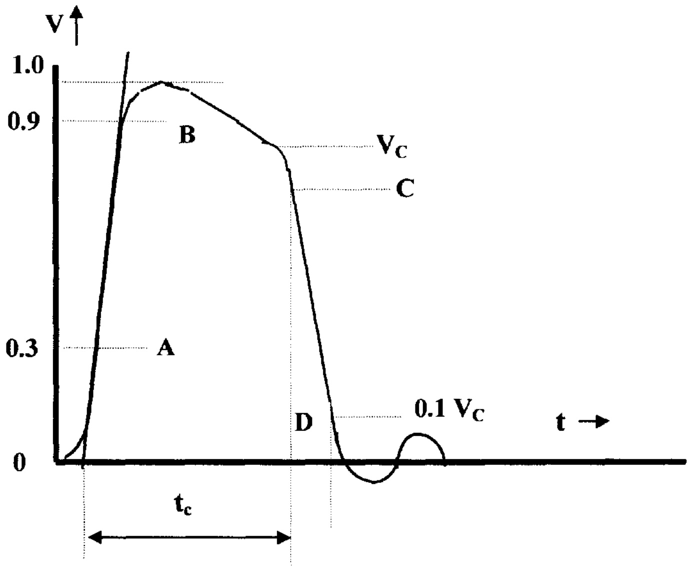

Figure 8.3 (b) Standard wave form for chopped wave tests.

Earlier ANSI documents (prior to C37.09-1999) specified a 3 × 3 test method, which meant that the impulse wave was applied three consecutive times to each test point. If a flashover occurred during the three initial tests, then three additional tests had to be performed where no flashovers were allowed.

The test method was revised and the new requirement defines a 3 × 9 test matrix. With this procedure, a group of three tests are performed, if one flashover occurs a second set of nine tests, where no flashovers are allowed, must be performed. The reason for the change in the test procedure was based on the desire to increase the confidence level on the withstand capability of the design.

IEC specifies a 2 × 15 method, which requires that a group of fifteen consecutive tests be made and where only two flashovers, across self-restoring insulation, are allowed during the series. However, IEC also recognizes the ANSI 3 × 9 method.

8.3.3.5 IEC Bias Test

In recognition of the effects produced by an impulse wave upon the power frequency wave, and of the fact that a lightning strike may reach the circuit breaker at any time IEC requires that for all circuit breakers rated 300 kV and above an impulse bias test be performed. This test is made by applying a power frequency test voltage to ground which when measured in relation to the peak of the impulse wave is no less than 0.572 times the rated voltage of the circuit breaker. No equivalent requirement has been established by ANSI.

8.3.3.6 Switching Impulse Withstand

This requirement is applicable to circuit breakers rated by ANSI at 362 kV or above and by IEC at 300 kV and above. These requirements are specified only at the lower voltage ratings, because at these levels the peak value of the specified power frequency withstand voltage exceeds the 3.0 per unit voltage surge. As it should be recalled this is the value that has been selected as the maximum uncontrolled switching surge that may be encountered on a system.

There are two sets of voltage levels listed in ANSI and IEC. With the exception of switching surge required for a 362 kV circuit breaker all the higher voltage levels are the same in both standards. The lower values required by ANSI are less than those required by IEC.

The required switching surge withstand capability across the isolating gap is higher for IEC except at the 550 kV level were the requirements are the same in both standards. Additionally a phase to phase requirement is specified by IEC but not by ANSI.

The lower voltages have been justified by arguing that when the circuit breaker is closed the source side arresters, which are always used, inherently protect the circuit breaker. However, with the circuit breaker in the open position, unless there are line side arresters, the circuit breaker would be unprotected and the specified levels would be inadequate, but nevertheless it is also recognized that all circuit breakers at these voltage levels use some form of surge control. This practice is reflected in the factors that are listed in ANSI C37.06, for circuit breakers specifically designed to control line closing switching surge maximum voltages.

8.3.4 Rated Transient Recovery Voltage

Recalling what was said earlier, in Chapter 3, the transient recovery voltages that are encountered in a system can be rather complex and difficult to calculate without the aid of a digital computer. Furthermore, it was learned that the TRV is strongly dependent upon the type of fault being interrupted, the configuration of the system and the characteristics of its components, i.e. transformers, reactors, capacitors, cables, etc.

Furthermore a distinction was made for terminal faults, short line faults and for the initial TRV condition. The standards recognize all of these situations and consequently have specific requirements for each one of these conditions. As stated earlier, for standardization and testing purposes, the prospective or inherent TRV could be simplified so it could be described in terms of simpler waveform envelopes. It is important to emphasize that what follows always refers to the inherent TRV, that means the recovery voltage produced by the system alone discounting any modifications or any other distortions that may be produced by the interaction of the circuit breaker.

8.3.4.1 Terminal Faults

ANSI adopted two basic waveforms to simulate the most likely envelopes of the TRV for a terminal fault condition under what can be considered as generic conditions.

For breakers rated 72.5 kV and below the waveform is mathematically defined as:

$$E_{TRV} = 1 - \text{cosine } \omega t$$

where:

$$\omega = \frac{\pi}{T_2} \quad \text{and}$$

T_2 = Specified rated time to voltage peak

For circuit breakers rated 123 kV and above the wave form is approximately defined as the envelope of the combined exponential-cosine functions, and the exponential portion [6] is given by the following equation:

$$e = E_1\left[1 - \varepsilon^{-\alpha t}\left(\cosh\beta t + \frac{\alpha}{\beta}\sinh\beta t\right)\right]$$

where:

$$\alpha = \frac{1}{2ZC}$$

$$\beta = \sqrt{\alpha^2 - \frac{1}{LC}}$$

$$Z = \frac{R \times 10^6}{\sqrt{2}\omega I} \quad \text{Ohms}$$

$$\omega = \frac{\pi}{T_2}$$

$$C = \frac{T_1 \times 10^{-6}}{Z} \quad \text{Farads}$$

$$L = \frac{\text{Rated Max. Voltage}}{\sqrt{2}\ \omega I}$$

where:

E_1, E_2, R, I, T_1, and T_2 are the values given in ANSI C37.06

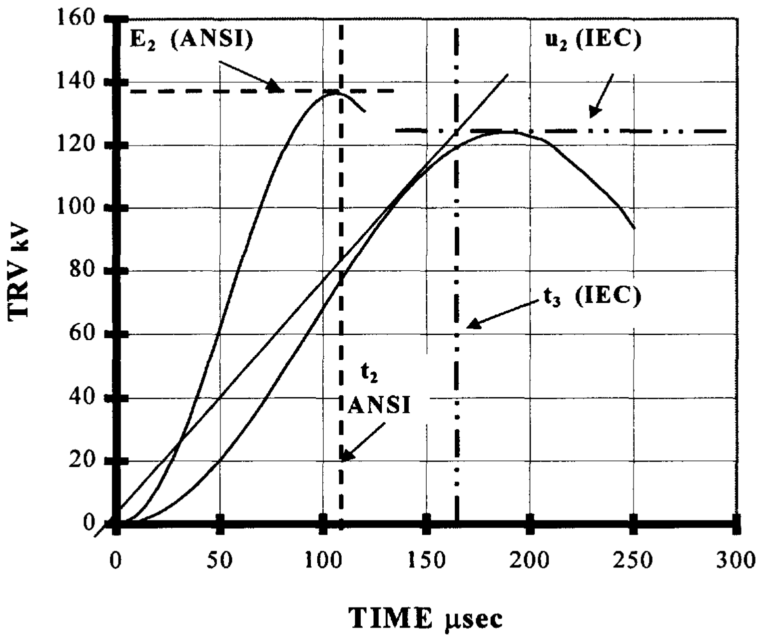

Figure 8.4 Comparison of ANSI (1 - cos) and IEC two parameter TRV for a 72.5 kV rated circuit breaker.

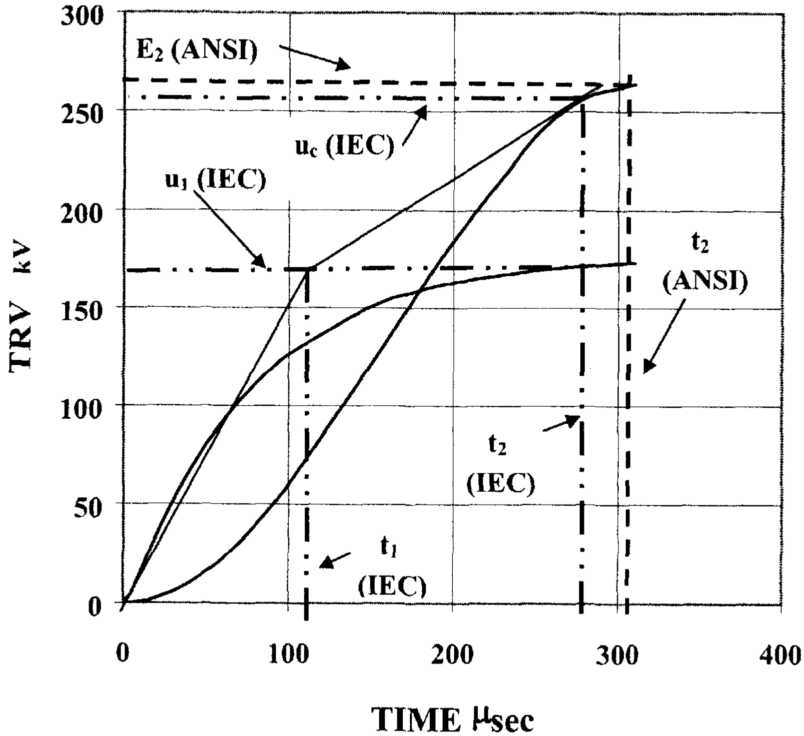

Figure 8.5 TRV comparison of ANSI (Exp-Cos) and IEC four parameter envelopes for a 145 kV circuit breaker.

IEC also defines two TRV envelopes, one that is applicable to circuit breakers rated below 100 kV that is defined by what is known as the Two Parameter Method, and the second, which is applicable to circuit breakers rated 100 kV and above, and known as the Four Parameter Method. In Figures 8.4 and 8.5 the TRV envelopes as defined by ANSI and IEC are compared, and the curves shown correspond to a 72.5 kV and a 145 kV rated circuit breakers respectively.

The method employed by IEC assumes that the TRV values may be defined by means of an envelope which is made of three line segments, however when the TRV approaches the 1 - cosine, or the damped oscillation shape, the envelope resolves itself into two segments.

The following procedure for drawing the aforementioned segments as described in IEC [6] can be used. The first line segment is drawn from the origin and in a position that is tangential to the TRV without crossing this curve at any point. The second segment is a horizontal line that is tangent the highest point on the TRV wave. The third segment is a line that joins the previous two segments, and which is drawn tangent to the TRV wave without crossing this wave at any point. However, when the point of contact of the first line and the highest peak are comparatively close to each other, the third line segment is omitted and the two parameter representation is obtained.

When all three segments are drawn the four parameters defined are:

u_1 = Intersection point of first and third line segments corresponds to the first reference voltage in kilovolts.
t_1 = Time to reach u_1 in microseconds.
u_c = Intersection point of second and third line segments corresponds to the second reference voltage (TRV peak) in kilovolts.
t_2 = Time to reach u_c in microseconds.

The two-parameter line is defined by:

u_c = Corresponds to reference voltage (TRV peak) in kilovolts.
t_3 = Time to reach u_c in microseconds.

Not only the adopted waveforms are different but there are a number of additional differences between the transient recovery voltages that are specified by ANSI and IEC. For example, the TRV characteristics described by IEC are independent of the interrupting current ratings of the circuit breaker, while the ANSI characteristics vary in relation to the interrupting rating. ANSI specifies different rates of change (dv/dt) for the TRV. These rates are also dependent on the interrupting current ratings but IEC establishes only a constant equivalent rate that is applicable to all ratings. Finally, ANSI assumes that all systems will be ungrounded, which is a conservative approach because it gives a 1.5 factor that is used as the multiplier for the first phase to clear the fault. IEC, on the other hand, makes a distinction between grounded and ungrounded applications and accounts for these differences by the usage of the multiplier 1.3 or 1.5 respectively for the first phase to clear. However, even in those cases where the same 1.5 multiplier is used by both standards, the corresponding ANSI values are higher because based on the recommendations made by the AEIC study committee [7] the amplitude factors used are equal to 1.54 for circuit breakers rated 72.5 kV and below and 1.43 for circuit breakers rated above 72.5 kV. In contrast, the amplitude factor used by IEC is 1.4 for all voltage ratings.

There is a relatively significant time difference observed between the ANSI and the IEC time to crest requirements for circuit breakers rated below 72.5 kV. This difference can be explained by considering the European practice where most of the circuits at these voltages are fed by cables, and, consequently, due to the inherent capacitance of the cables, the natural frequency of the response is lowered.

The influence of capacitance, on the source side of the breaker, produces a slower rate of rise of the TRV and, therefore, what amounts to a delay time before the rise in the recovery voltage is observed. ANSI does not specify a delay for the conditions of a 1 - cosine envelope. In this case the initial rate is equal to zero. IEC, however, due to the use of the two-parameter envelope does specify a time delay that ranges from a maximum of 16 microseconds down to 8 microseconds. For circuit breakers rated above 121 kV the delay time specified by IEC is a constant with a value of 2 microseconds. ANSI specifies different delay times for different voltage ratings and these times range from a low of 2.9 microseconds at 121 kV to a maximum of 7.9 microseconds for 800 kV circuit breakers.

Table 8.3
Breakers Rated 72.5 kV and Below
Multiplying Factors for Reduced Fault Currents

ANSI			IEC		
Fault Current %	E_2	t_2	**Fault Current %**	u_c	t_3
60	1.07	0.67	60	1.07	0.43
30	1.13	0.40	30	1.07	0.21
10	1.17	0.40	10	1.07	0.21

Table 8.4
Breakers Rated 121 kV and Above
Multiplying Factors for Reduced Fault Currents

<table>
<tr><th colspan="3">ANSI</th><th colspan="4">IEC</th></tr>
<tr><th>Fault Current %</th><th>E_2</th><th>t_2</th><th>Fault Current %</th><th>u_c</th><th colspan="2">t_3</th></tr>
<tr><td>60</td><td>1.07</td><td>0.50</td><td>60</td><td>1.07</td><td colspan="2">1.00</td></tr>
<tr><td>30</td><td>1.13</td><td>0.20</td><td>30</td><td>1.07</td><td colspan="2">1.00</td></tr>
<tr><td rowspan="5">10</td><td rowspan="5">1.17</td><td rowspan="5">0.20</td><td rowspan="5">10</td><td rowspan="5">1.09</td><td>121 kV</td><td>0.20</td></tr>
<tr><td>145 kV to 245 kV</td><td>0.17</td></tr>
<tr><td>362 kV</td><td>0.14</td></tr>
<tr><td>550 kV</td><td>0.12</td></tr>
<tr><td>800 kV</td><td>0.09</td></tr>
</table>

In both standards, consideration is given to the condition where currents significantly lower than the rated fault currents, and usually in the approximate range of 10 to 60%, are interrupted. This condition is assumed to occur when the fault occurs in the secondary side of the transformer, in such cases the currents are reduced due to the higher reactance of the transformer. This higher reactance in turn changes the natural frequencies of the inherent TRV. To account for these changes ANSI and IEC have selected three levels of reduced currents where the specified peak voltage is higher and the time to reach the peak is reduced. The factors by which the voltages are increased and the times are reduced are tabulated in Tables 8.3 and 8.4. The net result is that the peak TRV values given by ANSI are higher than the ones required by IEC but the time required to reach the peak is always higher according to IEC.

8.3.4.2 Proposed Harmonized TRV

In 1997 a joint working group between IEEE and IEC was formed. Their objective was to harmonize the TRV values for circuit breakers rated above 100 kV.

Presently a proposal for a revision of the TRV standards is undergoing the approval process. In IEC the document has been approved at the Committee Draft Vote (CDV) stage. In ANSI/IEEE the document is in the early stages of the required balloting process.

The main differences between the existing standards and the new harmonized version are that in the harmonized version the two and four parameter has been chosen for the representation of the TRV. In addition agreement was reached so the peak TRV value as well as the peak multipliers for reduced fault currents are the same in both standards. Other changes involve the first pole to clear factor, which in order to satisfy the different operating practices made it necessary to recognize grounded and ungrounded (solidly earthed and non-solidly earthed) applications. For rated voltages of 100 kV up to and including 170 kV a 1.3 and a 1.5 factor are recognized. For voltages of 245 kV and above only solidly grounded (earthed) applications are recognized and only the 1.5 factor is used.

Although there is no work being done in the medium voltage group, there is sufficient interest to work in harmonization and it is expected that in the near future this may take place.

8.3.4.3 Short Line Faults

The only important difference between ANSI and IEC for short line faults is that IEC requires this capability only on circuit breakers rated 52 kV and above, and which are designed for direct connection to overhead lines. ANSI requires the same capability for all outdoor circuit breakers.

8.4 CURRENT RELATED RATINGS AND REQUIREMENTS

These are ratings that are associated with the normal continuous current and the capabilities associated with fault currents and circuit interruption.

In the IEC most of these ratings are based on the R10 series of preferred number. For those that are not familiar with this number series the concept is reviewed below.

8.4.1 Preferred Number Series

Preferred numbers are series of numbers that are selected for standardization purposes in preference of any other numbers. Their use leads to simplified practices and reduced number of variations.

The preferred numbers are independent of any measurement system and therefore they are dimensionless. The numbers are rounded values of the following five geometric series of numbers: $10^{N/5}$, $10^{N/10}$, $10^{N/20}$, $10^{N/40}$ and $10^{N/80}$, where N is an integer in the series 0, 1, 2, 3, etc. The designations used for the five series are R5, R10, R20, R40 and R80 respectively, where R stands for Renard, of Charles Renard, the originator of this series, and the number indicates the root of ten on which the series is based.

The R10 series is frequently used to establish current ratings. This particular series gives 10 numbers that are approximately 25% apart. These numbers are 1.0, 1.25, 1.60, 2.0, 3.15, 4.00, 5.00, 6.30, and 8.00; this series can be expanded by using multiples of 10.

8.4.2 Rated Continuous Current

The continuous current rating serves to set the limits for the circuit breaker temperature rise. These limits are chosen to prevent a temperature run away condition, when the type of material used in the contacts or conducting joints is taken into consideration. Secondly, it is done so that the temperature of the conducting parts, which are in contact with insulating materials, do not exceed the softening temperature of such material. The temperature limits are given in terms of both the total temperature and the temperature rise over the maximum allowable rated ambient operating temperature. The temperature rise value is given to simplify the testing of the circuit breaker; for as long as the ambient temperature is between the range of 10 to 40°C no correction factors need to be applied.

The preferred continuous current ratings specified by ANSI are 600, 1200, 1600, 2000, or 3000 Amperes. The corresponding IEC ratings are based on the R10 series of preferred numbers and they are 630, 800, 1250, 1600, 2000, 3150, or 4000 Amperes.

The choice for the continuous currents made by each of the two standards are not that different. The real significance of the ratings is the associated maximum allowable temperature limits that have been established. The temperature limits as they were specified, by each of the standards prior to the ANSI harmonization of 1999, are shown in Tables 8.5 and 8.6.

Table 8.5
IEC 60694 Temperature Limits

COMPONENT		MAXIMUM TEMPERATURES	
CONTACTS		**Total Temp.°C**	**Temp. Rise°C**
Bare Copper	In Air	75	35
	In SF_6	90	50
	In Oil	80	40
Silver or Nickel Plated	In Air	105	65
	In SF_6	105	65
	In Oil	90	50
Tin Plated	In Air	90	50
	In SF_6	90	50
	In Oil	90	50
CONNECTIONS			
Bare Copper	In Air	90	50
	In SF_6	105	65
	In Oil	100	60
Silver or Nickel Plated	In Air	115	75
	In SF_6	115	75
	In Oil	100	60
Tin Plated	In Air	105	65
	In SF_6	105	65
	In Oil	100	60
EXTERNAL TERMINALS to CONDUCTORS			
Bare		90	50
Silver, Nickel, or Tin plated		105	65
INSULATING MATERIALS			
Class Y		90	50
Class A		100	60
Class E		120	80
Class B		130	90
Class F		155	115
Class H		180	140

Table 8.6
ANSI C37.04 Temperature Limits
(pre-harmonization)

COMPONENT		MAXIMUM TEMPERATURES	
CONTACTS		**Total Temp.°C**	**Temp. Rise °C**
Copper		70	30
Silver, Silver Alloy or Equivalent	In Air In Oil	105 90	65 50
CONNECTIONS			
Copper		70	30
Silver, Silver Plated or Equivalent	In Air In Oil	105 90	65 50
EXTERNAL TERMINALS to CONDUCTORS			
Bare		85	45
INSULATING MATERIALS			
Class O		90	50
Class A		100	60
Class B		130	90
Class F		155	115
Class H		180	140
Class C		220	180
Oil (top oil, upper layer)		90	50

The maximum temperature limits for contacts and conducting joints are based on the knowledge that exists about the change in resistance due to the formation of oxide films, and the prevailing temperature at the point of contact.

For insulating materials the temperature limits are well known and are directly related to the mechanical characteristics of the material. These limits follow the guidelines that are given by other standards, such as ASTM, that have classified the materials in readily identifiable groups.

An additional requirement that is given is the maximum allowable temperature of circuit breaker parts that may be handled by an operator. These parts are limited to a maximum total temperature of 50°C and for those points that can be accessible to personnel the limit is 70°C. But in any case the temperature of external surfaces are limited to a 100°C maximum.

The maximum values of temperature rise given in IEC 60694 (Table 8.6) were adopted by ANSI and they are published in C37.04-1999. There is only one exception that is applicable to indoor circuit breakers used inside enclosures where the maximum allowable 65°C temperature rise was kept. This value was retained primarily because this is the limit imposed by the corresponding enclosure standard.

8.4.3 Rated Short Circuit Current

The short circuit current rating as specified by both standards corresponds to the maximum value of the symmetrical current that can be interrupted by a circuit breaker. The preferred values of these short circuit currents for outdoor circuit breakers rated above 72.5 kV are based on the R10 series in both standards.

For circuit breakers with rated voltages of 72.5 kV or less IEC still uses the R10 series to establish the ratings. ANSI prior to 1964 based the interrupting current ratings on the MVA of the system and on what was then known as the total current basis. After this date the symmetrical current basis, which is still applicable today, was adopted.

This change coupled with other changes made to the standard at that time suggested that ratings based on the MVA were no longer applicable. The result was the preferred ratings that were in effect until the issuance of the C37.06-1997 document. In this latest standard as the K factor was reduced to 1 it was necessary to assign new ratings to cover the same range of applications that were common prior to the revision.

Associated with the symmetrical current value, which is the basis of the rating, there are a number of related capabilities, as they are referred by ANSI, or as definite ratings as specified by IEC. The terminology used for these capabilities may differ, but the significance of the parameters is the same in both standards. What it is important is to realize that both standards use the same assumed basis for the time constant which defines most of the related requirements for all transient current conditions.

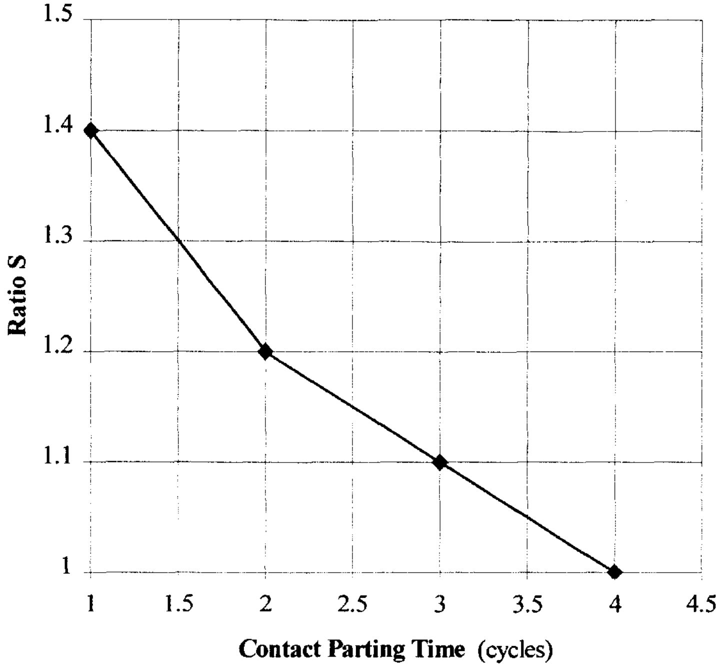

Figure 8.6 Factor S, ratio of symmetric to asymmetric interrupting capabilities.

8.4.3.1 Asymmetrical Currents

In most cases, as described in Chapter 2, the ac short circuit current has an additional dc component, which is generally referred as the "percent dc component of the short circuit current." The magnitude of this component is a function of the time constant of the circuit (X/R = 17 @ 60 Hz or 14 @ 50 Hz), and of the elapsed time between the initiation of the fault and the separation of the circuit breaker contacts.

After the 1999 revision ANSI is completely harmonized with the IEC requirements. Prior to that ANSI had established an asymmetry factor, S, which, when multiplied by the symmetrical current, defined the asymmetrical value of the current. The actual value of the factor S was calculated using the following relationship:

$$S = \sqrt{1 + 2\left(\frac{\%\,dc}{100}\right)^2}$$

where the % *dc* equals the dc component of the short circuit current at the time of contact separation.

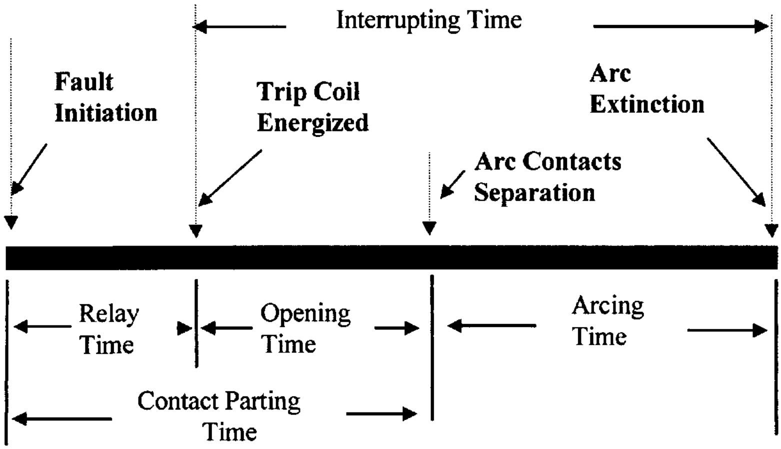

Figure 8.7 Interrupting time relationships.

ANSI, however, to simplify the process, and as illustrated in Figure 8.6, specified definite values for S, and referred them to the rated interrupting time of the circuit breaker.

The specified factors were 1.4, 1.3, 1.2, 1.1 and 1.0 for rated interrupting times of 1, 2, 3, 5 and 8 cycles respectively. IEC establishes the magnitude of the dc component based on a time interval consisting of the sum of the actual contact opening time plus one-half cycle of rated frequency. In essence, there was no difference between the requirements of the two standards, except that in the ANSI way the factors are not exact numbers but approximations for certain ranges of asymmetry.

Interrupting time. The interrupting time or breaking time of a circuit breaker has a common definition according to ANSI and IEC. It consists of the time, from the instant the trip coil is energized plus the maximum arcing time of the circuit breaker. Note that the contact parting time, as defined by ANSI, is the summation of the relay time plus the opening time. These relationships are illustrated in Figure 8.7.

8.4.3.2 Close and Latch or Peak Closing Current

The peak asymmetrical closing current is also referred to as the close and latch current or the peak making current. This current rating is established for the purpose of defining the mechanical capability of the circuit breaker, its contacts and its mechanism to withstand the maximum electromagnetic forces that can be generated when the circuit breaker closes into a fault.

The magnitude of the peak of the possible fault current against which the circuit breaker is closed is expressed in terms of multiples of the rated symmetrical short circuit current. ANSI used to specify a 2.7 factor, but recently it was reduced to 2.6 for the sake of mathematical accuracy.

IEC specifies a 2.5 multiplier. The difference between the two values is due to the difference in the rated power frequencies.

The equation that is used to calculate the peak current is:

$$I_C = \sqrt{2}\, I \left[\left(1 - \cos\omega t\right) + \varepsilon^{-\frac{t}{\tau}} \right]$$

where:

I_C = Peak of making current

I = Symmetrical short circuit current

t = 0.4194 cycles = Elapsed time to current peak

$$\tau = \frac{X}{R\omega} = \frac{17}{377} \text{ (for 60 Hz) or } \frac{17}{314} \text{ (for 50 Hz)}$$

8.4.3.3 Short Time Current

The purpose of this requirement is to assure that the short time heating capability of the conducting parts of the circuit breaker are not exceeded. By definition the short time current rating, or related capability, is the rms value of the current that the circuit breaker must carry, in the closed position, for a prescribed length of time.

The magnitude of the current is equal to the rated symmetrical short circuit current that is assigned to that particular circuit breaker and the required length of time that it must be carried. The time that was specified by ANSI prior to 1998 was 3 seconds. This has now been changed to 2 seconds for circuit breakers rated below 100 kV and 1 second for those rated above 100 kV and are now defined by the allowable tripping delay. The changes in ANSI were made after recognizing that the duration of the short time current does not have to be any greater than the maximum delay time that is permitted on a system.

The IEC requirement is 1 second for all circuit breakers. Nevertheless, IEC recommends a value of 3 seconds if longer than 1 second periods are required. The 1 second specification of IEC corresponds to their allowable tripping delay, which in the IEC document is referred to as the rated duration of short circuit.

8.4.3.4 Rated Operating Duty Cycle

The rated operating duty cycle, as is referred in ANSI, is known as the rated operating sequence by IEC.

ANSI specifies the standard operating duty as a sequence consisting of the following operations; O - 15 sec - CO - 3 min - CO, that is an opening operation followed, after a 15 second delay, by a close-open operation and finally after a 3 minute delay by another close open operation. For circuit breakers intended for rapid reclosing duty the sequence is O - 0.3 sec - CO - 3 min - CO.

IEC offers two alternatives, one is O - 3 min - CO - 3 min - CO and the second alternative is the same duty cycle prescribed by ANSI. However, for circuit breakers that are rated for rapid reclosing duties the time between the opening and close operation is reduced to 0.3 seconds.

ANSI normally refers to the reclosing duty as being an O - 0 sec - CO cycle, which implies that there is no time delay between the opening and the closing operation. However in C37.06 the rated reclosing time, which corresponds to the mechanical resetting time of the mechanism, is given as 20 or 30 cycles, which corresponds to 0.33 or 0.5 seconds respectively depending upon the rating of the circuit breaker. The reference to 0 seconds is supposed to mean that no intentional external time delays can be included.

When referring to reclosing duties ANSI allows a current de-rating factor R to be applied, but IEC does not make any de-rating allowance. In reality the de-rating factor was only applicable to older interrupting technologies and with modern circuit breakers there is no need for any de-rating.

Have you ever noticed the lights to go out, come back instantly, go out again and then after a short period of time (15 seconds) come on again and if they go out again there is a long period before power is restored? Well, what you have witnessed is a circuit breaker duty cycle including the fast reclosing option.

8.4.3.5 Service Capability

The service capability is a requirement that is only found in ANSI. It defines a minimum acceptable number of times that a circuit breaker must interrupt its rated short circuit current without having to replace its contacts. This capability is expressed in terms of the accumulated interrupted current and for older technologies (oil and air magnetic circuit breakers) a value of 400% is specified, for modern SF_6 and vacuum circuit breakers the required accumulated value is 800% of the maximum rated short circuit current. Except for the newly circuit breaker type designation created by IEC this type of requirement is not addressed by IEC. The definition of a Type E_2 circuit breaker, which is defined below, does not establishes a specific numerical value as does ANSI but when the test duties required are added the accumulated value would be greater than the 800% specified by ANSI.

8.4.3.6 Electrical Endurance

At rated voltages above 1 kV and up to and including 52 kV IEC has established two types of circuit breakers. Quoting from IEC 62271-100 type E_2 is a "circuit breaker designed so as not to require maintenance of the interrupting parts of the main circuit during its expected operating life, and only minimal maintenance of its other parts". Basically this is a circuit breaker that has an extended electrical endurance capability. Type E_1 is defined as a circuit breaker that does not fall into the E_2 category.

8.5 ADDITIONAL SWITCHING DUTIES

Aside from switching short circuit currents we know that circuit breakers must also execute other types of switching operations. Both standards recognize all of these additional needs. The requirements for these operations are defined in the corresponding standards but, as is the case with most of all other requirements, there are some noteworthy differences which are discussed in the sections that follow.

8.5.1 Capacitance Switching

Presently there are a number of significant differences between ANSI and IEC on this subject. Recognizing the need for commonality a joint working group was created to address these differences and to create a single standard. The proposed standard that was developed by this working group has already been accepted by IEC and is in the process of acceptance in IEEE/ANSI.

Fundamental changes have been made and they include the establishing of a new classification (C_2) for a circuit breaker that has a very low probability of re-strike. The old ANSI class of Definite Purpose circuit breaker will now become a Class C_1 that is defined as a "low probability" of restrike.

To demonstrate probabilities a significant amount of data is needed and consequently the test procedure has also been revised and specific tests are mandated to demonstrate the class assignments.

As it has been done throughout this chapter the paragraphs that follow will describe the differences that existed between the "old" pre-harmonization standards.

8.5.1.1 Single Bank

ANSI mandated that all circuit breakers must be designed to meet the requirements for the "general-purpose circuit breaker" classification as it was listed in ANSI C37.06-1987. Meanwhile IEC listed this duty as an optional rating. It did not assign any interrupting current values and only made the recommendation that these values be selected using the R10 series.

The values of currents for switching single capacitor banks that are applicable to general-purpose breakers are pre-assigned by ANSI and they had been selected using the R10 series.

In the new standards single bank switching capabilities is an optional rating and is not required for all circuit breakers.

8.5.1.2 Back-to-Back Capacitor Banks

Again this was an optional rating according to the IEC standard and in line with their practice regarding single capacitor banks the interrupting current values were not specified. ANSI handled the back-to-back capacitor bank rating by defining a group of "Definite-Purpose Circuit Breakers". This is an optional rating and it is not expected that every circuit breaker would meet this requirement, unless it is specifically designed for this purpose. In reality, however, most circuit breakers involving modern technologies are normally designed with this requirement in mind, and most manufacturers produce only one version rather than having two different designs. In the new standards this will still be optional rating that is not required for all circuit breakers.

8.5.1.3 Line Charging

Line charging requirements are included by ANSI as part of their capacitance switching specifications and therefore all outdoor circuit breakers have certain specific assigned requirements. In the old IEC standards the rating for line charging was only applicable to circuit breakers which are intended for switching overhead lines and rated at 72.5 kV or above. There are also differences on the magnitude of the specified currents. At 72.5 kV and up to 170 kV IEC values are approximately 30 to 50% lower than the ANSI values for general purpose circuit breakers, and about 90% lower than those for definite purpose breakers. At the 245 and 362 kV circuit breaker levels the IEC specified line charging current ratings are approximately 25% higher than the ANSI currents for general purpose breakers but are about 30% and 60% lower than ANSI values for the respective breakers. At 550 and 800 kV the required line charging currents are the same in both standards.

In the new standard all of these differences disappear and the requirements are mandatory for all circuit breakers rated 72.5 kV and higher.

8.5.1.4 Cable Charging

Cable charging is considered to be only a special case of capacitance switching, and therefore is included by ANSI with all of the other requirements for capacitance switching. Since IEC did not make capacitance switching a mandatory requirement, then neither was cable switching.

Again, in the new standard all of these differences disappear and the requirements are made mandatory for all circuit breakers rated equal or less than 52 kV.

8.5.1.5 Reignitions, Restrikes, and Overvoltages

These requirements serve to define what is considered to be an acceptable performance of the circuit breaker during capacitive current switching. The limitations that have been specified in the standards are aimed to assure that the effects of restrikes and the potential for voltage escalation, which have been described earlier, are maintained within safe limits.

The maximum overvoltage factor is specified because it is recognized that certain types of circuit breakers, most notably oil types, are prone to have restrikes. What this rating does is to allow restrikes only when appropriate means have been implemented within the circuit breaker to limit the overvoltages to the maximum value given in the respective standard. The most common method used for voltage control is the inclusion of shunt resistors to control the magnitude of the overvoltage.

8.6 MECHANICAL REQUIREMENTS

These requirements include operating life, endurance design tests, and operating mechanism functional characteristics.

8.6.1 Mechanical Operating Life

Mechanical life refers to the number of mechanical operations that can be expected from a circuit breaker. One mechanical operation consists of an opening and one closing of the action. Traditionally, for indoor applications ANSI has made the number of operations a function of the current and voltage ratings of the circuit breaker. For these circuit breakers servicing intervals also have been determined on the same basis.

The required number of operations range from a low of 1500 operations for circuit breakers rated at 38 kV regardless of the current ratings to 10,000 operations for circuit breakers rated 4.76 kV and 15 kV having a maximum interrupting capability of 31.5 kA and when the continuos current does not exceed 2000 Amperes. All outdoor circuit breakers have a common requirement of 2000 operations.

In the latest version of IEC 62271-100, circuit breakers of the E_1 type have a 2000 operations requirement; those belonging to the E_2 type require 10,000 operations.

8.6.1.1 Trip Free Operation

This is a characteristic that is specified in ANSI that often causes some confusion. It simply requires that the circuit breaker be able to open without any delay once the auxiliary switch that controls the application of the electric signal to the operating solenoid closes. Under these conditions the contacts of the circuit breaker are permitted to touch momentarily. The second part of the requirement refers to the case when a mechanical trip signal is trying to override the closing operation. In this case the breaker contacts are not allowed to move. IEC does not have any similar specification to these.

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9

SHORT CIRCUIT TESTING

9.0 INTRODUCTION

Since a circuit breaker represents the last line of defense for the whole electric system it is imperative to have a high degree of confidence in its performance. This confidence level can only be attained by years of operating experience, or by extensive testing under conditions that simulate those that are encountered in the field applications. Short circuit testing, whether it involves an individual interrupter or a complete circuit breaker, is one of the most essential and complex tasks that has to be performed during the development process.

Short circuit testing is also important from the technical engineering design point of view because, in spite of all the knowledge gained about circuit interruption and today's ability to model the process the modeling itself is based, to a great extent, on the experimental findings and, consequently, testing becomes the fundamental tool that is used for the development of circuit breakers.

Short circuit testing has always presented a challenge, because what must be replicated is the interaction of a mechanical device, the circuit breaker, and the electric system where, as we already know, the switching conditions can vary quite widely depending upon the system configuration and therefore so can the type of conditions which must be demonstrated by tests.

Another challenge has always been the development of appropriate test methods that can overcome the potential lack of sufficient available power at the test facility. One has to consider that the test laboratory should basically be able to supply the same short circuit capacity as that of the system for which the circuit breaker that is being tested is designed. However, this is not always possible, especially at the upper end of the power ratings.

Presently it is possible to test a three phase circuit breaker up to 145 kV and a maximum symmetrical current of 31.5 kA. Anything above these levels must be tested on a single phase basis, unless it is tested directly out of an electrical network, a condition which is highly unlikely.

In the early days of the industry, however, practically all testing was done in the field using the actual networks to supply the required power. Even today, in some cases, direct field tests are still being performed. However, in the majority of the cases the testing is done at any of a number of dedicated testing stations available in many countries around the world. The majority of these test stations use their own power generators which have been specially designed for short circuit testing.

With a three phase capacity of 8,400 MVA, N. V. KEMA, Arnhem, The Netherlands, is the largest test station in the world. An aerial view of this test laboratory is shown in Figure 9.1. Its subsidiary, KEMA-Powertest located in Chalfont, Pennsylvania, has the largest capability (3,250 MVA) in the US.

In addition to the above named laboratories there are a number of other important testing facilities around the world; in North America the newest laboratory with a three phase capacity of 2,200 MVA is LAPEM which is located in Irapuato, Mexico, a view of this modern and well equipped facility is shown in Figure 9.2.

Additionally, in Canada there are IREQ in Quebec and Power-Tech in Vancouver. In Europe there are Siemens and AEG in Germany, CESI in Italy, Electricity de France in Fonteney, and ABB in both Sweden and Switzerland, MOSKVA in Russia, VUSE in Czechoslovakia, Warszava in Poland, and in Japan Mitsubishi and Toshiba laboratories.

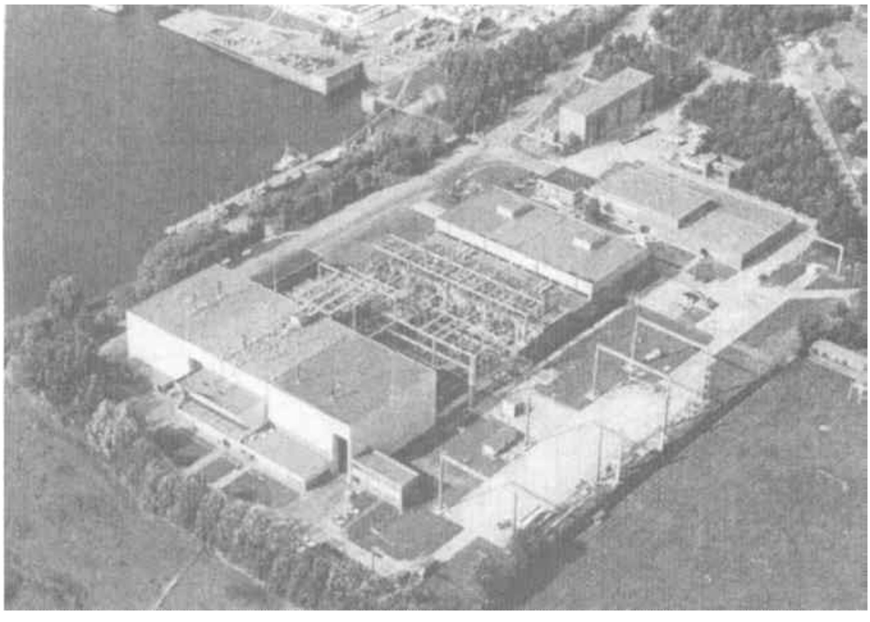

Figure 9.1 Aerial view of the N. V. KEMA laboratory located in Arnhem, The Netherlands (Courtesy of B.V. KEMA, Arnhem, The Netherlands).

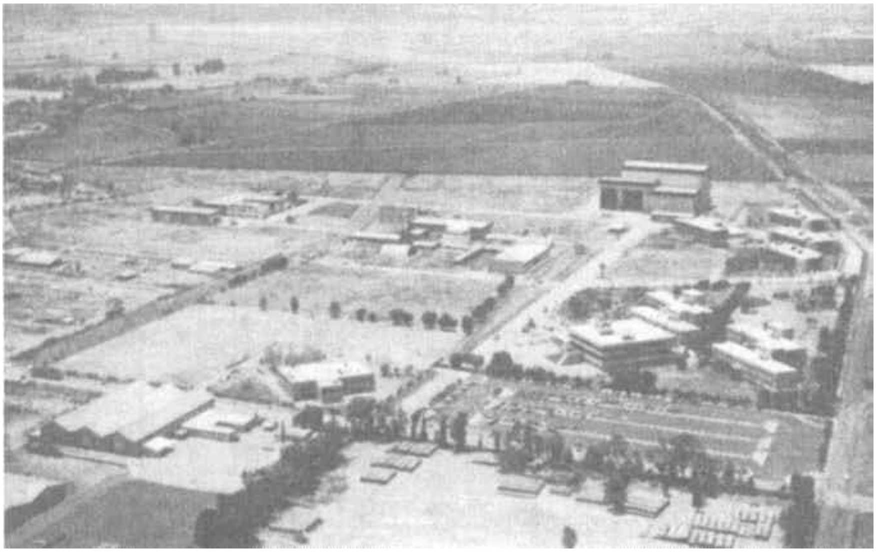

Figure 9.2 Aerial view of the LAPEM laboratory located in Irapuato, Gto. Mexico (Courtesy of LAPEM, Irapuato, Gto. Mexico).

9.1 TEST METHODOLOGY

A great deal of latitude is given as far as short circuit current design testing of a circuit breaker is concerned. Because of the levels of power needed, the complexity of the tests and the very high costs involved with these tests, this latitude is not only a convenience but a necessity.

To reduce the otherwise required amount of testing, it is permissible to analyze results from similar design tests and to use engineering judgment to evaluate these results. However, this judgment must be technically sound, supported by good data and backed up by a strong knowledge about the characteristics of the circuit breaker in question.

As long as sufficient evidence is gathered, and as long as it is satisfactorily demonstrated that the most severe testing conditions are met, one can certify the interrupter's performance by combining, in any order, the listed operating test duties. This means that they do not necessarily have to be performed in any particular sequence, and that they do not even have to be done using the same interrupter, as long as the total accumulated current duty is reached with one individual unit.

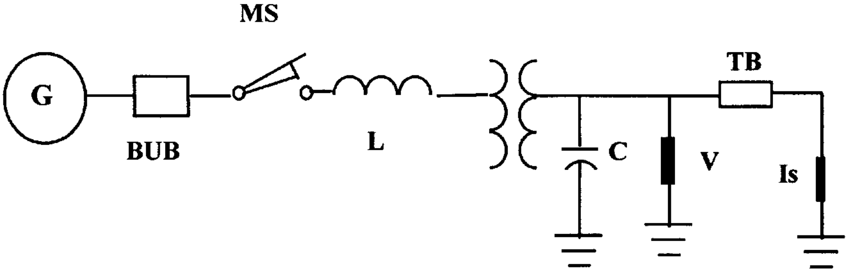

Figure 9.3 Elementary schematic diagram of the basic circuit used for short circuit current tests.

Since, even at the largest of the test stations, it is not always possible to supply the full amount of power needed, alternate appropriate methods that require less power but that yield equivalent results had to be developed. Other challenges that had to be overcome had to do principally with signal isolation, surge protection, reliability control, and high speed instrumentation.

The difficulties that can be encountered during high current tests can only be appreciated when one considers the need for an absolutely proper sequential coordination of a number of events, and where a failure within the sequence may result in aborting the test or what is worse in a disastrous failure, and where, during an individual test, there is only a single chance to capture the test record.

In recent years, with the advent of high speed, high resolution digital instrumentation and data acquisition systems the quality and reliability of tests, test records, and in general of the total accompanying documentation have been greatly enhanced. Today it is possible to measure, store and later replay at high-resolution levels the complete test sequence; this provides a very powerful tool for the analysis of the events taking place during current interruption.

A typical short circuit current test set-up is illustrated by the schematic diagram of Figure 9.3. The test circuit consists of a power source (G) which can be either a specially designed short circuit generator, such as the ones that are illustrated in Figures 9.4 and 9.5, or the system's electric network itself.

For the protection of the generator, or power source, a high capacity back-up circuit breaker (BUB) is used for interrupting the test current in the event that the circuit breaker being tested (TB) would fail to interrupt the current. Back-up circuit breakers, in the majority of cases, are of the air blast type. A single pole of the air blast back-up circuit breakers manufactured by AEG and which are used at LAPEM is shown in Figure 9.6.

In series with the back-up circuit breaker there is a high speed making switch (MS) which is normally a synchronized switch capable of independent pole operation and of precise control for closing the contacts at a specific point on the current wave.

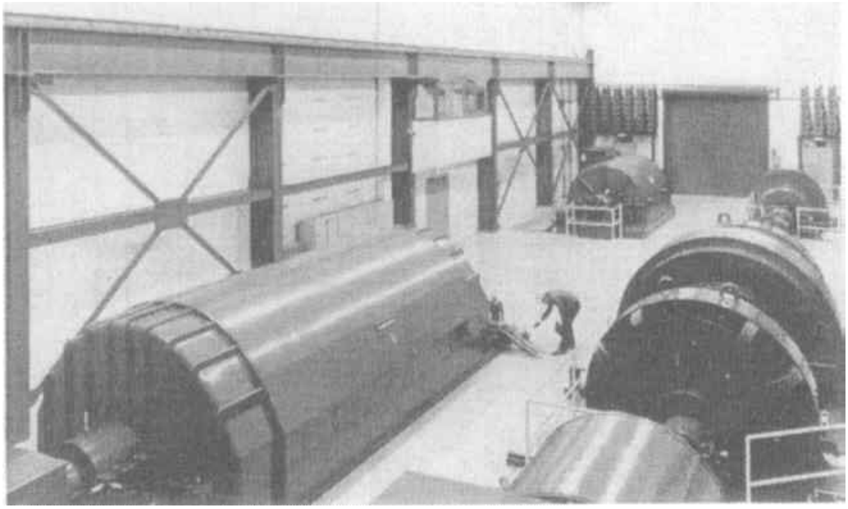

Figure 9.4 Generator hall with 2,250 MVA and 1,000 MVA short-circuit test generators (Courtesy KEMA-Powertest, Chalfont, PA, USA).

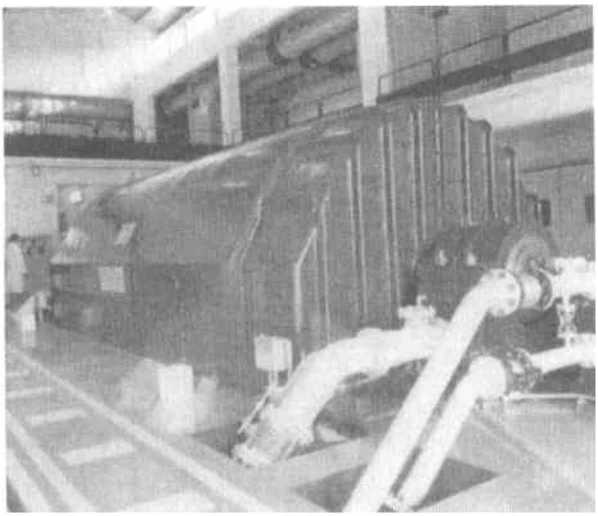

Figure 9.5 View of LAPEM's test generator (Courtesy of LAPEM, Irapuato, Gto. Mexico).

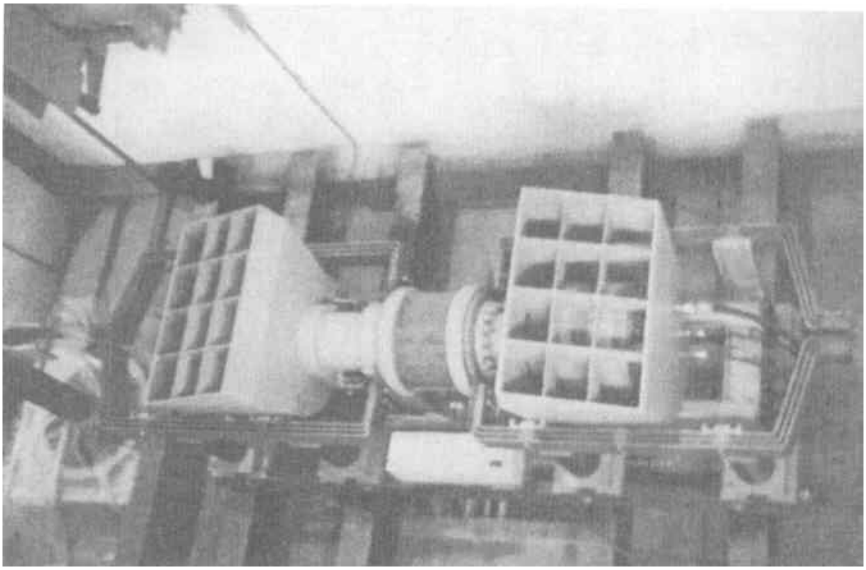

Figure 9.6 Single pole of an air-blast high current interrupting capacity circuit breaker used for back-up protection of test generator at LAPEM (Courtesy of LAPEM, Irapuato, Gto. Mexico).

This type of operation allows precise control for the initiation of the test current and consequently gives the desired asymmetry needed to meet the specific conditions of the test.

Current limiting reactors (L) are connected in series with the making switch; their mission is to limit the magnitude of the test current to its required value. These reactors can be combined in a number of different connection schemes to provide a wide range of impedance values.

Specially designed test transformers (T), such as those shown in Figure 9.7, that have a wide range of variable ratios are connected between the test circuit breaker and the power source. These transformers are used primarily to allow for flexibility for testing at different voltage levels, and in addition to provide isolation between the test generator and the device that is being tested.

Across the test breaker terminals a bank of TRV shaping capacitors (C) is connected. To measure these voltages at least one set of voltage dividers (V) which are usually of a capacitive type are used. In most cases the short circuit current flowing through the test device is measured by means of a shunt (Is) however, measurements using current transformers are also often made, especially for the current at the upstream side of the circuit breaker that is being tested.

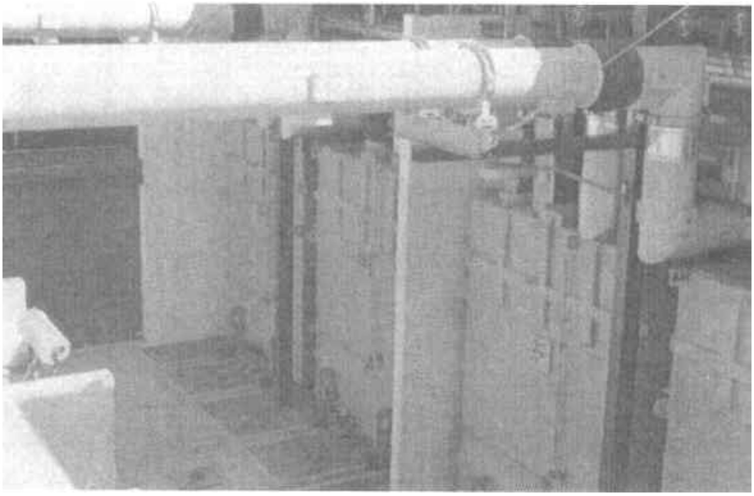

Figure 9.7 Test transformers installed at the LAPEM laboratory. Two transformers per phase are used in this installation (Courtesy of LAPEM, Irapuato, Gto. Mexico).

When one is interested in investigating the interrupting phenomena at the precise instant of a current zero, the use of coaxial shunts is highly recommended for distortion free measurements. However, caution should be taken to limit the current flowing through the shunt since these types of shunts normally have only limited current carrying capabilities.

The typical test set-up that has just been described is used for practically all direct tests as the primary current source, and even for those situations where the available power is insufficient and where alternate test methods have been developed, the primary source of current still is similar to the one that has been just described.

9.1.1 Direct Tests

A direct test method is one where a three phase circuit breaker is tested, on a three phase system, and at a short circuit MVA level equal to its full rating. In other words this is a test where a three phase circuit breaker is tested on a three phase circuit at full current and at full voltage. It should be obvious that testing a circuit breaker under the same conditions at which it is going to be applied is the ultimate demonstration for its capability and naturally, whenever possible, this should be the preferred method of test.

9.1.2 Indirect Tests

Indirect tests are those which permit the use of alternate test methods to demonstrate the capabilities of a circuit breaker for applications in three phase grounded or ungrounded systems.

The methods most commonly employed are:

1. Single phase tests
2. Two part tests
3. Unit tests
4. Synthetic tests

9.1.3 Single Phase Tests

When one thinks only in terms of an individual interrupter it is realized that, as far as the interrupter is concerned, it makes no difference whether a three phase or a single phase power source is used, as long as the current and the recovery voltage requirements for the test are fulfilled; therefore, the use of a single phase test procedure is totally acceptable. However, when the final application of the interrupter is considered, and since in most cases it turns out to be in a three phase circuit breaker, then the neutral shift of the source voltage and some of the potential mechanical interactions that may occur between the poles have to be taken into consideration.

In the first place, in a three phase application at the instant of current zero, and in the phase where the current interruption is about to take place, the interrupter itself does not know that there are another two phases lagging slightly behind on time. If the first phase which sees a current zero fails to interrupt, then the next sequential phase will attempt to clear the circuit. This, basically, gives the circuit breaker an additional two chances to interrupt the current and therefore, as it has been shown by W. Wilson [1], there is a higher probability of successfully interrupting a three phase current than of interrupting a single phase fault.

The oscillogram which is shown in Figure 9.8 depicts the condition where interruption is attempted sequentially at each current zero. As it can be seen in the figure, the first attempt is made on phase B (shown as B_1), since no interruption is accomplished the second attempt is made at the next current zero which is in phase A (shown as A_1). Again the interrupter is not successful on this try and finally on the third try, the current is interrupted in phase C. The other two phases are seen to interrupt the current simultaneously at A-B.

During the first few microseconds following the interruption of the current it only matters that the proper transient recovery voltage be applied across the interrupter, and since in a three phase circuit, as the high frequency oscillations of the load side TRV die down, and before the other two phases interrupt the current, the source side power frequency recovery voltage is reduced to 87% of the line-to-line voltage, due to the neutral shift, as seen in the vector diagram for the power source voltage which is shown in Figure 9.9.

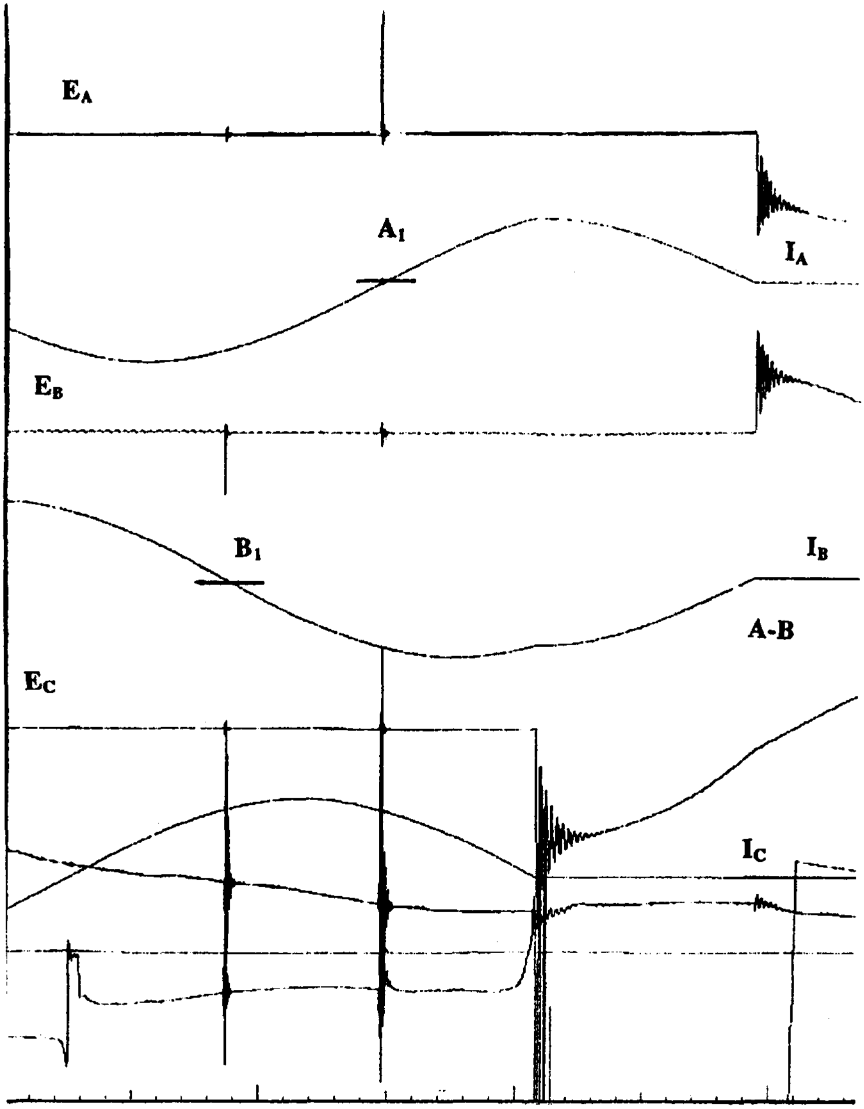

Figure 9.8 Oscillogram of a three phase asymmetrical current interruption test. It illustrates the sequential attempts that are made by the interrupter to clear the current at each successive current zero of each of the three phases.

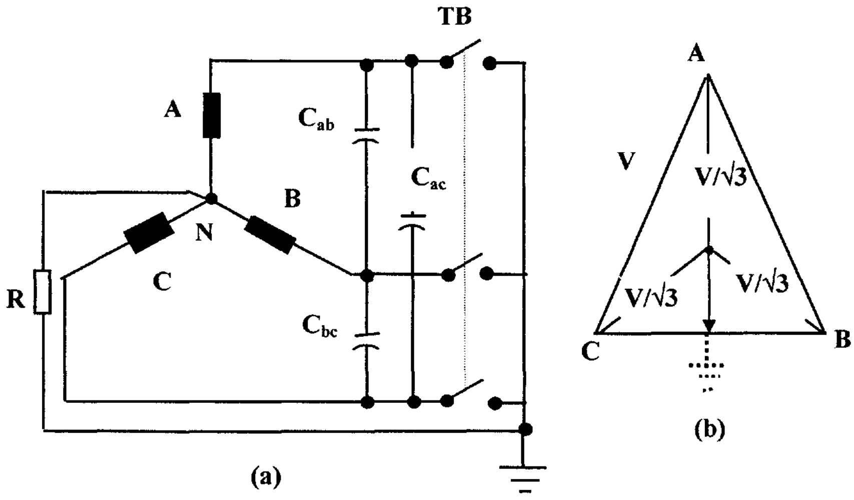

Figure 9.9 Source voltage shift following the interruption of current by one phase (first phase to clear).

After the currents in all the phases are interrupted, the voltage in each phase becomes equal to the line-to-neutral voltage, which corresponds to 58% of the line-to-line voltage. However, this reduction to 58% of the voltage occurs approximately four milliseconds after the current is interrupted by the first phase. This is a relatively long time and when taken into consideration, especially with today's interrupters, that it occurs long enough, after the interrupter has withstood the maximum peak of the TRV. It is then justifiable to expect that the interrupter has regained its full dielectric capability and thus in most cases it becomes only academic the fact that the voltage reduction takes place.

Aside from the purely electrical considerations that have been given above, the possible influence of the electromechanical forces produced by the currents and of the gas exhaust from adjacent poles should be carefully evaluated. It is also important to carefully balance the energy output of the operating mechanism to compensate for the reduced operating force needed to operate a single pole, so that the proper contact speeds are attained. This last recommendation is especially important when testing puffer type circuit breakers.

Naturally, these concerns about the possible pole interaction do not apply to those circuit breakers which have independently operated poles.

9.1.4 Unit Tests

Unit tests can be considered to be simply a variation of the single phase test method which has been used almost exclusively for the extra high voltage class of circuit breakers where, as it should be recalled, it is common practice to install several identical interrupters in series on each pole, mainly for the purpose of increasing the overall voltage capability of the circuit breaker.

This test method, provided that all the interrupters are identical, demonstrates the interrupting capability of a single interrupter from a multiple interrupter pole. The test is performed at full rated short circuit current and at a voltage level that is equivalent to the ratio of the number of interrupters used in the pole assembly to the full rated voltage of the complete pole.

The distributed voltage must be properly adjusted to compensate for the uneven voltage distribution that normally exists across each series interrupter unit and which is due to the influence of stray capacitance. This capacitance is influenced by adjacent poles, and by the proximity and location of the ground planes. However, in any case the test voltage must be at least equal to the highest stressed unit in the complete breaker.

When this test method is used the frequency of the TRV does not change. But, due to the lower voltage peak of the individual interrupter, the rate of rise of the recovery voltage is proportionally lower. This characteristic response holds not only for terminal fault tests but also for short line fault tests.

Whenever the unit test method is utilized, and as it was the case with the previous test method, care must be taken to properly scale the mechanical operating parameters to ensure the validity of the tests.

9.1.5 Two Part Tests

A two part test consists of two essentially independent tests. The first test is one where the interrupter is tested at full rated voltage and at a reduced current. In the second test the maximum current is applied at a reduced voltage.

The idea behind this method is to test for the dielectric recovery region with the first portion of the test and then to complement the results by exploring the thermal recovery region by means of the second test. Application of this test method has always been limited to the extra high voltage interrupters where, as it should be recalled, the TRV is represented by a waveform that is composed of an exponential and a (1 - cos) function. When the two part tests are performed, the first portion of the test is made at full rated current and with a TRV that is equal to the exponential portion of the waveform. The second part of the test, where the requirements for the voltage peak and for the time to reach this peak are verified, is made at a reduced current but at full voltage and with a TRV equal to the (1 - cosine) component.

This test method is often difficult to correlate with actual operating conditions and therefore it is somewhat difficult to justify. This is a test that was frequently used prior to the development of the synthetic test methods described below and consequently today this approach should only be used when all other testing alternatives are not suitable.

9.1.6 Synthetic Tests

Synthetic tests [2] are essentially a two part test that is done all at once. The test is performed by combining a moderate voltage source which supplies the full primary short circuit current with a second, high voltage, low current, power source which injects a high frequency, high voltage pulse at a precise time near the natural current zero of the primary high current.

Effectively, what has been accomplished is to reproduce the conditions that closely simulate those that prevail in the interrupter during the high current arcing and the high voltage recovery periods. As long as the sources, voltage and current are not appreciably modified or distorted by the arc voltage then the energy input into the interrupter during the high current arcing time region is no different than the energy input obtained from a full rated system current and voltage because, as we well know, the energy input to the interrupter is only a function of the arc voltage and not of the system voltage.

The behavior of the interrupter in the two classical regions of interest, namely the thermal and the dielectric regions, are evaluated by the high voltage that is superimposed by the injected voltage/current which when properly timed embraces the transition point where the peak of the extinction voltage just appears and the point where the peak of the recovery voltage is reached thus covering the required thermal and dielectric recovery regions.

In general, synthetic tests are performed on a single phase basis and even though schemes have been developed that enable the tests to be made on a three phase circuit, it is only the largest laboratories that are capable of doing so. In the majority of the facilities the high voltage source for these tests is only available on a single phase basis, simply because in most cases some of the same power limitations that existed for three phase direct test still exist.

As it was said before the synthetic test method utilizes two independent sources, one a current source that provides the high current, and which for all practical purposes is the same source that is normally used for direct tests, and a second, a voltage source, which in most cases consists of a capacitor bank charged to a certain high voltage that is dependent upon the rating of the circuit breaker that is being tested.

There are a number of synthetic test schemes that have been developed, but in reality they all are only a variation of the basic voltage or current injection schemes. In actual practice, what is used most often by all testing laboratories is the parallel current injection technique.

9.1.6.1 Current Injection Method

The current injection method is illustrated in the schematic diagram of the equivalent circuit as shown in Figure 9.10. This method is characterized by the injection of a pulse of current that is supplied by the high voltage source.

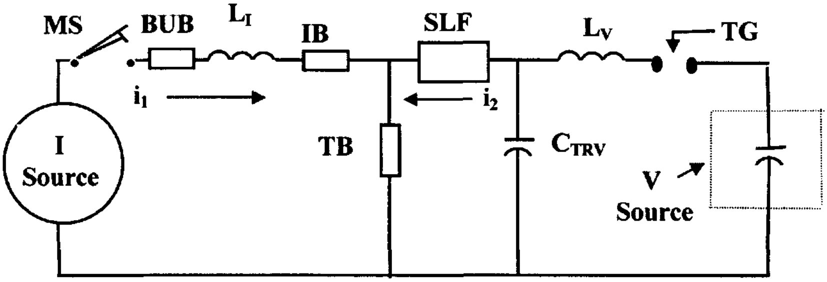

Figure 9.10 Schematic diagram of a parallel current injection synthetic test circuit.

The high current source, as mentioned before, is composed of a short circuit generator, a back-up circuit breaker for the protection of the test generator, a set of current limiting reactors, a high speed making switch and an additional component, an isolation circuit breaker (IB) whose purpose, as its name implies, is to effectively separate, or isolate, the current circuit from the high voltage circuit.

The high voltage section of the circuit is made up of a high voltage source (VS) consisting of a capacitor bank that is charged to a predetermined high voltage level. Connected in series with the capacitor is one side of a triggered spark gap (TG). The other side of the trigger gap is connected to a group of frequency tuning reactors. Connected in series with these reactors there is a short line fault (SLF) TRV shaping network, which consists of a combination of capacitors and reactors that in most instances are connected in a classical pi (π) circuit configuration. Generally it is required that at least five of these sections be connected in series in order to accurately represent the TRV of a short line fault. This SLF network, however, is only used when the tests that are being performed simulate a short line fault condition.

It is recommended that the frequency for the injected current be kept within the range of 300 to 1000 Hz. These limits depend primarily on the characteristics of the arc voltage. What is important is that the period of the injected current be at least four times longer than the transition period where a significant change in the arc voltage is observed. The magnitude of the injected current should be adjusted so that the rate of change of the injected current $(di/dt)_i$ and the rate of change of the corresponding rated power frequency current $(di/dt)_p$ are equal at their respective current zeroes. The timing for the initiation of the current pulse is controlled so that the time during which the arc is fed only by the injected current is not more than one-quarter of the period of the injected frequency.

Parallel current injection. The schematic diagram of the circuit that was shown in Figure 9.10 represents the equivalent circuit configuration that is used for the parallel injection method, and in Figures 9.11 and 9.12, the relationship between the power frequency and the injected current is shown.

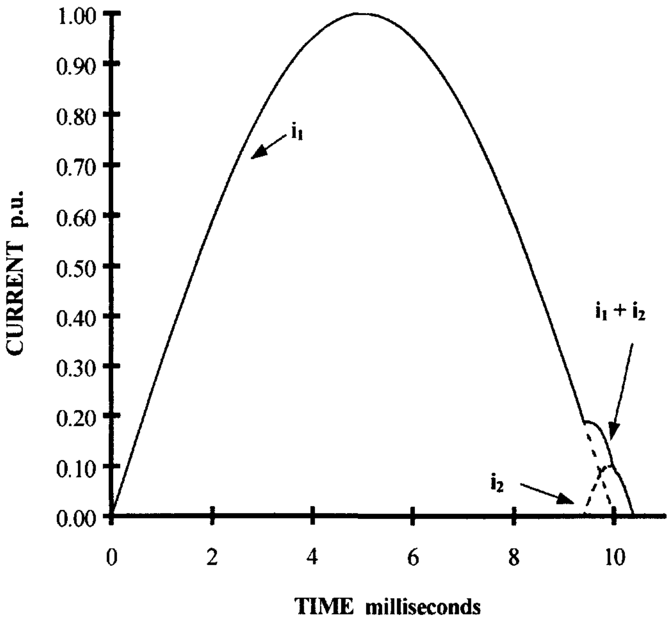

Figure 9.11 Relationship between primary current and injected current in a synthetic test parallel current injection scheme.

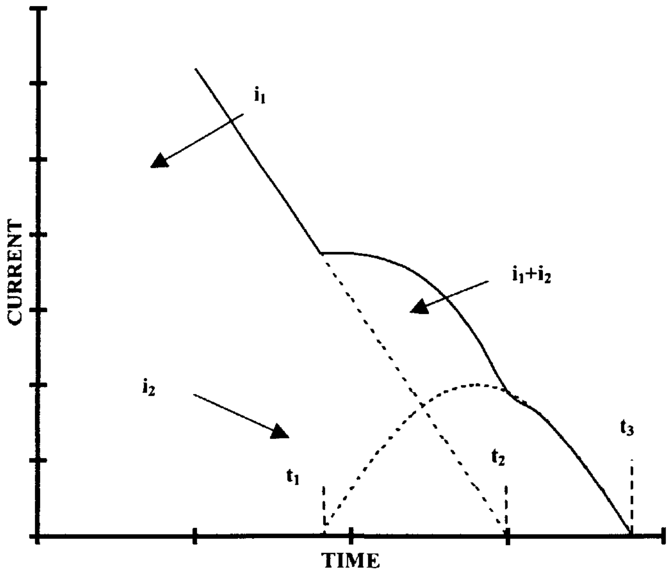

Figure 9.12 Expanded view of the parallel current injection near current zero.

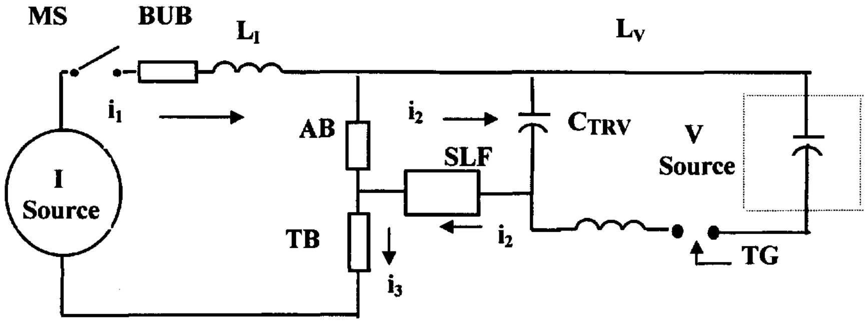

Figure 9.13 Schematic diagram of a typical series current injection synthetic test circuit.

The test is initiated by closing the making switch (MS), which initiates the flow of the current i_1, from the high current source (IS) through the isolating breaker (IB) and the test breaker (TB). As the current approaches its zero crossing the spark gap is triggered and at time t_1 (see Figure 9.12) the injected current i_2 begins to flow. The current $i_1 + i_2$ flows through the test breaker until the time t_2 is reached. This is the time when the main current i_1 goes to zero and when the isolation breaker separates the two power sources. At time t_3 the injected current is interrupted and the high voltage supplied by the high voltage source provides the desired TRV which subsequently appears across the terminals of the circuit breaker that is being tested.

Series current injection. The series current injection circuit is shown schematically in Figure 9.13 while in Figures 9.14 and 9.15 the algebraic summation of the injected currents is shown. The notable difference between the series current injection and the parallel injection methods is that the high voltage source for the series injection version of the test is connected in series with the high current source voltage.

At the initiation of the test the making switch is closed and at time t_1 the spark gap is triggered, thus allowing the current i_2 to flow through the isolation breaker but in the opposite direction to that of the current i_1 from the high current source. At time t_2, when the currents i_1 and i_2 are equal and opposite, the current in the isolating breaker is interrupted and during the time interval from t_2 to t_3 the current that is flowing through the test breaker is equal to i_3. This current corresponds to the summation of the currents i_1+i_2 that is produced by the series combination of the high current and the high voltage sources. Following the interruption of the current i_3 at time t_3 the resulting TRV supplied by the high voltage source appears across the breaker terminals.

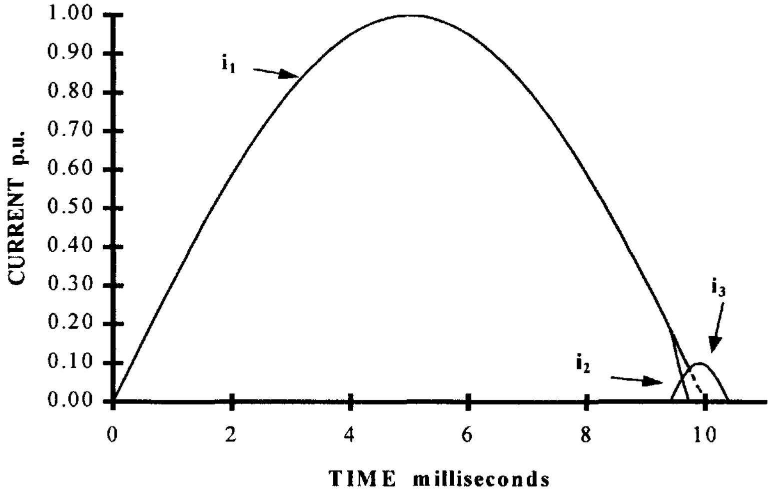

Figure 9.14 Relationship between primary current and injected current in a synthetic test series current injection scheme.

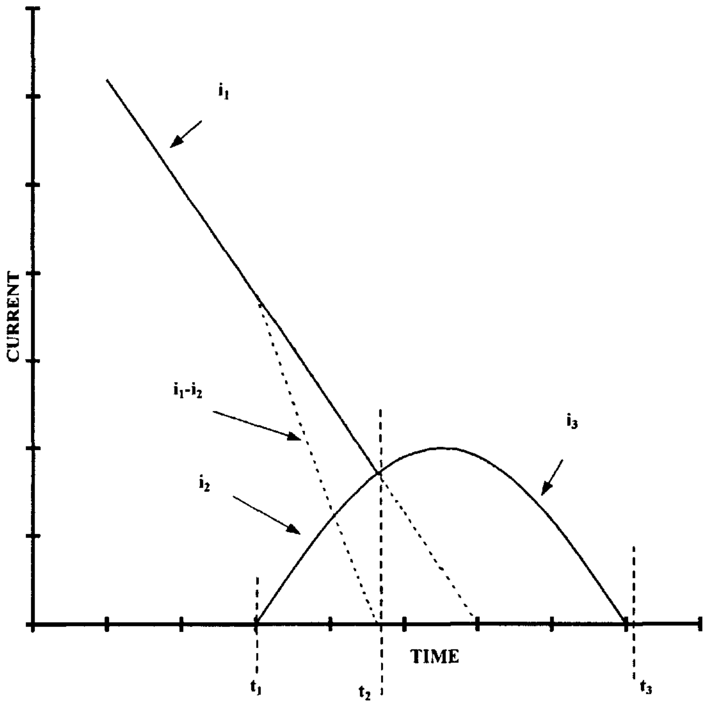

Figure 9.15 Expanded view of the series current injection near current zero.

9.1.6.2 Voltage Injection Method

The voltage injection method, in principle, is the same as the parallel current injection. The only difference is that the output of the high voltage source is injected across the open contacts of the test breaker following the interruption of the short circuit current which, as explained before, is supplied by the high current source. The high voltage is injected immediately after the current zero and near the peak of the recovery voltage that is produced by the power frequency current source. A capacitor is connected, in parallel across the contacts of the isolation breaker, in order to effectively apply the recovery voltage of the current source to the test breaker.

This test method is not very popular because it requires a very accurate timing for the voltage injection. This timing becomes a critical parameter which in most cases is rather difficult to control.

9.1.6.3 Advantages and Disadvantages of Synthetic Tests

As is the case with any of the other test methods, there are a number of advantages and disadvantages that are associated with synthetic tests.

The principal advantage that should be mentioned is that these tests are of a non-destructive nature and therefore they are ideal for development test purposes, where the ultimate limits of the device can be explored without destroying the test model. Also the synthetic test method is the most adequate, and in some cases the only way of performing short line fault tests.

The main disadvantage of synthetic tests is that these tests are primarily a single loop test, which explains why they are considered to be a non-destructive test, and although a reignition circuit can be used to force a longer arcing time, or a second loop of current, it still is very difficult to do a fast reclosing with extended arcing times. Another disadvantage is that this method is not suitable for testing interrupters which have an impedance connected in parallel with the interrupter contacts in which case it is likely that the full recovery voltage can not be attained due to the power limitations of the high voltage source.

9.2 TEST MEASUREMENTS AND PROCEDURES

Test procedures and instrumentation naturally vary in accordance, not only with the test method, but also with the purpose of the tests that are being performed. The test instrumentation, can be significantly different, for example, when doing interrupter development tests than when doing verification or circuit breaker performance tests.

In the investigative portion of the tests it is likely that special attention will be paid to the phenomena occurring at, or very near, current zero, where a higher degree of resolution is needed. In these tests, what is of interest is what takes place around current zero in a time region which is normally in the microsecond range, while for verification tests, or complete circuit breaker interruption tests, and with the exception of the TRV, the time of interest is in the millisecond range.

For development tests in most cases it is important to have accurate measurements of arc voltage, interrupter pressure, post arc current and other very definite measurements, depending solely on the type of information that is being sought. While because the tests that are made to demonstrate the capability of the circuit breaker, and the requirements that have been set to demonstrate its compliance with the existing standards, are well defined in the applicable standards [3], [4] and because in most cases it is assumed that a significant number of development tests have already been performed, the needed instrumentation is what may be considered as conventional, consisting of measurements of phase currents, phase voltages and TRV.

Since the procedures for development tests are rather specialized and specific in nature according to the circumstances, or to the objectives of the tests being performed it is then difficult to provide firm guidelines for the instrumentation to be used and for the test procedures to be followed; however, the techniques that are to be described and which are used for the design verification tests can also be used for other purposes, such as exploratory tests.

9.2.1 Measured Parameters and Test Set-Up

It goes without saying that the fundamental parameters of phase currents and corresponding phase voltages must be measured. In addition to these parameters it is advisable, especially when testing vacuum circuit breakers, to make measurements of the amplified arc voltage. This measurement can be very helpful in determining the precise instant where contact part occurs. It also serves to determine the stability of the arc and the effectiveness of the interrupter at the transition point of the current regions.

Another valuable and important measurement, that sometimes is neglected, is the measurement of the breaker contact travel which, when everything goes right on a test, may not be needed but for those times when there is a failure this measurement would help to answer questions such as: Was the circuit breaker fully open, did it stall, was it fully closed?

The test current is generally measured using a low resistance shunt, and in some occasions, for even better accuracy and response, a coaxial shunt is used. The voltage measurements are usually made with a capacitive compensated voltage divider, and the measurement is preferably made on a differential mode to avoid distortions due to possible ground shifts.

9.2.1.1 Grounding

The one essential requirement is that grounding of the circuit must be either at the source or at the test breaker but not at both places. The test circuit breaker must be connected in a test circuit that has the supply's neutral isolated and the short circuit point grounded.

9.2.1.2 Control Voltage

Although in the standards it is indicated that the rated control voltage of the device should be used, one could take exception to this because in most cases it is very convenient to use a higher control voltage, perhaps as much as 20% over the rated value as the means for minimizing the variation in the time that it takes to open the contacts. In addition to the higher control voltage it is advisable to use a dc supply whenever possible, rather than an ac supply. This is done with the sole objective of minimizing the variation of the contact opening time, which is important because of the need for proper control of the point on the wave where it is desired to break the circuit so that the proper current symmetry is achieved during the test.

9.2.1.3 Close-Open Operations

In some laboratories, performing a close-open operation at high asymmetrical currents can be quite harmful to the health of the circuit breaker. This happens because when attempting to meet both requirements, closing against the peak of a fully asymmetrical current and opening at the point of maximum total rms current there is a risk that the peak of the closing current may be substantially higher than what is required. This risk exists because, even though super excitation is applied to the test generator, the asymmetrical value at contact part can not be easily achieved and when the symmetrical value of the current is raised to compensate for the rapid dc decrement, the initial peak of the current is also proportionally increased. One method that has been used successfully to overcome this difficulty has been the addition of a series reactor which limits the peak of the current during the closing operation, but as soon as the circuit breaker is closed, and before the opening is initiated, a switch that is connected in parallel with the reactor is closed, effectively shorting out the reactance and thus increasing the current at the time of contact separation.

9.2.1.4 Measuring the TRV

Despite the fact that in most cases the TRV is measured during the actual interruption testing this measurement is not always a valid one due to the influences exerted by the characteristics of the arc voltage, the post arc conductivity, and the presence of TRV modifying components such as capacitors and resistors that may have been installed across the contacts and which will most definitely affect the TRV wave of the circuit. Therefore unless the above mentioned effects are insignificant and the short circuit current does not have a dc component, most of the commonly obtained test records can not be used and special procedures must be utilized to determine the inherent TRV of the test circuit.

The methods most commonly used are:

1. Current injection

2. Capacitor injection, and
3. Network modeling/calculation

Current injection. This method consists of injecting a small power frequency current signal into a de-energized circuit and then interrupting the injected current using a switching device that has negligible arc voltage and post arc current. A device with such characteristics could be a fast switching diode, one that exhibits a reverse recovery time of less than 100 nanoseconds. When using these types of diodes, it is permissible to have a shorting switch across the diode if there is a possibility that the current carrying capabilities of the diode could be exceeded. The shorting switch will have to be opened shortly before the zero current crossing where the TRV measurement is to be made. The measurements of the current and voltage waveforms must be made using instrumentation suitable for high speed recording.

Capacitor injection. Here a low energy capacitive discharge is used as the source for the injected current. In reality this method is no different than the previous method except that in this case the ac source for the injected current has been replaced by the dc voltage stored in a charged capacitor. Since the frequency of the discharged current is proportional to capacitance of the source and the inductance of the circuit, then the frequency of the measured voltage defines the inherent TRV.

For best results the frequency of the discharge current for these measurements should be ≤ 0.125 of the equivalent natural frequency of the circuit being measured.

Network modeling/calculation. This method consists of either an analog or a digital modeling of the network that is being evaluated. The accuracy of this method, of course, depends upon the selection of the appropriate representative parameters of the circuit that is being evaluated.

9.2.2 Test Sequences

As it was the case with regard to ratings, so it is for testing; the ANSI and IEC test requirements are not exactly the same. Nevertheless, the required tests are sufficiently close in both documents, and with only a little extra effort in choosing equivalent test parameters, especially for TRV, and by adding a few extra tests, the requirements of both standards can be concurrently met.

9.2.2.1 IEC62271-100 Requirements

The short circuit capability, according to the IEC standards, is demonstrated by a test series consisting of five test duties. Test duties T10, T30 and T60 consist of three opening operations which are demonstrated using the standard duty cycle which, as it can be recalled, consists of the sequence, O-t-CO-t'-CO where t is either 3 minutes or 0.3 seconds depending on whether the circuit breaker is rated for reclosing duty or not. These test duties are performed with symmetrical currents of 10% (± 20%), 30% (± 20%) and 60 % (± 10%) of the rated short circuit current respectively. The TRV requirements include a slightly higher voltage peak and a significantly shorter time duration to reach the voltage peak from those listed for the full fault. These test duties are performed with the intent of simulating the interrupting behavior of a circuit breaker in the event of a fault in the secondary side of a transformer, where as the current is reduced the TRV becomes more severe, as it has been verified by Harner et al. [5].

Test duty T100s consists of the prescribed operating duty cycle at full rated fault currrent. The opening operation is made under symmetrical current conditions, while the maximum asymmetrical current peak must be attained during the closing operation in order to demonstrate the close and latch capability of the circuit breaker. The symmetrical current for the opening following the closing is obtained by delaying the trip sufficiently so that the dc and ac transient components have decayed to an asymmetrical value of less than 20%.

Test duty T100a is a test similar to test duty T100s except that both the opening and closing operations are made with an asymmetrical current. The asymmetry of the current is that which corresponds to a time constant of approximately 45 ms which, corresponds to an X/R value of 14 for 50 Hz or 17 for 60 Hz.

The asymmetrical value of the current is determined using the actual contact opening time of the circuit breaker to establish the elapsed time that is measured from the time of current initiation to the point of contact separation. This time determines the asymmetrical value for the test by following the procedure which was described previously in Chapter 8.

For circuit breakers intended for use in solidly grounded systems an additional symmetrical current single-phase test is required. Also short line fault tests at 90% and 75% of the fault current must be performed on outdoor circuit breakers that are rated above 52 kV and 12.5 kA and that are intended to be connected di rectly to overhead lines.

9.2.2.2 ANSI C37.09 Test Sequences

Prior to 1999. The ANSI test requirements were specified as shown in the included Table 9.1. By observing this table it can be seen that there were significant differences in comparison to IEC 600056. It is also evident that a rather extensive test series would have been required if every test was performed precisely as described. However, when one looks closely to the requirements it is found that it was possible to combine some of the tests, thus simplifying the testing program. Having eliminated in the 1999 edition of the standards the voltage range factor K further simplified the test program by eliminating the duplicate testing at the two limits of the K factor.

Additional changes intended primarily to simplify and to facilitate the experimental demonstration of the circuit breaker capabilities were also implemented.

Table 9.1

Three Phase Tests for Demonstrating the Short Circuit Rating
of a High Voltage Circuit Breaker

Test Duty	Operating Duty	Phases	V Initial Recov.	Making Current at 1st. Major Loop		Current Interrupted at Contact Part	
				A, rms	A, Peak	A rms	%Asym
1	One O & One CO	3	V			.07 to.13 I	> 50
2	One O & One CO	3	V			.2 to .3 I	< 50
3	One O & One CO	3	V			.4 to .6 I	> 50
4	O-15s-O, O-15s-CO or CO-15s-CO	3	V			I	< 50
5	O-15s-O, O-15s-CO or CO-15s-CO	3	V/K			KI	< 20
6-1	CO-15s-CO	3	V	1.6 I	2.7 I	SI	> 50
6-2	C	3	V	1.6 I	2.7 I		
6-3	O-15s-O	3	V			SI	> 50
	121 kV and above						
7A-1	CO-15s-CO-15m-CO-1h-CO	3	V/K	1.6 KI	2.7 KI	KSI	> 50
7A-2	C-15s-C-15m-C-1h-C	3	V/K	1.6 KI	2.7 KI		
7A-3	O-15s-O-15m-O-1h-O	3	V/K			KSI	> 50
	All other breakers						
7B-1	CO-15s-CO-1h-CO	3	V/K	1.6 KI	2.7 KI	KSI	> 50
7B-2	C-15s-C-1h-C	3	V/K	1.6 KI	2.7 KI		
7B-3	O-15s-O-1h-O	3	V/K			KSI	> 50
8	Several O and CO	3	V/K				Random
9	O-0s-CO or CO-0s-CO	3	V			RSI	> 50
10	O-0s-CO or CO-0s-CO	3	V/K			RSI	> 50
11	C-T s-O	3	V/K	1.6 KI	2.7 KI	KI	
12	In closed position	1					
13	1 O and 1 CO or 2 O	1	.58V			Smaller of 1.15 I or KI	< 20
14	1 O and 1 CO or 2 O	1	.58V			Smaller of 1.15 I or KSI	> 50
15	O-15s-O or O-15s-CO	1	.58V			.7 to .8 I	< 20
16	O-15s-O or O-15s-CO	1	.58V/K			.9 to .95 I	< 20

One such change was the elimination of test duty 11 which required for the circuit breaker to be closed against the full value of a fault current, to carry this current for a time equal to the maximum rated permissible trip delay (2 seconds for breakers rated 72.5 kV and below, or 1 second for higher voltage ratings) and then to interrupt the full rated symmetrical short circuit current. This was a very difficult test to perform, mainly because the thermal rating of the test generators are almost always exceeded. Furthermore this kind of power is simply not available on a three phase basis at any test laboratory for the higher voltage rated circuit breakers.

In some laboratories this test was performed synthetically, using two power sources. The closing operation was done using a high voltage and high current source. This initial closing portion of the test obviously was no different than any of the routine closing operations that are performed as part of the circuit breaker duty cycle required by some of the routine test duties. However, immediately after the circuit breaker was closed the high voltage source was removed by means of an isolating switch and then a high current, supplied by a low voltage source, was superimposed upon the closed circuit breaker contacts. The high current was maintained for the required length of time and afterwards, when the time requirements were met, the high current source was removed and the high voltage high current source was once again inserted into the circuit so that the current interruption portion of the test be performed.

Prior to the publication of the 1964 edition of the standards C37.04 and C37.09 the requirements for this test duty 11 were promulgated separately, and a close and latch and a momentary current rating were published. The testing to demonstrate these requirements was done independently and in separate operations. This approach continued to be taken in most cases because of a tacit agreement about the impracticality of the requirements. What must be remembered is that the close and latch test is made to prove the mechanical capability of the circuit breaker and that this demonstration is made several times while performing the complete test sequences required for breaker certification. The requirement for carrying the current for a specific time duration (longer than that required in the previous test duty) is demonstrated by the short time test sequence, where the test demonstrates the short time thermal capability of the contacts. It is generally agreed that if this capability is built into the contact structure, the higher contact temperature at the moment of contact part does not have any negative effect upon the interrupting capability of the circuit breaker.

Test duties 6, 7A and 7B were also a demonstration of the standard test duty cycle, except that in test duty 7A, which was intended for circuit breakers rated above 121 kV, a second test duty cycle was performed after 15 minutes of the first.

Remembering that these standards were written primarily with air and oil circuit breakers in mind, it is understandable that the possible effects of the stored heat and the drop in pressure due to the previous interruption had to be investigated. With today's vacuum or SF_6 circuit breakers it is known that this does not constitute a problem and therefore the only justification for the extended duty cycles is to accumulate the required 800% interrupted currents and the demonstration of the worst switching condition. The time interval between duty cycles also is no longer that important and the tests can be made within a time frame of only a few minutes as it may be dictated strictly by convenience.

It is important to note that the high asymmetrical values, those above 50%, that were specified in the test tables were unrealistically high and basically unattainable for a circuit breaker with normal interrupting times of 3 or 5 cycles and for a system having an X/R value of 17. Therefore the alternative was to test with a lower asymmetry, say 35 to 45%, or, as suggested by the standards, to adjust for the total current at the time of contact part but to reduce the symmetrical rms of the current and test with the higher total rms asymmetrical current value. Nevertheless, a test made with a reduced symmetrical rms and with a higher dc component was valuable because it provided at least some indication of the breaker capability for applications in systems where the X/R values are higher than 17.

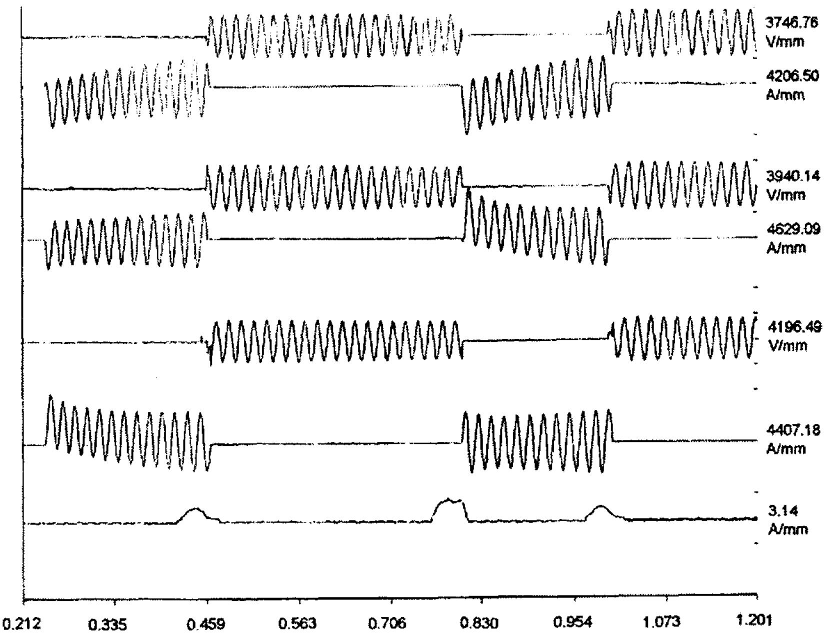

Figure 9.16 Typical record oscillogram of a three phase Close-Open-0.3 sec-Close-Open operation with an asymmetrical current.

Test duties 13 and 14 were supposed to demonstrate the capability of the circuit breaker to interrupt a line-to-ground fault in a grounded system. The tests, naturally, were performed on a single phase basis and were only required when the previous test duties had been done on a three phase basis; these tests were not required when all the testing was done using a single phase source.

The last two test duties, 15 and 16, were also single phase tests, but were applicable only to outdoor circuit breakers. The aim of these tests was to prove the short line fault capability of the circuit breaker. However, in regards to these test duties, another inconsistency existed between two of the ANSI documents. C37.04 stated that all outdoor circuit breakers must be capable of interrupting a short line fault, but in C37.09 it was said that it is not needed to demonstrate this capability for circuit breakers rated 72.5 kV and below.

Post 1999. In ANSI/IEEE C37.09-1999 the number of test sequences required were reduced and the whole test program was in principle fully harmonized with the IEC 62271-100 requirements.

The first three ANSI sequences, test duties 1, 2 and 3, are quite similar to those required by IEC 62271-100 (test duty T10, T30, T60); they consist of three opening operations at current values equal to 10%, 30% and 60% of the rated fault current. ANSI allows the possibility of doing this sequence either as three straight openings or as a complete duty cycle (O-t-CO-t'-CO). ANSI further requires that at least one of the openings be made with a greater than 20% asymmetry. This additional requirement should be easily obtained if the test is done using the duty cycle option. The random opening, following a closing operation, most likely will produce the desired asymmetry in one of the phases.

Test duties 4 and 5 are full rated fault current symmetrical and asymmetrical tests respectively. These tests are the same as IEC test duties T100s and T100a. The specified operating sequence for test duty 4 is based on the rated operating duty of the circuit breaker. However, if there are limitations imposed by the testing facility it is permissible to separate the opening and the closing operations and to perform them independently as indicated by test duties 4a and 4b. These tests provide verification not only of the interrupting capability but also about the close and latch capability of the circuit breaker. It is also possible, as it is done in IEC 62271-100, to perform this test duty with a time interval of 0.3 seconds and thus meet the test requirements for a fast reclosing duty. However, when this is done the possible need of derating the interrupter must be considered. Derating was almost always applied to older style circuit breakers, but when considering the application of the new technologies, this is a requirement that does not appear to have much value left. This test duty is illustrated in Figure 9.16. Test duty 5 does not require the duty cycle sequence but only three opening operations performed at full rated fault current and with an asymmetry greater than 20%.

Test duties 6 and 7 are single phase tests. These tests are mandatory in ANSI and are applicable to all circuit breakers. They are not limited, as in IEC, only to circuit breakers intended for solidly grounded applications. These tests are not required only in the case when the testing program used the single phase option.

It is important to realize that these two tests are rather unique because they are performed at a voltage of .58% of the maximum line-to-line rated voltage and that this is in contrast with the .87% of the line-to-line voltage which is used when all the testing is done with a single phase source.

Test duties 8 and 9 are tests designed to demonstrate the short line fault capability of the circuit breaker. Experience has shown that the short line fault requirements are not confined only to the very high voltage circuit breakers and, as a matter of fact, a number of medium voltage circuit breaker failures which can be directly attributable to the inability to properly handle the short line TRV have been reported.

9.2.2.3 Most Severe Switching Conditions

The most severe switching conditions generally refer to the case where the interrupter is subjected to a maximum arcing time, or what amounts to a condition of maximum arc energy input.

Basically what is intended by testing for the most severe switching conditions is to show that in the worst case the interrupter in any one of the poles of the circuit breaker is capable to withstand the maximum arc energy input.

The most unfavorable conditions will be those where the contact separation occurs during a minor current loop and where the duration of the arcing time is just short of the minimum arcing time required for interruption by that particular design. As we already know, if the minimum arcing time requirement is not met then interruption will only take place after an additional half cycle of current, which for the worst case condition will constitute a major current loop.

Since in a three phase system under symmetrical current conditions the current zeroes occur at a sixty electrical degrees interval then, there is a 2.77 millisecond window to accommodate the variation in the possible arcing time. What this means is that, with symmetrical currents in a three phase system, if one of the phases fails to clear the fault at its first current zero, this phase most likely will never see its true maximum arcing time because one of the other phases is likely to interrupt the current before the original phase reaches a repeat current zero, and even though the energy input to the interrupter which failed to clear the current at its first attempt continues to increase, because when the current in one of the phases has been interrupted the remaining two phases will evolve into a single phase current which is then interrupted by the two remaining poles in series, the total energy input still will be less than what can be expected from a fully asymmetrical single phase fault that has a maximum arcing time.

Figures 9.17 and 9.18 illustrate the condition where the sequence of current zero crossing is related to an arcing time window. The current zero where interruption should occur is designated by the letters A, B, and C. This designation matches the identification that is given to the corresponding arcing windows.

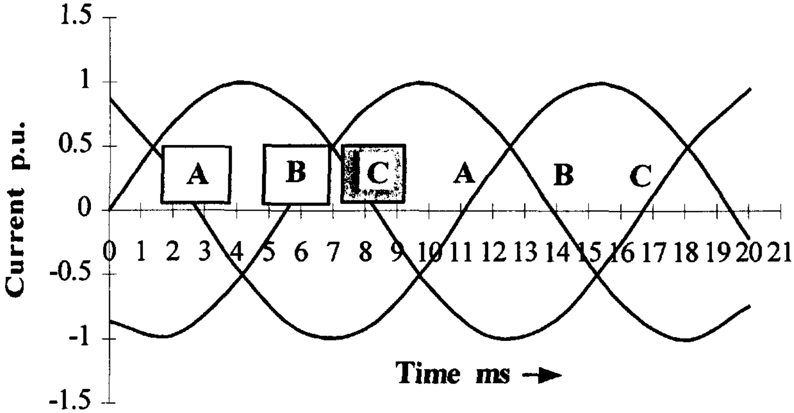

Figure 9.17 Relation of arcing time for symmetrical currents and for different contact parting windows for a circuit breaker with a minimum arcing time of 4 ms.

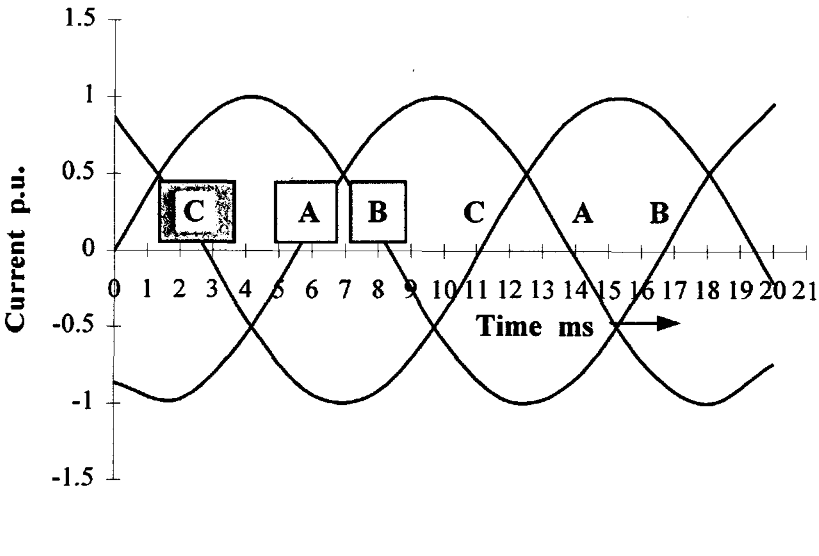

Figure 9.18 Relation of arcing time for symmetrical currents and for different contact parting time windows for a circuit breaker with a minimum arcing time of 10 ms.

Figure 9.17 represents a circuit breaker that has a minimum nominal arcing time of approximately 4 ms. This arcing time is generally a characteristic of vacuum interrupters with currents greater than 15 kA.

Figure 9.18 shows a minimum arcing time of 10 ms which is representative of a SF_6 circuit breaker, where the range of the minimum arcing times is generally between 7 to 13 ms.

One suggested method that can be used to determine the maximum arcing time is illustrated in Figure 9.19. For the first interruption the contact part is adjusted so that it occurs at a current zero of any of the three phases, in our example phase A was selected first. By observing Figure 9.19 we can see that: a) if the minimum arcing time is less than 3 ms then interruption will take place at B, b) if the minimum arcing time is less than 6 ms then interruption will occurs at C, and c) if the minimum arcing time is less than 8 ms then the current will be interrupted at A. For the second test the contact part is advanced by approximately 2.5 ms to t_2 and in this way the arcing time window that we had mentioned before is not exceeded and if the test is repeated the point of interruption will be the same as in the previous test, any further advances of the contact part will then result in a shifting of the corresponding current zero where interruption takes place.

The method recommended by ANSI requires that the contact parting time then be modified by 40 electrical degrees or approximately 2 ms between each operation.

The same situation, as it was described for the symmetrical currents, does exist with asymmetrical currents, except that now the arcing time window is no longer a constant 2.77 ms, but depends upon the dc and ac components of each of the phase currents. Figures 9.20 and 9.21 serve to illustrate the shift of the interruption point for a circuit breaker that has a minimum arcing time of 4 ms, when the contact parting point is displaced by about 5 ms. What should be noticed is that for the conditions shown in the figures the maximum energy input to the interrupter, shown in arbitrary per unit values, does not occur on the first phase to clear but rather on one of the last phases to interrupt. However, there are now two phases in series that are interrupting the current thus making the interruption an easier task.

In Figure 9.22 it is shown how one may accomplish the required interruption of the current after a portion of a minor loop plus a full major loop by only varying the point of contact part. This is done by controlling the tripping of the circuit breaker so that, for our example which corresponds to a circuit breaker with a minimum arcing time of 4 ms, the contacts will separate on the phase with the highest asymmetry (phase A in our example), at a point on the minor loop that is less than 4 ms from its next current zero, and which in the case that is illustrated corresponds to a current that is close to the peak of the minor loop; interruption then will take place after the full major loop. For the next test the trip is advanced by 4.2 ms and the interruption will occur on phase C, and finally for the last test the trip signal is retarded by 4.2 ms and interruption then will occur in phase B.

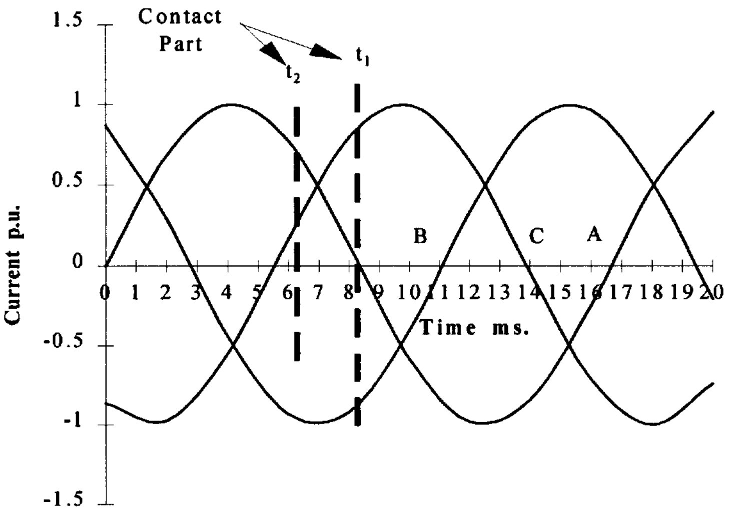

Figure 9.19 Method for obtaining the maximum arcing time for a symmetrical three phase current test.

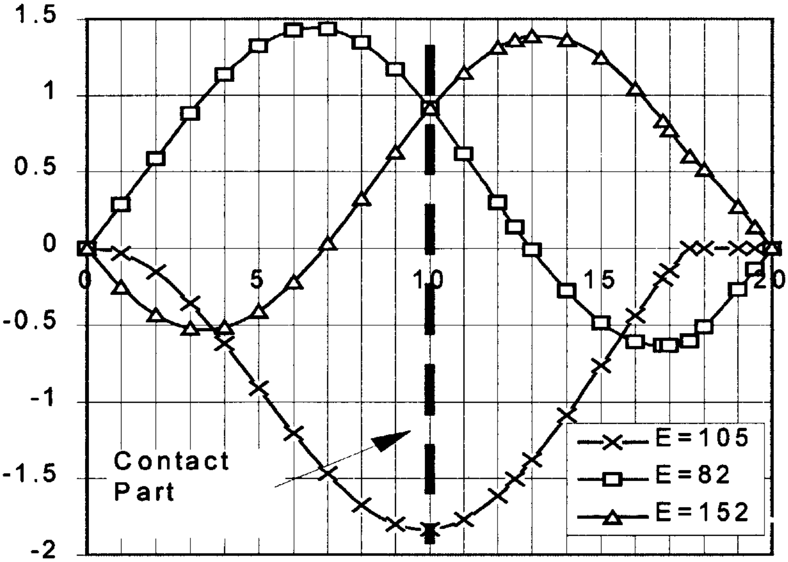

Figure 9.20 Arcing time variation depending on point of contact part for asymmetrical currents. Assumed minimum arcing time 4 milliseconds, a comparative value of arc energy input E (arbitrary per unit value) is shown in enclosed box.

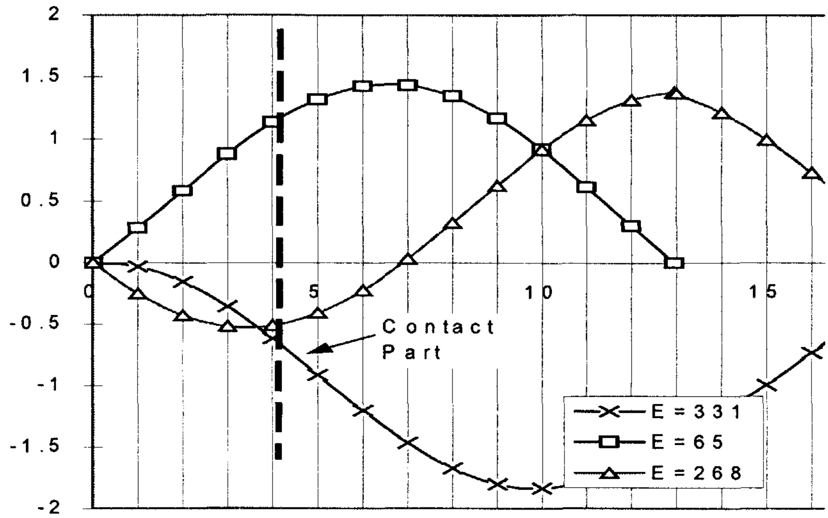

Figure 9.21 Arcing time variation produced by advancing approximately 4.5 ms the point of contact part from the original position shown in Figure 9.20.

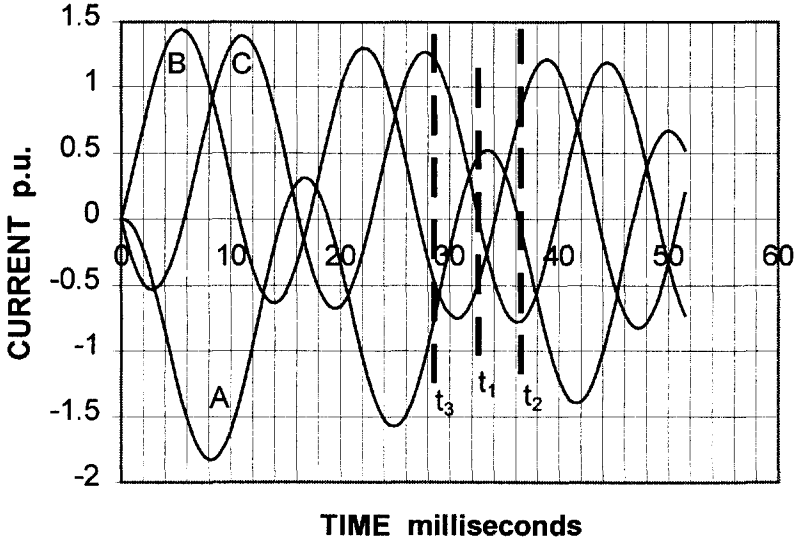

Figure 9.22 Three phase asymmetrical current times t_1, t_2, and t_3 show the changes in the contact parting time to obtain the required maximum energy conditions.

The procedures given by IEC for obtaining the worst switching condition call for the following sequences:

1. For the first operation the point of contact part is set so that the required value of the total current is obtained.
2. For the second test, the initiation of the short circuit current is shifted by 60 electrical degrees and if in the first test the first phase to clear did so after a major current loop, the trip time is advanced by approximately 130 electrical degrees otherwise it is advanced by only 25 degrees.
3. For the third operation the procedure of the second operation may be repeated and the same criteria about the first phase to clear is applicable.

The only objection that perhaps may be raised about the procedure is in connection with the change that is required of the inception angle of the short circuit current, which is required so that the asymmetries of the currents are transposed between the phases; it seems that it would be simpler to change only one parameter, the contact parting time, rather than two parameters at the time, considering that the results for similar contact part conditions for each individual phase would be the same.

A more realistic and an easier demonstration for the maximum arcing time capabilities of an interrupter is obtained with a single phase test because in a single phase test the arcing time can be better controlled without having to be concerned about the interference from the other phases in the event that the interrupter fails to interrupt at the first current zero.

For single phase tests with symmetrical currents (refer to Figure 9.23), the maximum arcing time can be obtained by first adjusting the contact part to coincide with a current zero crossing (at time t_1); interruption will occur at either the first current zero (point **2**), for circuit breakers that have minimum arcing times of less than eight milliseconds, or at the second current zero (point **3**), for circuit breakers with arcing times greater than eight milliseconds.

For the next test, the point of contact part (t_2) is advanced by approximately 4.5 milliseconds; under these conditions interruption will take place at the first current zero (point **1**) for circuit breakers with minimum arcing times of less than 4 milliseconds (vacuum circuit breakers for example), at the second current zero (point **2**) for circuit breakers that have a minimum arcing time greater than 4 milliseconds but less than 12 milliseconds, or at the third current zero (point **3**) for circuit breakers that have minimum arcing times greater than 12 milliseconds. Applying the above described procedure will ensure that the interrupter has been subjected to the longest possible arcing time when interrupting symmetrical currents.

The maximum arcing time for a single phase symmetrical test should be as defined below:

$$\text{Arcing time} = \text{minimum arcing time} + 0.75 \times t_1$$

where:

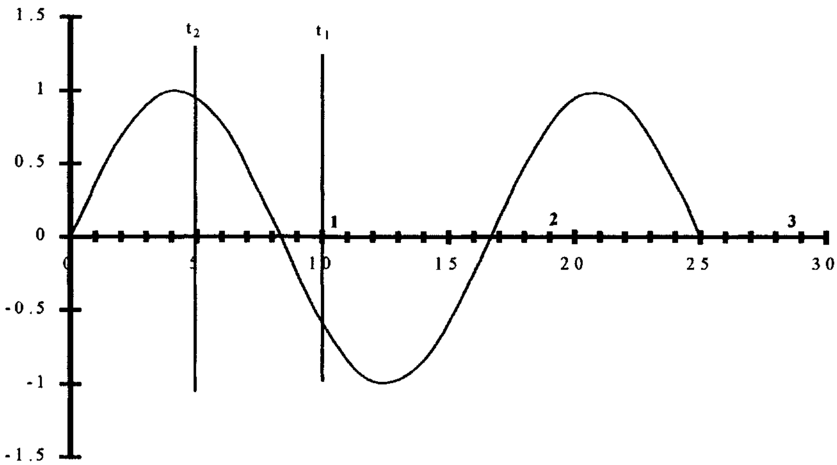

Figure 9.23 Graphical representation of a method for obtaining maximum arcing times during single phase symmetrical current tests.

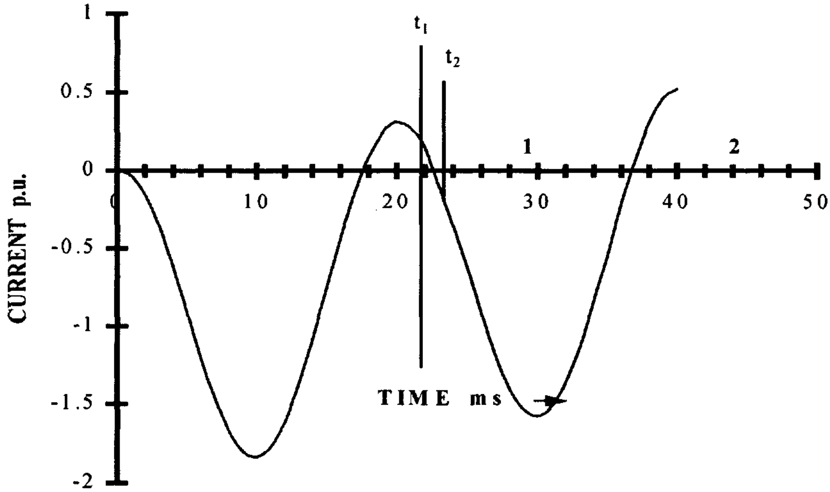

Figure 9.24 Graphical representation of a method for obtaining maximum arcing times during single phase asymmetrical current tests.

t_1 = Time for ½ cycle of rated power frequency

For an asymmetrical condition a similar procedure, see Figure 9.24, may be used as follows:

First, the region where the contacts must part to satisfy the total current requirements should be chosen; this time is then adjusted to coincide with the beginning of the minor loop shown as time t_1. If interruption occurs at the first current zero (point **1**) the time should be retarded by about 3 milliseconds, to time t_2; interruption then will most likely take place at current zero corresponding with point **2.** This last test will demonstrate the maximum arcing time conditions for circuit breakers that have minimum arcing times in the range of 4 to about 12 milliseconds. Since this is generally the range of minimum arcing time of modern circuit breakers the above test will be sufficient to verify the maximum energy input condition within reasonable limits of accuracy for most of today's vacuum and SF_6 high voltage circuit breakers.

In accordance with ANSI the maximum arcing time for a single phase asymmetrical test is defined by the expression written below:

Arcing time = minimum arcing time + length of major loop - 1 ms

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10

CIRCUIT BREAKER APPLICATIONS

10.0 INTRODUCTION

In an earlier chapter, a circuit breaker was defined as "a mechanical device, which is capable of making, carrying and breaking currents...". It was also learned that there are a number of different types of circuit breakers and a number of different system conditions where they may be applied and that, as a consequence, it is to be expected that unusual conditions, or situations that deviate from what is considered to be a standard or normal condition, can be encountered, and that in most instances these non-standard conditions will have a significant effect upon the application of a circuit breaker.

The primary aim of this chapter is to provide some simple and practical answers to questions relating to non-standard applications, so they can be used to facilitate the evaluation of a given circuit breaker for a given application. Naturally, there are so many unique conditions that it will not be possible to cover all of the foreseeable applications; but we will concentrate on those that are most frequently encountered.

Among the most fundamental and often asked questions about circuit breaker applications are those relating to:

1. Overload currents and temperature rise
2. High X/R systems and current generators protection
3. Systems with frequencies other than 50 or 60 Hz
4. Size of capacitor banks for capacitor switching operations
5. High TRV applications
6. High altitude installations
7. Low current, high inductive load current switching
8. Choice between SF_6 and vacuum

10.1 OVERLOAD CURRENTS AND TEMPERATURE RISE

The continuous current carrying rating of a circuit breaker is predicated on the premise that the ambient temperature and the elevation where the circuit breaker is applied is within the limits that have been set by the applicable standards. As ambient temperatures vary widely on a daily and on a seasonal basis, to provide a constant base of reference an ambient temperature of 40°C was selected as the upper limit.

This selection was based on the meteorological reports provided by the US Weather Bureau, which indicate that the ambient temperatures in the continental US very seldom exceed this upper limit. The maximum standard altitude as it will be recalled is 1000 meters (3300 feet) over sea level. This elevation is considered to be within the limits of the standard operating conditions because the majority of the applications worldwide do not exceed this limit.

The altitude limitations are related to the lower air density and therefore lesser convective cooling capability of the air at higher elevations. The ambient temperature, on the other hand, is directly related to the total temperature of the equipment, which is dictated by the limitations that are established based on the characteristics of the materials that are employed in the construction of the circuit breaker.

To evaluate the behavior of the circuit breaker under conditions which are deemed to be different than those considered as standard, be they larger currents, higher ambient or higher altitudes, the problems reduce to one of establishing the ultimate temperature rise required to dissipate by convection and radiation losses the watts generated at specific currents.

For electrical equipment that has only few ferrous material components the losses are essentially proportional to the square of the current. However, as the temperature increases, so does the resistance and if the losses were due to the conductors alone then the loss curve will rise slightly faster than the square function. But in most circuit breakers there is a significant amount of ferrous components and the losses due to eddy currents are approximately proportional to the 1.6 power of the current. Considering these two values to be the extreme limits and based primarily on practical experience an exponent value of 1.8 has been established as a suitable compromise.

When the circuit breaker has reached its ultimate temperature rise for a given steady state current it is clear that the total losses must be dissipated since the equipment is then no longer storing any of the generated heat. These losses are divided essentially into radiation and convection losses. The former varies approximately as the difference, raised to the fourth power, of the absolute temperatures, while the latter varies at a much lower power of the temperature. The above statements about the losses are given only as general reference and it is not implied nor is it necessary to calculate these dissipation factors before solving the problem at hand.

10.1.1 Effects of Solar Radiation

For outdoor applications, in addition to the heating produced by the load current and by the ambient air temperature, one must be aware of the possible additional heating that may result from the effects of solar radiation. On the basis of field tests and accumulated operating data it has been determined that in most cases a maximum temperature rise of approximately 15°C (27°F) may be expected on the conducting parts of the circuit breaker.

When the circuit breaker is operated at a monthly normal maximum ambient temperature above 25°C (77°F) derating of the continuous current capability of the circuit breaker may be necessary. The derating factor to be used [1] is given in Figure 10.1 as a function of the maximum monthly normal temperature as given by the US Weather Bureau.

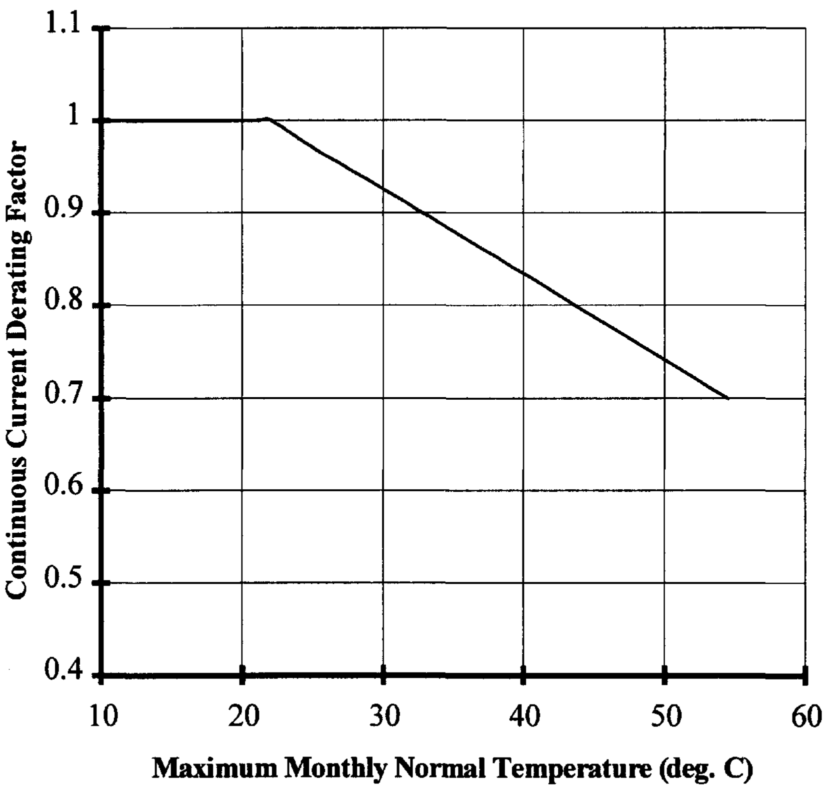

Figure 10.1 Altitude correction factors for continuous currents.

10.1.2 Continuous Overload Capability

There are times when it becomes necessary to operate a circuit breaker with load currents that are higher than those corresponding to the full rating of the circuit breaker. Operation under these conditions is possible provided that the ambient temperature is consistently below the maximum allowable 40°C.

To find the allowable current that can be carried at a given ambient temperature the following equation is given.

$$I_a = I_r \left(\frac{\theta_{\max.} - \theta_a}{\theta_r} \right)^{\frac{1}{1.8}}$$

where:

I_a = Allowable current
I_r = Rated continuous current
θ_{max} = Allowable hottest spot total temperature
θ_a = Actual ambient temperature
θ_r = Allowable hottest spot total temperature rise at rated continuous current

In order to assure that the maximum temperatures at any given point and for any given material are not exceeded when the load current is adjusted to compensate for the lower ambient temperatures the following rules should be observed [2].

1. "If the actual ambient temperature is less than 40°C, the component with the highest specified values of allowable temperature limitations should be used for determining $\theta_{\max.}$ and θ_r."
2. "If the actual ambient is greater than 40°C, the component with the lowest specified values of allowable temperature limitations should be used for determining $\theta_{\max.}$ and θ_r."

By using these values for the calculations it is assured that the temperatures of any parts of the circuit breaker would not be exceeded. However, in many cases it would be perfectly safe to exceed these limits without the risk of impairing the performance or the life of the circuit breaker. This is so because generally the minimum limits of temperature are at circuit breaker locations that are readily accessible to the operating personnel while the maximum temperatures are allowed at external locations that are not accessible to operating personnel. If these parts are excluded from consideration higher values of permissible currents will be obtained from the calculations. But these calculated values should be used judiciously and only when the particularities of the design are well known to insure that there is no possibility of damage to adjacent lower temperature materials.

As an example, let us consider a circuit breaker that has a continuous current rating of 1200 A. This circuit breaker is going to be applied at an ambient temperature of 25°C. The maximum allowable temperature rise is limited to 65°C by its bushings. It is desired to find what is the maximum current capability for this circuit breaker under the new given conditions.

When the new parameters are substituted into the given equation the following value for the maximum allowable current for this circuit breaker is obtained.

$$I_a = 1200\left(\frac{105-25}{65}\right)^{\frac{1}{1.8}}$$

I_a =1246 amperes

10.1.3 Short Time Overloads

The permissible time duration of overload currents, which are predicated upon a specific temperature ceiling, are intimately concerned with the thermal capacities of the components and hence with the rate of growth of temperature with time. Therefore, to determine what would be a safe overload, in terms of current or time, it is essential to have a good understanding of the interrelation that exists between the watts that are generated at specific currents, the ultimate temperature rise that is allowed, and the nature of the growth of the temperature with respect to time.

For simple structures, where circuit breakers may be considered to be one such structure, it is fairly accurate to assume that the temperature increases exponentially towards the ultimate temperature rise. This means that the growth of the temperature is progressing in such a way that it is continuously consuming a fixed proportion of the remaining temperature rise in equal intervals of time. The exponential temperature rise curve reaches 63% of its remaining rise in an interval of time equal to its time constant τ.

The time constant on critical circuit breaker parts generally falls between 30 to 90 minutes, and this value may be specified by the circuit breaker manufacturer, but if not, it would be safe to use a value of 30 minutes.

To calculate the time duration of a short time overload the following equations should be used.

$$t_s = \tau\left[-\ln\left(1-\frac{\theta_{\max}-Y-\theta_a}{Y\left[\left(\frac{I_s}{I_i}\right)^{1.8}-1\right]}\right)\right]$$

$$Y = \left(\theta_{max} - 40°C\right)\left(\frac{I_i}{I_r}\right)^{1.8}$$

where:

θ_{max} = Maximum allowable total temperature °C
θ_a = Actual ambient temperature °C
I_i = Initial current carried during the preceding 4 hours
I_s = Short time load current in amperes
I_r = Rated current in amperes
τ = Thermal time constant of the circuit breaker
t_s = Permissible time in hours for carrying overload current

The emergency load current capability for a circuit breaker is treated on the referenced application standard [2] by establishing emergency load current carrying capability factors. These factors are based on an ambient temperature of 40°C for two distinct overload allowable periods, a four-hour and an eight-hour period. For the numerical values of these factors refer to Figure 10.2.

According to the rules, it is permissible to operate 15°C above the limits of total temperature for the four-hour period and 10°C for the eight-hour period. The following guidelines are a direct quote from the referenced standard:

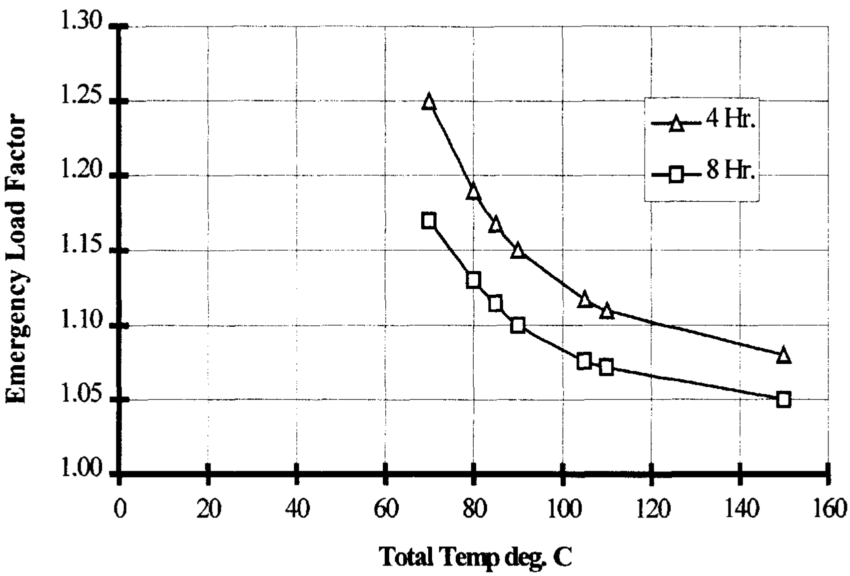

Figure 10.2 Overloading factors for four- and eight-hour intervals.

"Each cycle of operation is separate, and no time-current integration is permissible to increase the number of periods within a given cycle. However, any combination of separate four-hour and eight-hour emergency periods may be used, but when they total sixteen hours, the circuit breaker shall be inspected and maintained before being subjected to additional emergency cycles."

For ambient temperatures other than the 40°C maximum specified, the procedures that were previously outlined may be used.

10.1.3.1 Four-Hour Factor

This factor shall be used for a cycle of operation consisting of separate periods of no longer than four hours each, with no more than four such occurrences before maintenance.

10.1.3.2 Eight-Hour Factor

This factor shall be used for a cycle of operation consisting of separate periods of no longer than eight hours each, with no more than two such occurrences before maintenance.

10.1.4 Maximum Continuous Current at High Altitude Applications

Generally, applications at high elevations do not pose much of a problem because the interrupters that are used in today's circuit breakers are sealed devices and consequently the contact structure itself is not affected by the high altitude and the lower air densities. Those parts of the circuit breaker which are exposed to the outside atmosphere are not generally the most critical parts and more importantly as the altitude increases it is less likely that the ambient temperature would reach the 40°C upper limit. In the event that it is desired to calculate the maximum allowable current at high elevations the appropriate multiplying factor is plotted in Figure 10.3 as a function of the maximum monthly normal temperature as given by the US Weather Bureau. As it may be seen in the figure, even at 3,000 meters (10,000 ft) and at ambient temperatures of 35°C the circuit breaker is capable of carrying its full rated continuous current.

To determine the short time overload characteristics of a circuit breaker it is possible to calculate what the overload would be at sea level, and then multiply this value by the factor obtained from Figure 10.3 for the corresponding ambient temperature.

10.2 INTERRUPTION OF CURRENT FROM HIGH X/R CIRCUITS

The short circuit ratings assigned by the standards are based on an X/R value of 17 at 60 Hz or 14 at 50 Hz. This naturally constitutes only a compromise average value which is representative of the majority of the applications found in the industry. However, there are still a significant number of applications where the X/R of the system is greater than the values adopted by the standards. When this happens then these questions arise. What rating do I need in the circuit breaker? What is the circuit breaker I have good for?

To answer these questions, first it should be remembered that circuit breaker ratings are based on the symmetrical current magnitude and that these symmetrical current ratings are the values that should not be exceeded. However, it is also known that the current asymmetry is a function of a time constant, or X/R of the system, and therefore for a given constant contact opening time of a circuit breaker, the total rms current at the point of contact separation increases as a function of the increase of the asymmetry, which in turn is the result of the increase in the time constant of the circuit.

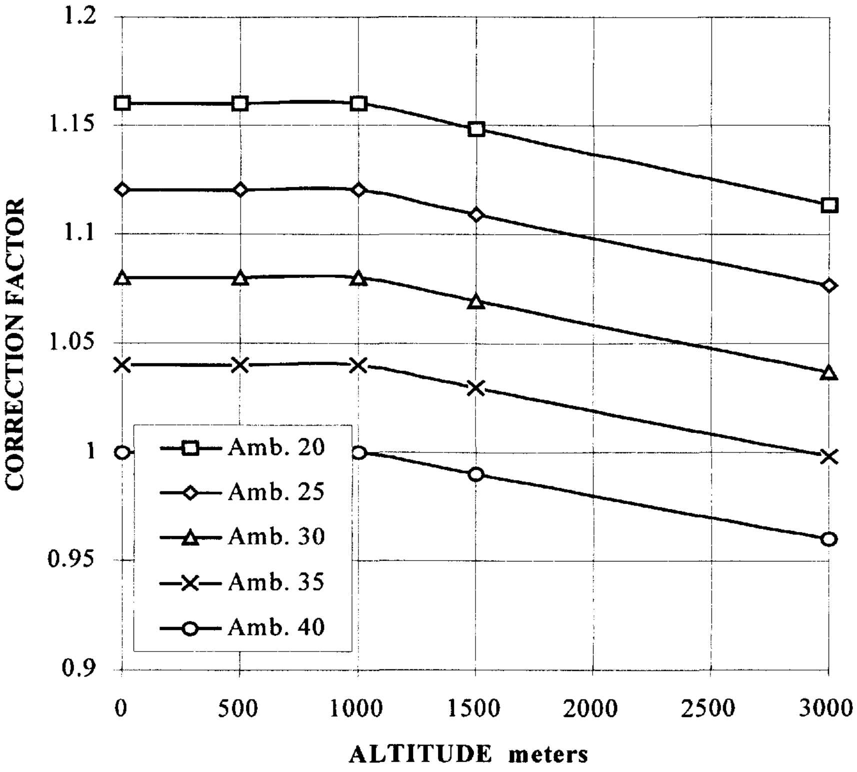

Figure 10.3 Altitude correction factor.

Whenever a fault occurs at a location that is physically close to a large power generator, there may be a significant ac exponential component of the asymmetric current which decays very rapidly during the first few cycles after the initiation of the fault.

However, this ac decay is generally considered not to be significant at locations that are distant from the power generator, where the short circuit current is fed through two or more transformations, or those applications where the reactance of the system is greater than 1.5 times the subtransient reactance of the generator.

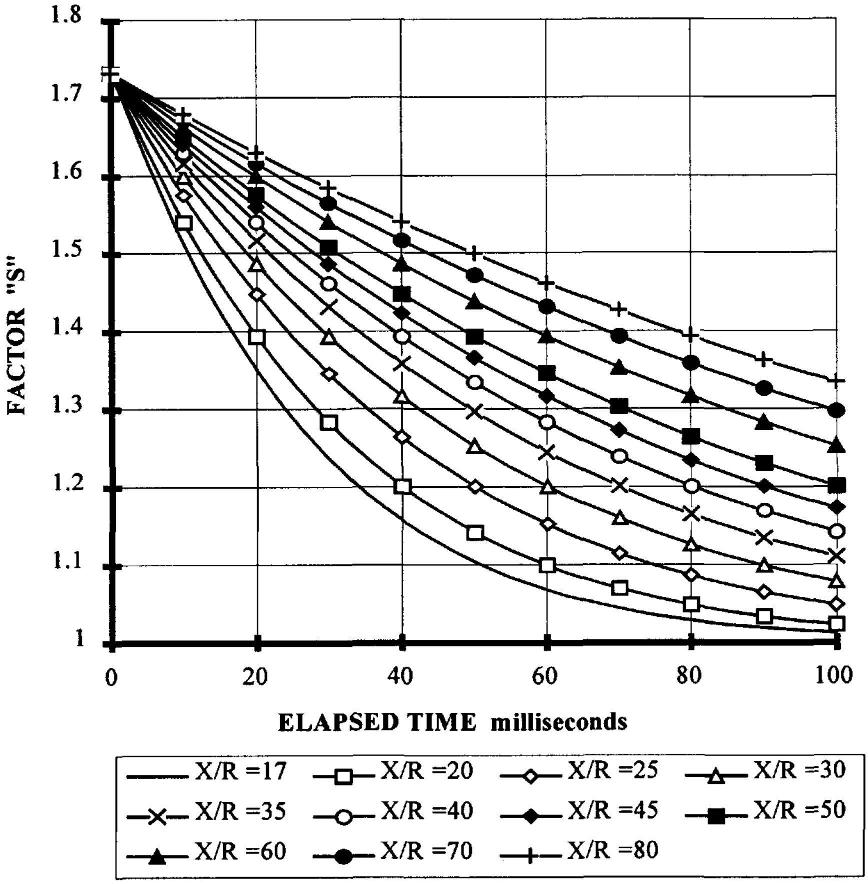

Figure 10.4 Factor "S" for asymmetrical current values with dc decrement only.

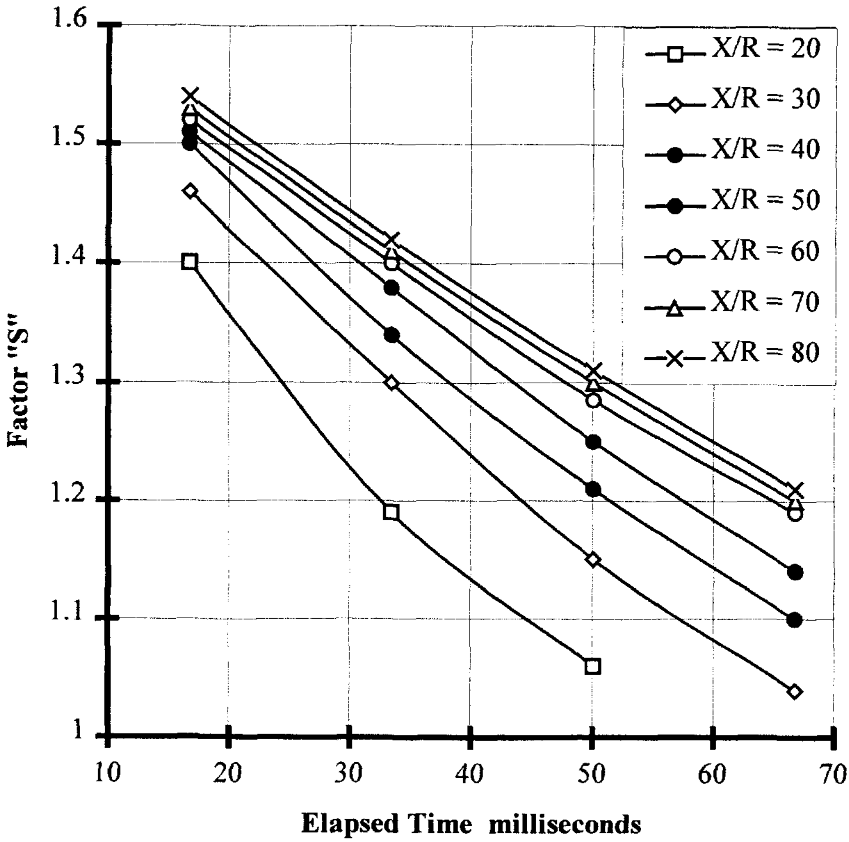

Figure 10.5 Asymmetrical factor "S" including ac decrement.

For high voltage circuit breaker applications, in practically all cases, it is possible to ignore the effects of the ac transient component and to consider only the dc component. Obviously, this introduces some error in the calculation, especially in the distribution class circuit breakers, where there are a few instances where closer attention should be paid to the effects of the ac transient component as it will be explained later when dealing with the application of distribution class circuit breaker as a generator circuit breaker. The expected errors, however, would be on the conservative side and the results would lead to specify a circuit breaker with a higher rating thus assuring a greater margin of safety. We must also recognize that the error is within what can be considered to be acceptable operating limits since a rigorous mathematical analysis of the complete circuit is not feasible and, moreover, where the data available for the values of the components very rarely would have an accuracy better than 10%.

Furthermore, there is something to be said about operating experience, which has shown that this is a relatively conservative and valid approach.

For the discussions that follow, and to answer the two questions posed earlier, a plot of the ratio of the total rms asymmetrical to the symmetrical rms current at contact separation is plotted for different X/R values as a function of the elapsed time, starting from the instant of the inception of the fault. The result is shown in Figure 10.4.

The ratio between the two currents is commonly called the asymmetry factor "S" and is used as a multiplier to establish the related values between the symmetrical and the asymmetrical currents or vice versa.

To determine a preliminary set of requirements for a given application, the first step on the process is to determine the magnitude of the short circuit current which can be calculated using either of the methods that were given in Chapter 2.

Once this is done the next step is to calculate the X/R value for the circuit. Having done this then using the factor S the approximated symmetrical interrupting rating for the circuit breaker in question can be determined.

If the X/R value is equal to or less than 17 then it is possible to simply choose a circuit breaker with a symmetrical current interrupting capability that is equal to or greater than the calculated short circuit current.

If the X/R factor of the circuit is greater than 17, then it is necessary to determine the elapsed time or contact parting time, which according to its definition is equal to a one-half cycle relay time plus the contact opening time of the circuit breaker. Once this value has been established, from Figure 10.4 the S factors may be determined for the calculated X/R and for the standard value of 17. Multiply the calculated short circuit current by the S factor that corresponds to the higher X/R to obtain the total rms value of the asymmetrical current. Next, divide this value by the factor S corresponding to the X/R of 17. This is the minimum interrupting current rating that is needed for this particular application.

For example, let us assume a 121 kV circuit capable of delivering a short circuit current of 14,000 amperes and having an X/R of 50. It is desired to select, from a table of preferred ratings, a 5-cycle circuit breaker with a contact parting time, or elapsed time of 50 milliseconds. From Figure 10.4 the S value for an X/R of 50 is 1.39 and for X/R of 17 is 1.1.

$$I_T = 14{,}000 \times 1.39 = 19{,}460 \text{ Amperes}$$
$$I_R = 19{,}460 \div 1.1 = 17{,}691 \text{ Amperes}$$

where:

I_T = Total rms current at X/R = 50
I_R = rms symmetrical current at X/R = 17

The results above indicate that a standard circuit breaker having as a minimum the next higher preferred interrupting rating which is 20 kA should be selected.

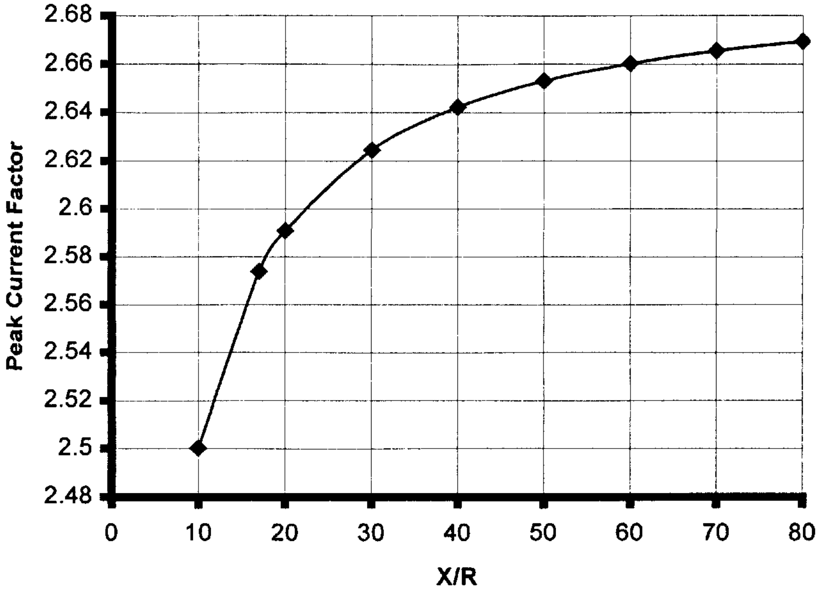

Figure 10.6 Peak current factor as a function of X/R.

Now, contemplate the case where, for example, a standard 20 kA, 3 cycle circuit breaker is available and it is desired to apply this breaker on a system that has an X/R value of 80. The maximum interrupting capability of this circuit breaker for this application can be determined by simply multiplying the rated symmetrical capability by the ratio of the standard circuit S factor to the S factor corresponding to the high X/R system. The elapsed time, or contact parting time, for this circuit breaker is 35 ms and the two S factors, from Figure 10.4, are 1.2 and 1.56 respectively. The S factor ratio is then equal to 0.77 and the product of this factor times the symmetrical current rating is 20 x .77 = 15.4 kA, which represents the new rated symmetrical current for the application on a system with an X/R of 80. If we were to assume that this circuit breaker was being installed in close proximity to a source of generation and if we were to consider the effects of the transient ac component, then the multiplying factor for the high X/R condition, as given in Figure 10.5, would be approximately 1.42 and the ratio between factors is 0.84. The interrupting capability now becomes 16.9 kA. Comparing the results we see that the difference is within the range of accuracy of the circuit components and that in any case the error is on the safe side.

The only consideration that has been given so far is to the interrupting capability of the circuit breaker. However, attention should also be given to the maximum current peak that can occur since this current peak is a function of the time constant, or X/R of the circuit, and care must be taken not to exceed the maximum current peak that has been assigned to the circuit breaker.

In Figure 10.6 the multiplying factor for the peak currents is plotted as a function of the system's X/R and for the example given above we find that the current peak multipliers are 2.6 and 2.775 and the peak currents are 20 x 2.6 = 52 kA and in the worst case 16.9 kA x 2.775 = 46.9 kA for the standard rating and for the higher X/R respectively.

To further illustrate the process the following example is presented. For this example a typical system such as the one shown in Figure 10.7 is assumed. The single line diagram shows an installation that is being fed from a 145 kV grid system.

There are five 15 kV identical substations connected to the feed. These substations are assumed to have a 100 MVA capacity and all the motors that are connected in each substation are assumed to be lumped into a single equivalent motor load of 10 MVA.

The MVA method will be used for solving the circuit. The equivalent block diagrams for the circuit are shown in (a) and (b) of Figure 10.8, block 1 represents the grid, block 2 is the transformer T1, blocks 3 though 7 represent the substation transformers 2 through 7, and finally block 8 is the equivalent load contribution from the motors.

Combining the MVA's the following results are obtained:

Grid and T1 contribution

$$\text{MVA-1, 2} = \frac{\text{MVA1} \times \text{MVA2}}{\text{MVA1} + \text{MVA2}} = \frac{5000 \times 100}{5000 + 100} = 98\ \text{MVA}$$

Distribution Transformers 2 to 7 contribution

$$\begin{aligned}\text{MVA T2 to T7} &= \text{MVA1+MVA2+MVA3+MVA4+MVA5} \\ &= 5\text{x}20 = 100\ \text{MVA}\end{aligned}$$

And finally the summation of all the contributions

$$\Sigma\,\text{MVA} = 98 + 100 + 10 = 208$$

The total fault current available is then

$$I_{fault} = \frac{208\text{MVA}}{\sqrt{3} \times 5\text{kV}} = 24\ \text{kA}$$

The equivalent impedances and X/R factors are then calculated with the following results:

For the system grid

$$Z_g = \frac{145^2}{5000} = 4.205\ \Omega$$

$$Z_g = 0.247 + j\,4.205$$

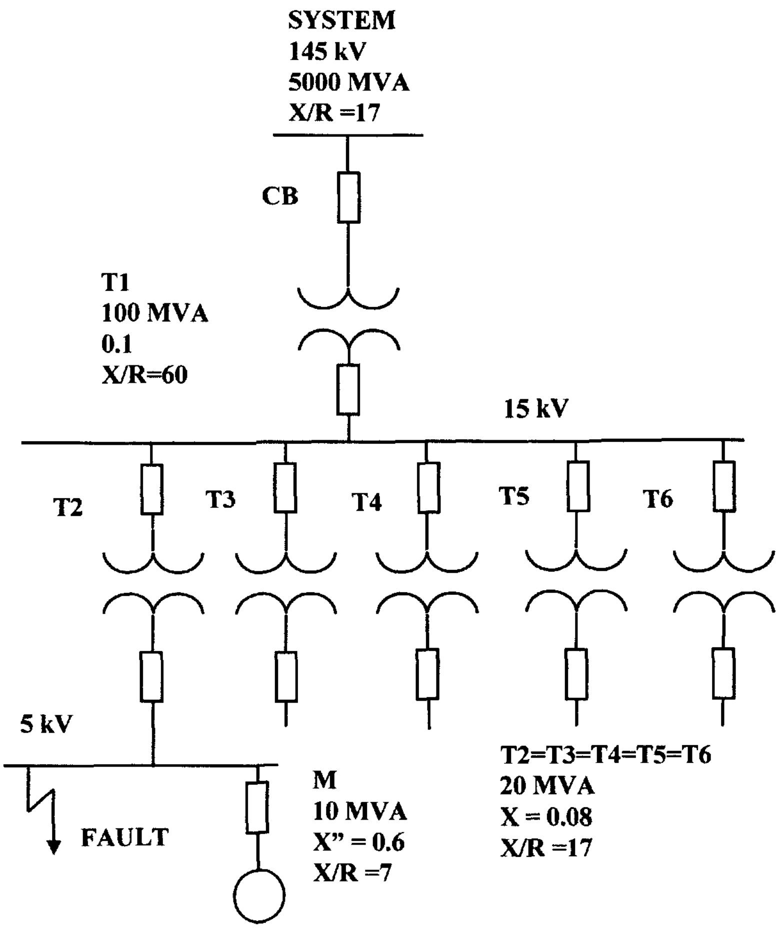

Figure 10.7 Single line schematic of system used for higher X/R example.

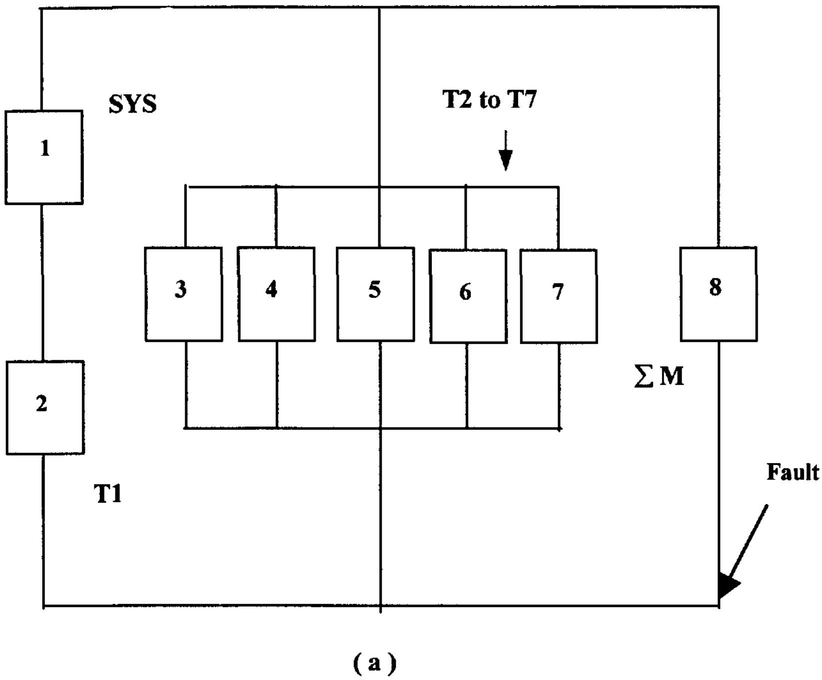

Figure 10.8 MVA block representation for solution of Figure 10.7 circuit.

Transposing to the 15 kV bus

$$Z_g\ (@15\ \text{kV}) = 0.00264 + j\ 0.045$$

Transformer T1 impedance

$$Z_{T1} = 0.1 \times \frac{15^2}{100} = 0.225\ \Omega$$

$$Z_{T1} = 0.00375 + j\ 0.225$$

The branch impedance becomes

$$Z_{Total} = 0.00639 + j\ 0.270$$

which yields an X/R factor equal to 42.2.

The reactances for the substation transformers and the motors are

$$Z_{T2\text{-}T7} = 0.08 \times \frac{5^2}{20} = 0.1\ \Omega$$

$$Z_M = 0.0848 + j\ 0.594$$

and the combined values are

$$Z_{T\text{-}M} = 0.0907 + j\ 0.694$$

This gives an X/R ratio of 7.6.

The final X/R ratio at the point of the fault is then 34.6.

The estimated value for the fault current was 24 kA. A 25 kA circuit breaker is shown in the preferred ratings list. But since this fault level is required at an X/R of approximately 35 then we must pick a suitable alternate. Assuming that the required circuit breaker is a 3 cycle rated circuit breaker then, from Figure 10.4 the S factor is selected at an elapsed time of 35 ms for an X/R = 17; the S factor is equal to 1.2 while for an X/R of 35 at the same time the value is 1.42. We can proceed as it was shown in an earlier example.

$$I_T = 24{,}000 \times 1.42 = 34{,}080\ \text{Amperes}$$
$$I_R = 34{,}080 \div 1.20 = 28{,}400\ \text{Amperes}$$

This suggests that a listed circuit breaker having a preferred interrupting rating of 31.5 kA should be selected. The required closing peak current capability for this application is determined using the factor that is given in Figure 10.6 and is equal to 63 kA. If the 31.5 kA circuit breaker is selected its closing peak current capability (82 kA) obviously exceeds the requirements for the application.

A second alternative would be to delay the opening of the 3-cycle circuit breaker so it effectively becomes a 5-cycle circuit breaker. Under these conditions the S factor becomes 1.2 and consequently the original circuit breaker that had an interrupting rating of 25 kA and a peak closing rating of 65 kA may be applied.

10.3 GENERATOR CIRCUIT BREAKER APPLICATIONS

Although from a qualitative point of view the rules for the application for a generator circuit breaker, whether at a power station or at an industrial installation, are the same, for the discussion that follows a distinction is made between circuit breakers connected to large generators (≥80 MVA and 15 to 38 kV) or to smaller industrial type units (5 to 50 MVA at 15 kV).

The difference between these two situations is that specially designed circuit breakers are available for those applications that involve the protection of large power plant generators. These circuit breakers have continuous current carrying ratings in the tens of thousands of amperes and their short circuit interrupting current capabilities are generally greater than 100 kA.

For the direct protection of generators used in industrial applications and mainly for economic reasons there is not much choice but to use a general-purpose type circuit breaker. Generally the maximum continuous carrying current of these circuit breakers is limited to 3000 A and the maximum available interrupting rating is limited to 63 kA at 15 kV and 40 kA at 25 kV and 38 kV.

In any event further consideration must be given to the X/R values, which for these types of applications are greatly increased. In many instances values of X/R as high as 80 are encountered. In addition to the high X/R ratios the possible delay of current zero crossings must be taken into account to avert a circuit breaker failure.

10.3.1 Short Circuit Current Ratings

In a typical application a generator circuit breaker must meet two different interrupting current requirements that depend upon the location of the fault and the contributions of the total installation to this fault. In Figure 10.9 a typical single line diagram of an installation and two possible fault locations are shown. Referring to this figure, the two possible locations and the sources for the fault current are:

1. At location **A** the fault is fed by the system.
2. At location **B** the fault is fed by the generator.

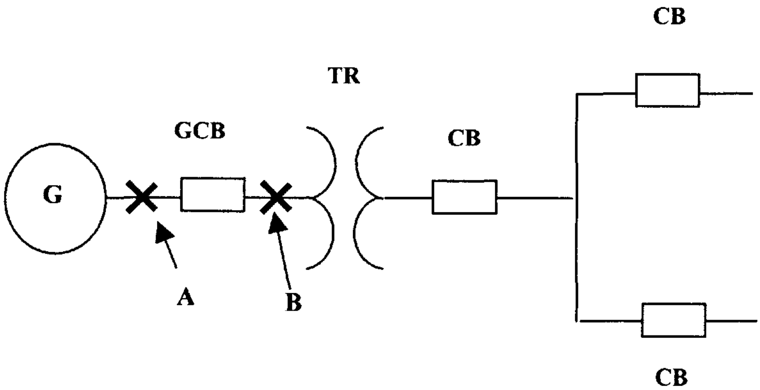

Figure 10.9 Typical generating station diagram.

It is important to realize that in all applications the magnitude of the system fed short circuit current is greater than that of the generator fed faults. This is due to the lower reactance of the transformer and the system in comparison to the sub-transient and transient reactances of the generator. Additionally the X/R ratio for the system fed fault will always be less than the X/R of the generator fed fault.

10.3.1.1 Fault Current Fed by the System

Considering that a fault that has the system as a source always delivers the highest magnitude of fault current then it is this maximum current magnitude that becomes the determining factor for the selection of the interrupting rating of a generator circuit breaker.

When selecting a circuit breaker specifically designed as a generator circuit breaker, that is one that meets the requirements of IEEE standard C37.013, then the choice is rather straightforward and the task is one of matching the circuit breaker ratings to the requirements of the application. However, in those instances when it is desired to select a standard circuit breaker for an application where a generator is to be protected attention must be given to the time constant of the circuit and to the level of asymmetry that can be expected.

For these applications, it must be remembered that the interrupting rating of the circuit breaker being considered is related to a system that has an X/R value of 17. To determine the suitability of a circuit breaker for this application the same methodology that was outlined in the previous section that described the application at high X/R ratios can be applied. However this cannot be the only criteria to be used and as it will be presented later the effects of the generator fed current may be the determining parameter for the circuit breaker selection.

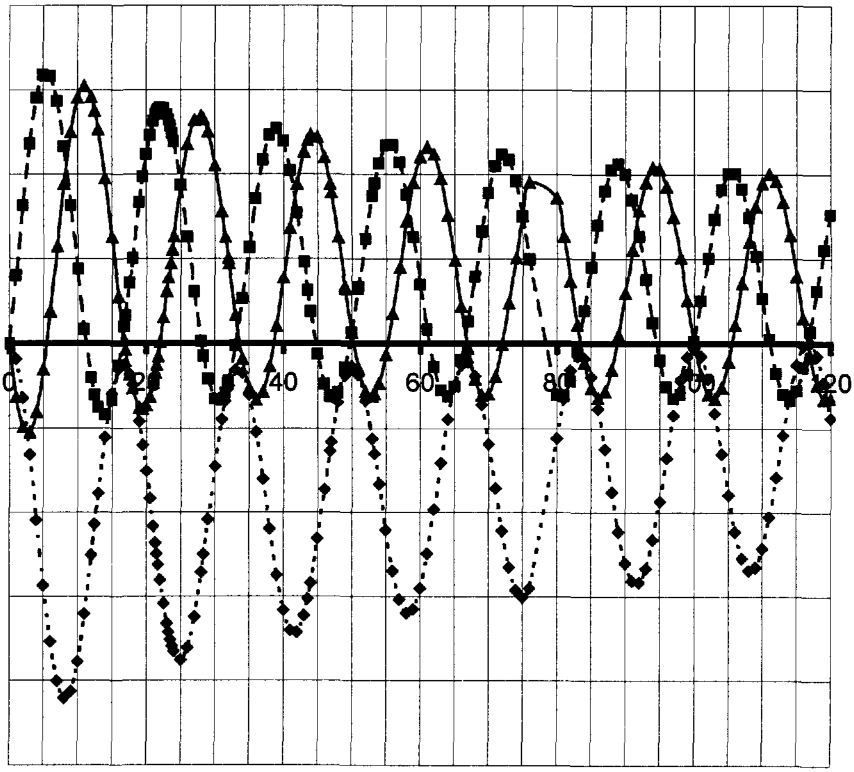

Figure 10.10 Three phase asymmetrical generator fault.

10.3.1.2 Fault Current Fed by the Generator

The following general principles are applicable to faults where the source of the current is the generator: (a) the symmetrical fault current available from a generator source is significantly lower than the current supplied by the system. (b) In the event of a fault close to the generator the effects of the ac component of the short circuit current must be taken into account. (c) The decay of the ac component is a function of the subtransient and the transient time constants of the generator. (d) The dc component at the time of contact parting can be higher than the peak value of the ac component. (e) As a result there is the possibility that under certain circumstances the short circuit current may not cross the zero axis for an extended period of time.

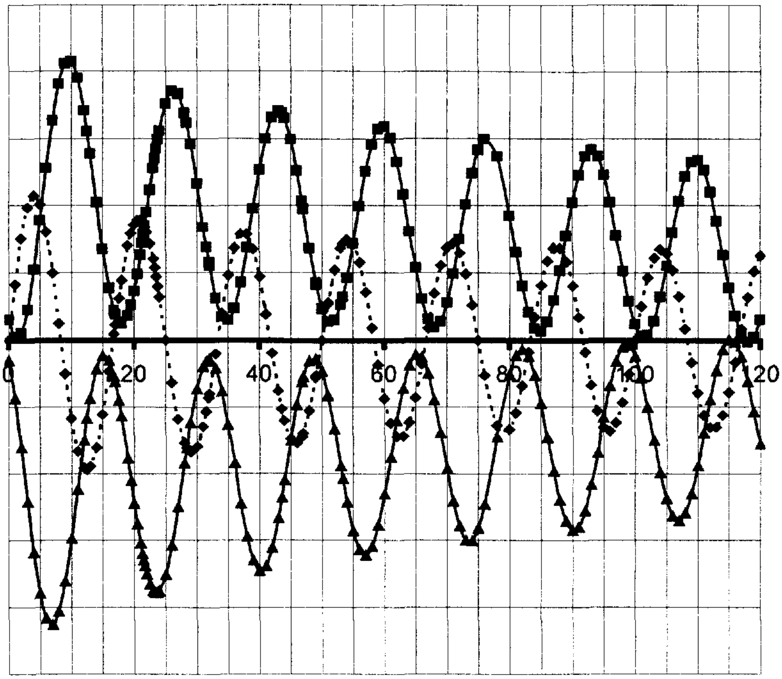

Figure 10.11 Generator fault with asymmetry in two phases.

The absence of a current zero arises from the fact that in any distribution system if a short circuit occurs near the generator, especially when the generator is unloaded, then both the ac and the dc components of the fault current will decrease concurrently and thus if the difference between the transient reactances and the X/R ratio is high then the possibility of missed current zeroes exists.

If there is a ≥100% asymmetrical current in one phase it is likely that there will not be a current zero crossing in that phase for several cycles. However in an ungrounded system there will be a current zero in each of the other two phases, as shown in Figure 10.10. When the current is interrupted in any of these phases the current in the phase with the delayed current zero is also automatically interrupted during the time interval where the fault current evolves into a single phase current.

A more critical condition occurs when one phase is symmetrical then, as it should be recalled, the other two phases must be asymmetrical; this condition is illustrated in Figure 10.11. Under these conditions the phase with the symmetrical current will be interrupted but then the evolution of the fault in the other two phases may result in a phase to phase current which does not have a zero crossing for an extended period, as illustrated in Figure 10.12.

Generator circuit breakers are specifically designed to overcome this condition. They accomplish the task by generating a sufficiently high arc voltage.

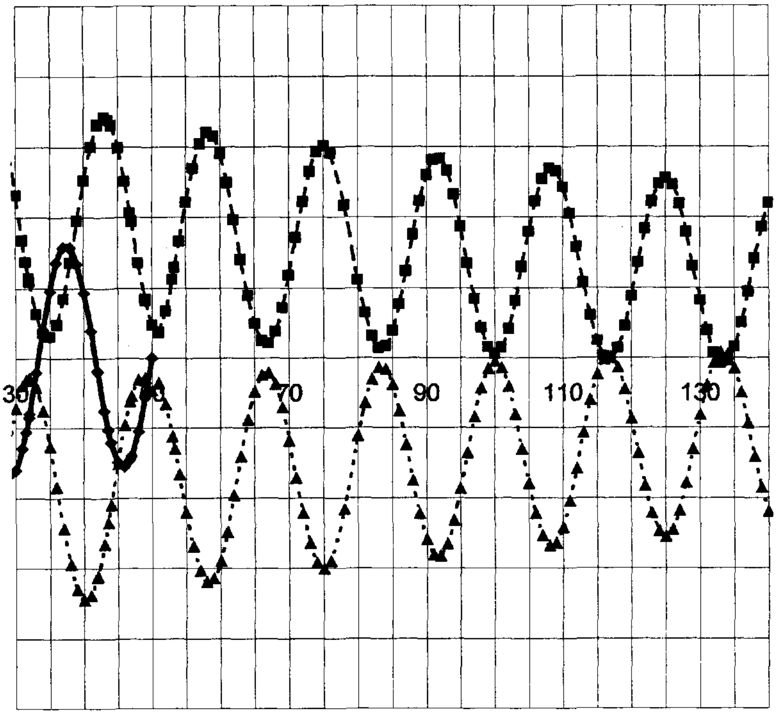

Figure 10.12 Currents after interruption of symmetrical faulted phase.

The additional resistance produced by the arc voltage then serves to reduce the time constant of the fault current thus reducing the time delay until a zero crossing is effected. However, when this same condition arises and a non-generator vacuum circuit breaker is being considered, because of its characteristic low arc voltage it is unable to force a current zero. Consequently the total arcing energy input to the interrupter is increased and simply choosing a circuit breaker with a higher interrupting rating to compensate for the extended arcing time is not enough. What is required is to increase the contact parting time of the circuit breaker so that a current zero occurs within the typical normal maximum to minimum range of arcing times of the particular circuit breaker. Increasing the contact parting time can be easily accomplished by adding a time delay to the trip circuit. However, it is recommended that the time delay be added as an integral part of the circuit breaker trip circuit and not just by adding an external time delay relay. This should be done to avoid the possibility of accidentally deleting the timer or altering the length of the delay.

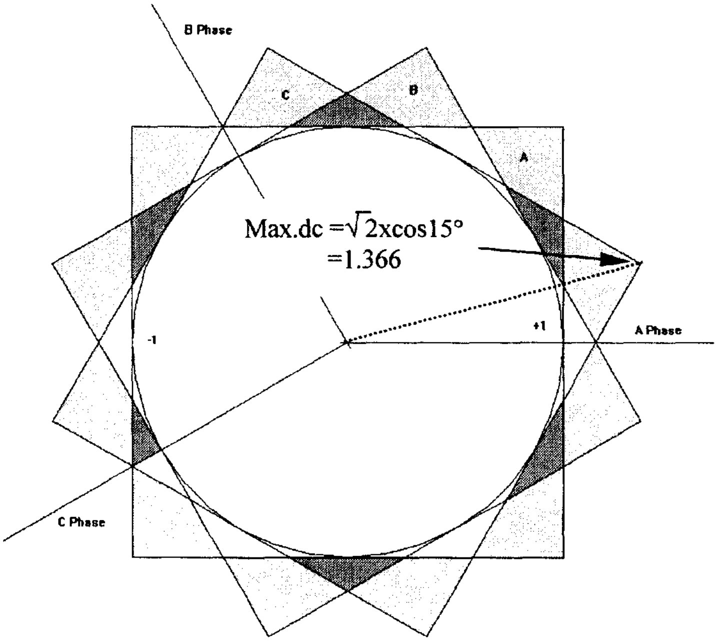

Figure 10.13 Range of dc components.

In applications where the generator is rated less than 10 MVA it should only be necessary to consider this as a case of a high X/R ratio and then the recommendations of the previous section are applicable. For generators rated at 10 MVA or more it is necessary to add a time delay, in most cases the required time delay should be between 60 to 90 milliseconds depending upon the characteristics of the generator.

10.3.1.3 Fault Evolution

In general terms a fault evolution refers to the condition where the fault may be initiated as either a single phase to ground, a phase to phase or a three phase fault and in time the fault is changed by involving a different number of phases from those that were involved originally.

The consideration of the fault evolution phenomena is important because in most cases this condition leads to an absence of current zeroes for prolonged lengths of time.

A convenient tool for determining the possible non-zero crossing is a diagram developed by F. Bachofen [4]. This diagram is based on the representation of a set of dc components as a point (P) located on a set of orthogonal coordinates.

The dc component of one of the phases is located on the abscissa and the dc component of one of the other phases represents the ordinate axis. By using a system of three axes displaced 120 electrical degrees the three-phase condition of symmetry is met. The method allows representing the dc components of a three-phase fault by a circle with a radius of 1. The evolved phase to phase dc components then are contained inside a square within the boundaries of +1 to −1.

From the diagram which is shown in Figure 10.13 the following general observations can be derived.

(a) The dc components in a three-phase fault maintain their relative proportions while decaying exponentially. Therefore the point P moves radially towards the center of the circle.

(b) A dc component larger than 1 suggests the likelihood of an absence of a current zero.

(c) In a three phase fault a dc component larger than unity may exist only in one phase.

(d) The shaded area in Figure 10.13 represent zones where the dc component can reach values greater than 1 when the fault evolves from a three phase to a two-phase fault.

(e) It shows that both the initiation of the original phase to phase or the fault evolution have to occur at or near a voltage zero.

(f) The maximum dc component as shown in the figure is equal to 1.366.

10.3.2 Generator Asymmetrical Short Circuit Current Calculation

The highest value of the asymmetric current produced by a generator occurs whenever the generator is operating in an underexited mode and with a leading power factor. In most cases under this operating condition the dc component will be greater than the symmetrical component of the fault current and therefore the resulting current will be one that is fully displaced from the zero axis. As we already know the decay of the ac component is dependent upon the subtransient and transient time constants, T_d”, T_d’, T_q”, T_q’ of the direct axis (d) and the quadrature axis (q) of the generator. The magnitude of the current is a function of the direct axis and the quadrature axis subtransient and transient reactances X_d”, X_d’, X_q”, X_q’. But, since for most generators, X_d” is approximately equal to X_q” the following equation which is based only on the direct axis subtransient reactance and the synchronous reactance X_d can be used to calculate the time dependent short circuit current.

$$I_{gc}=\frac{\sqrt{2}P}{\sqrt{3}E}\left[\left(\left(\frac{1}{X_d{}''}-\frac{1}{X_d{}'}\right)\varepsilon^{\gamma}+\left(\frac{1}{X_d{}'}-\frac{1}{X_d}\right)\varepsilon^{\beta}+\frac{1}{X_d}\right)\cos\omega t-\frac{1}{X_d{}''}\varepsilon^{\alpha}\right]$$

where:

$$\gamma = \frac{-t}{T_d''}$$

$$\beta = \frac{-t}{T_d'}$$

I_{gc} = Generator short circuit current
P = Rated power of generator
E = Rated maximum voltage of generator
X_d'' = Direct axis subtransient reactance
X_d' = Direct axis transient reactance
X_d = Synchronous reactance
t = Time in ms
T_d'' = Direct axis subtransient time constant
T_d' = Direct axis transient time constant
T_a = Armature short circuit time constant

When the arc resistance is included in the calculations the armature time constant changes and the new value is calculated using the following relationships.

$$R_a = \frac{X_d''}{2\pi f T_a}$$

$$T_a = \frac{X_d''}{2\pi f (R_a + R_{arc})}$$

The additional resistance represents the summation of the resistance of the path between the connection of the generator to the point of the fault plus the actual resistance of the arc across the contacts of the circuit breaker.

10.3.3 Transient Recovery Voltage

The general principles for TRV that were discussed in Chapter 3 are still valid for this type of application. The TRV seen by the circuit breaker is equal to the sum of two frequencies, one is the generator source frequency, and the other the system frequency. The system frequency is mainly controlled by the impedance characteristics of the transformer. The natural frequency of the transformer is significantly higher than the frequency of the HV system and its rate is at its maximum when the short circuit current is also a maximum. As it can be recalled this is contrary to what takes place in other applications where the TRV rate increases as the short circuit current decreases.

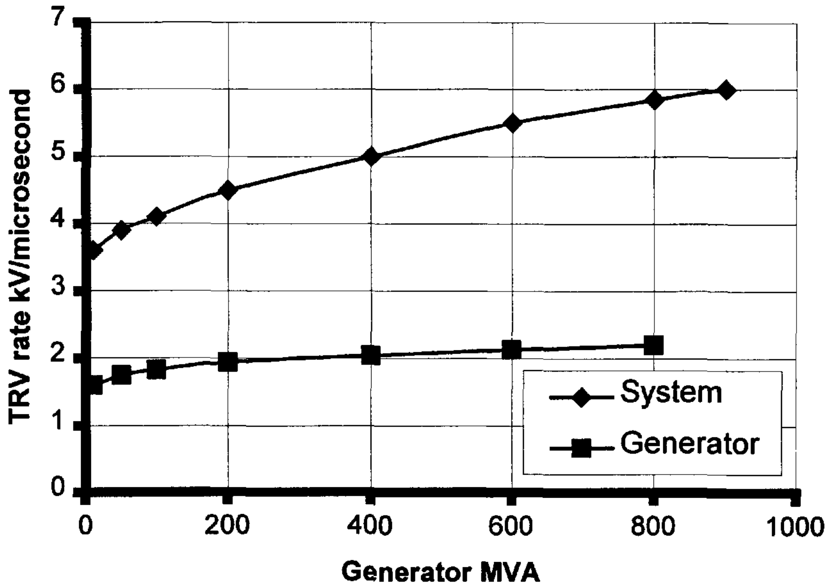

Figure 10.14 Typical TRV rates for generator circuit breakers.

As a result of the high frequency and the rate effect it is possible that superimposed upon the expected 1 - cosine waveform there may be a fast initial transient with rates as high as 3 to 6 kV per microsecond. Typical expected rates are shown in Figure 10.14.

If calculations show that the inherent rates of TRV are higher than those assigned to the circuit breaker then modifications must be made to reduce the TRV. Connecting either a low ohmic resistor or a few nanofarads capacitor across the interrupting contacts can reduce the TRV. A large reduction in TRV can also be obtained by installing capacitors on the low side of the step-up transformer. For example a reduction from 6 kV per microsecond to about 4 kV per microsecond is achieved with the addition of a 0.1 to 0.2 microfarad capacitor.

10.4 APPLICATION FREQUENCIES OTHER THAN 50 OR 60 HERTZ

In general the question of how a circuit breaker will behave when applied at a higher or a lower power frequency than that for which it was designed is posed mostly in applications involving medium voltage and up to 145 kV equipment. The most common lower frequencies that may be considered are those which are associated with transit applications. The two most popular frequencies are twenty-five (25) Hz and sixteen and two-thirds (16 and 2/3) Hz.

High frequency applications are rare and usually they are associated with very specialized applications mostly in pulsing or capacitor discharge circuits and generally only in the medium voltage class.

Vacuum interrupters have demonstrated that it does not make any difference whether they are used on 50 or 60 Hz. At lower frequencies, primarily because of a lack of applicable data, it is customary to reduce the interrupting capability of the interrupter as a function of $I^2 t$.

The derating function is expressed as:

$$I_2 = I_1 \sqrt{\frac{f_2}{f_1}}$$

where:

I_1 = Original symmetrical interrupting rating of circuit breaker
I_2 = Derated capability
f_1 = Normal rated frequency (50 Hz)
f_2 = Desired low frequency

For example for an application at 25 Hz the short circuit current should be limited to 0.707 of the rated current at 50 or 60 Hz.

For applications of vacuum circuit breakers at frequencies higher than 60 Hz, experience has shown that the interrupter is not sensitive to the rate of change of current (di/dt). However, this does not mean that because of the shorter periods higher currents are allowable. The maximum short circuit current is still limited by the peak value of the current, which is that of the original rating at 50 or 60 Hz.

For SF_6 circuit breakers the situation is different, as it was described in Chapter 5 the interrupters, in most cases, are sensitive to the rate of change of current. This would imply that at lower frequencies higher currents can be interrupted. However, in the case of a puffer circuit breaker, even when the interrupter can successfully handle the extra input energy caused by the longer periods, it is unlikely that the speed and travel requirements can be properly accommodated by conventional designs. Therefore it is generally advisable that unless the manufacturer specifically sanctions it, applications at low frequencies should be avoided. The same could be said for high frequency applications, first because of the derating required which is a function of the di/dt at the high frequency current and secondly because the TRV would also increase as a function of the system frequency and by now we are cognizant of the high sensitivity of SF_6 interrupters to TRV values.

10.5 CAPACITANCE SWITCHING APPLICATIONS

Capacitance switching applications involve not only interrupting capacitive currents, a subject which has been dealt with in previous chapters, but also the energizing of overhead lines, cables and capacitor banks.

When relating to capacitor banks or cables, the physical connection of the capacitor banks or cable systems will determine whether they are considered to be either isolated or back-to-back connected.

The definition given [3] for an isolated capacitor bank, or cable, is: "Cables and shunt capacitors shall be considered isolated if the maximum rate of change, with respect to time, of the transient inrush current does not exceed the maximum rate of change of the symmetrical interrupting current capability of the circuit breaker at the applied voltage."

This definition can be represented mathematically by the following expression.

$$\left(\frac{di}{dt}\right)_{\max} = \sqrt{2}\,\omega I\left[\frac{V_{\max.(rated)}}{V_{applied}}\right]$$

where:

$$\left(\frac{di}{dt}\right)_{\max} = \text{Rate of change of inrush current}$$

$\omega = 2\pi f$ or 377 for 60 Hz.
f = Power frequency
$V_{\text{max. (rated)}}$ = Rated maximum voltage
V_{applied} = Maximum applied voltage
I = Rated short circuit current

The following is the definition that is given [3] for back-to-back capacitor banks or cable circuits: "Cable circuits and shunt capacitor banks shall be considered to be switched back-to-back if the highest rate of change of inrush current on closing exceeds that specified as the maximum for which the cable or shunt capacitor bank can be considered isolated."

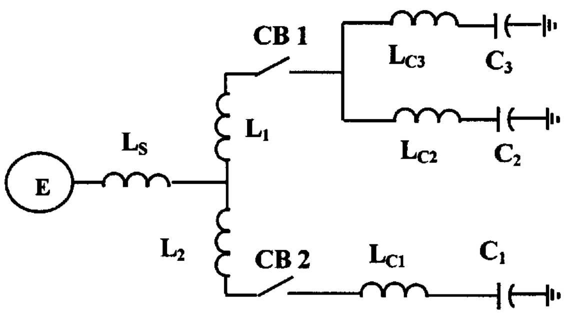

Figure 10.15 Single line diagram of a typical installation showing capacitor banks connected in a back-to-back fashion.

In simpler terms, an isolated cable circuit or capacitor bank means that only one cable, or one bank, is on one bus, while a back-to-back configuration means that more than one cable, or capacitor bank, is connected to the same bus. A typical system illustrating a back-to-back connection of capacitor banks is shown in Figure 10.15.

10.5.1 Open Line

Energizing or de-energizing an open line must be considered as one of the normal duties of a circuit breaker. The application of a circuit breaker therefore must take into consideration its line charging switching current rating. This rating must be greater than the estimated value for the open line charging current of the system where the circuit breaker is to be located. The approximate magnitude of the line charging current is shown in Figure 10.16, which is based on the values estimated with the aid of the following formula.

$$i_c = \frac{V_s \tanh\left(\sqrt{\frac{-X_l}{X_c}}\right)}{\sqrt{X_l \times X_c}} \approx \frac{V_s}{X_c}\left[1 + \frac{X_l}{3X_c}\right]$$

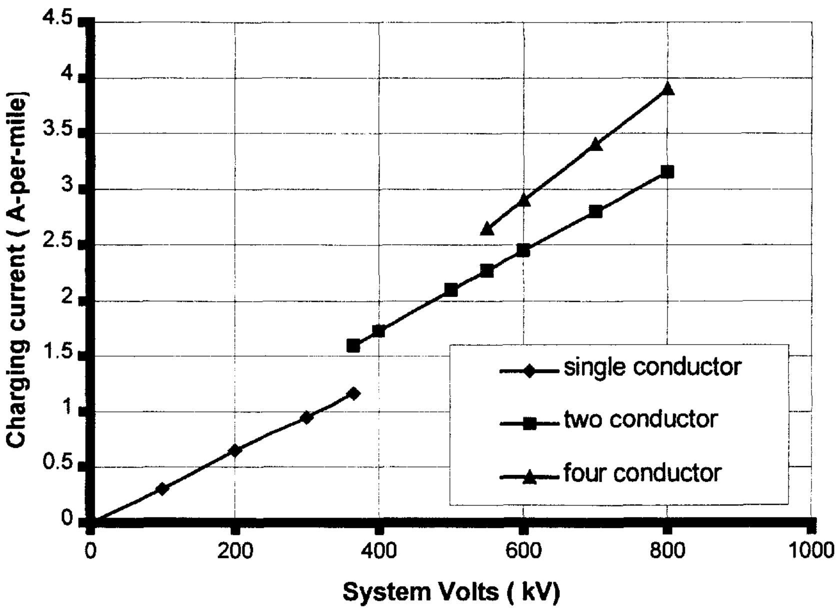

Figure 10.16 Cable charging current from Ref. 5.

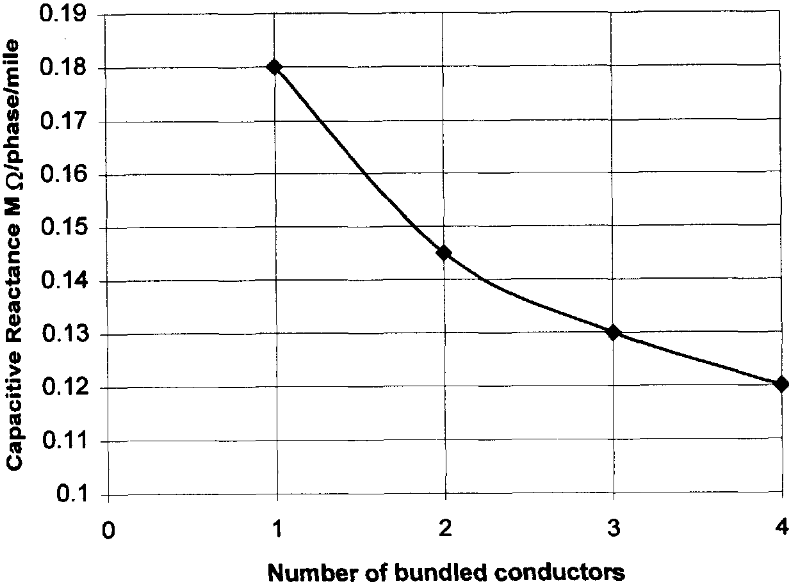

Figure 10.17 Capacitance values for bundled conductors.

$$i_c = \frac{V_s \tanh\left(\sqrt{\frac{-X_l}{X_c}}\right)}{\sqrt{X_l \times X_c}} \approx \frac{V_s}{X_c}\left[1+\frac{X_l}{3X_c}\right]$$

where:

V_s = Sending end line-to-ground voltage
X_l = Line positive-sequence inductive reactance in ohms per phase
X_c = Line positive-sequence capacitive reactance in ohms per phase, see approximate values shown in Figure 10.16

10.5.1.1 Compensated Open Line

Generally whenever the length of the line is longer than approximately 100 miles it is customary to provide some kind of line compensation to reduce the amount of charging current that is required to flow. This compensation is provided by means of adding shunt reactors to the line and the amount of compensation is expressed by the compensation factor "F_c" which is defined as:

$$F_c = \frac{X_c}{X_R}$$

The compensated line current then is equal to:

$$I_{Lc} = I_{Lu} \times (1 - F_c)$$

where:

I_{Lc} = Compensated line charging current
I_{Lu} = Uncompensated line charging current
F_c = Compensation factor
X_R = Inductive reactance of compensating reactor

An added advantage of adding compensation is that the line side component of the recovery voltage is no longer a trapped charge but instead is an oscillating voltage with a frequency of oscillation that is defined by the compensating reactors and the capacitance of the line.

10.5.2 Isolated Cable

Energizing a cable by closing the contacts of a circuit breaker will result in the flow of a transient inrush current. The magnitude and the rate of change of this inrush current is, among other factors, principally a function of the applied voltage, the cable geometry, the cable surge impedance and the length of cable (see Figure 10.17).

Since it is given that the circuit breaker must be able to withstand the momentary short circuit requirements of the system the transient inrush current to an isolated cable is never a limiting factor in the application of a circuit breaker.

10.5.3 Back-to-Back Cables

When switching back-to-back cables high magnitude transient inrush currents that are accompanied by a high initial rate of change may flow between the cables being switched. The typical configuration for this condition is shown in the diagram of Figure 10.18 (a), while in (b) the equivalent electric circuit is illustrated.

The transient inrush current is limited by the surge impedance of the cables and any inductance that may be connected between the energized cable and the cable being switched.

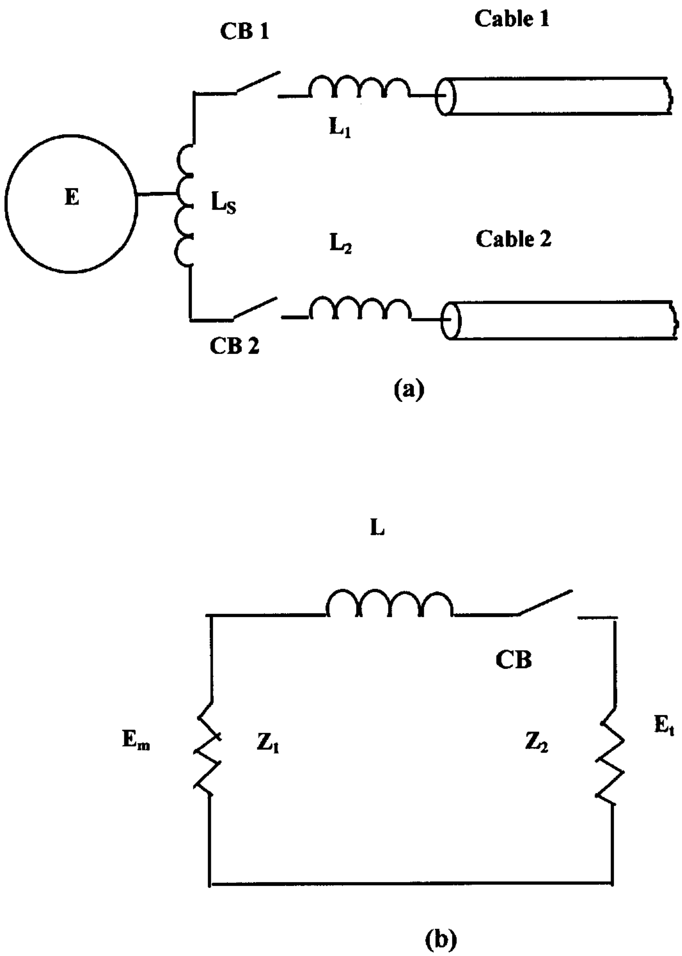

Figure 10.18 Back-to-back cable connected cables: **(a)** circuit single line diagram, **(b)** equivalent circuit for calculation of current.

When dealing with long lengths of lines, the initial pulse of the inrush current can be defined by the following relationship.

$$i(t) = \frac{E_m - E_t}{Z_1 + Z_2}\left[1 - \exp\left(-\frac{Z_1 + Z_2}{L}t\right)\right]$$

Table 10.1
Typical Inductance Values

Rated Maximum Voltage (kV)	Inductance per Phase of bus (μH/ft)	Typical Inductance between banks (μH)
15.5 & above	0.214	10 - 20
38	0.238	15 - 30
48.3	0.256	20 - 40
72.5	0.256	25 - 50
121	0.261	35 - 70
145	0.261	40 - 80
169	0.268	60 - 120
242	0.285	85 - 170

where:

E_m = Peak of applied voltage
E_t = Trapped voltage on cable being switched
Z_1, Z_2 = Cable surge impedance
L = Total circuit inductance between cable terminals
$I_{(t)}$ = Inrush current

10.5.4 Isolated Shunt Capacitor Bank

The magnitude and the frequency of the inrush current resulting from energizing an isolated capacitor bank is a function of:

a) the point on the wave of the applied voltage where the contacts were closed,
b) the capacitance and inductance of the circuit,
c) the charge on the capacitor at closing time and
d) any damping resistance contained in the circuit.

When switching an isolated capacitor bank the value of the inrush current and its frequency is given by the following expressions.

$$i = \frac{E}{\sqrt{\frac{L}{C}}} \sin\left(\frac{t}{\sqrt{L_s C}}\right)$$

$$I_{peak} = \frac{\sqrt{2}E_{LL}}{\sqrt{3}}\sqrt{\frac{C}{L_s}} \quad \text{and}$$

$$f = \frac{1}{2\pi\sqrt{L_s C}}$$

where:

E_{LL} = Line to line system voltage
L_s = System line inductance
C = Bank's capacitance

It should be noted that the isolated capacitor bank inrush current for an isolated capacitor bank application is of no consequence for the application of the circuit breaker. The reason for this is that the transient inrush current that flows into an isolated capacitor bank is less than the normally rated short circuit current of the selected circuit breaker. Furthermore, the momentary current rating of the circuit breaker reflects the maximum short circuit current of the system and therefore its magnitude is greater than that of the inrush current.

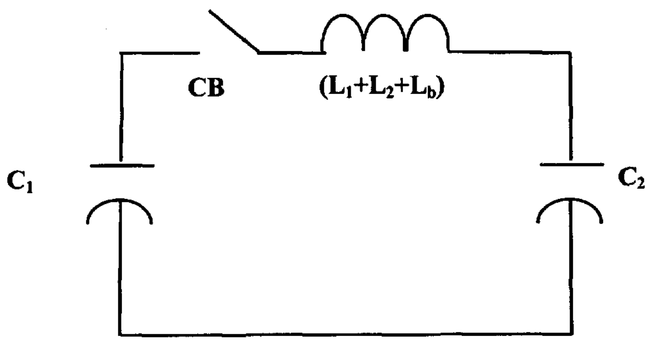

Figure 10.19 Simplified equivalent circuit for back-to-back capacitor banks calculations and where L_1 and L_2 are the inductance between capacitor banks and L_b is the bus inductance.

Table 10.2
Summary of Equations for Inrush Currents from Ref. 5

CONDITION	PARAMETER	EQUATION
Using Current as Variable		
Inrush current isolated bank	I_{max} (peak) Amperes	$\sqrt{2 \times I_{sc} \times I_1}$
	Frequency (f) Hertz	$f_s \times \sqrt{\frac{I_{sc}}{I_1}}$
Energizing one bank with another in the same bus	I_{max} (peak) Amperes	$1747\sqrt{\frac{V_{LL} \times I_1 \times I_2}{L_{eq} \times (I_1 + I_2)}}$
	Frequency (f) kilo-Hertz	$9.5\sqrt{\frac{f_s \times V_{LL} \times (I_1 + I_2)}{L_{eq} \times I_1 \times I_2}}$
Energizing a bank with other equal energized bank on same bus	I_{max} (peak) Amperes	$1235\sqrt{\frac{V_{LL} \times I_1}{L_{eq}}}$
	Frequency (f) kilo-Hertz	$13.5\sqrt{\frac{f_s \times V_{LL}}{L_{eq} \times I_1}}$
Using Surge Impedance as Variable		
Inrush current isolated cable	I_{max} (peak) Amperes	$\frac{E_m - E_t}{Z}$
	Frequency (f)	$f_s\left[\frac{\sqrt{2} \times I_{sc}}{I_{MR}}\right]$
Energizing a cable with another in the same bus	I_{max} (peak) Amperes	$\frac{E_m - E_t}{Z_1 + Z_2}$
	Frequency (f)	$f_s\left[\frac{E_m + E_t}{\omega I_{MR}(L_1 + L_2)}\right]$
Energizing a cable with other equal energized cable on same bus	I_{max} (peak) Amperes	$\frac{E_m - E_t}{2 \times Z}$
	Frequency (f)	$f_s\left[\frac{E_m + E_t}{\omega I_{MR}(L_1 + L_2)}\right]$

10.5.5 Back-to-Back Capacitor Banks

In applications where back-to-back capacitor banks are being energized high current magnitudes coupled with high frequencies of the inrush currents can be expected. The high magnitude of current is the result of the current being limited only by the impedance of the capacitor bank and by the inductance between the banks that are being energized.

A typical single line circuit representing the back-to-back condition is shown in Figure 10.19 and the equations that define this condition are given below.

$$\mathrm{i} = \frac{E}{\sqrt{\dfrac{(L_l + L_2 + L_b)}{C_T}}} \sin\left(\frac{t}{\sqrt{(L_l + L_2 + L_b)C_T}} \right)$$

$$I_{peak} = \frac{\sqrt{2}E_{LL}}{\sqrt{3}} \sqrt{\frac{C_T}{(L_1 + L_2 + L_b)}}$$

$$f = \frac{1}{2\pi\sqrt{(L_1 + L_2 + L_b)C_T}}$$

where:

$$C_T = C_1 + C_2$$

10.5.6 General Application Guidelines

Among others the following factors need to be taken into consideration in the application of a circuit breaker for capacitance switching duty.

10.5.6.1 Inrush Current Frequency

With modern circuit breakers the frequency of the inrush current is a lesser concern for the circuit breaker itself. However, in most cases it still constitutes the limiting factor because of other equipment in the system such as linear couplers and current transformers and also due to the effects of the induced voltages on the control wiring and the possible rise on ground mat potentials.

The problem with linear couplers and current transformers is related to the secondary voltage that is induced across the terminals and which can be calculated using the following formulas:

For linear couplers

$$E_s = \frac{f_2}{f_1} \times \text{LCR} \times I$$

For current transformers

$$E_s = \frac{f_2}{f_1} \times \text{CTR} \times I \times L_{relay}$$

where:

E_s = Secondary voltage across device terminals
LCR & CTR = Linear coupler or current transformer ratio
f_1 = System power frequency
f_2 = Transient frequency
I = Transient current
L_{relay} = Relay's inductance ≈ 0.3 ohms

Just for illustration purposes let us assume an inrush current of 25 kA and an inrush frequency of 6400 Hz; for a linear coupler and a current transformer both having a ratio of 1000 to 5, then the calculated secondary voltages are:

$$\text{Linear coupler } E_s = \frac{6400}{60} \times \frac{5}{1000} \times 25000 = 13{,}330 \text{ volts}$$

$$\text{Current transformer } E_s = \frac{6400}{60} \times \frac{5}{1000} \times 25000 \times 0.3 = 4000 \text{ volts}$$

10.5.6.2 Inrush Current Magnitude

The magnitude of the peak inrush current, as long as it does not exceed the maximum peak of the given close and latch capability of the circuit breaker, should not present any problem even if it is greater than the given values published as standard ratings for capacitance switching.

Nevertheless before exceeding the rated values it should be verified with the manufacturer of the circuit breaker that there are no design features that may say otherwise

It is evident from the above discussion that for many applications it would be advisable to limit the magnitudes and the frequency of the inrush currents. There are a number of relatively simple measures that can be taken either as an integrated part of the circuit breaker design or as an external addition to the system to effectively accomplish this task.

10.5.6.3 Limiting Inrush Frequency and Current

When found that it is necessary to limit the magnitude and the frequency of the inrush current, what is recommended is the use of:

1. Closing resistors or inductors, which are inserted momentarily during the capacitor energizing period and then are subsequently bypassed.
2. Fixed reactors, which are permanently connected to the circuit. This procedure reduces the efficiency of the capacitors and increases the losses of the system.
3. Synchronous switching where the closing of the contacts is synchronized so that it takes place at or very near the zero voltage thus effectively reducing the inrush current. The poles of the circuit breaker for this operation must be staggered by 2.7 milliseconds.

10.5.6.4 Application of Circuit Breakers Near Shunt Capacitor Banks

A single line diagram illustrating a circuit configuration where large amounts of out-rush currents are present is shown in Figure 10.20. This is an especially troublesome situation and special care must be taken to insure that line circuit breakers are properly selected. In the case illustrated in the figure the contribution made to the fault by the out-rush current from the capacitor banks will expose the circuit breaker to currents that are, in most cases, greater than those encountered on back-to-back switching.

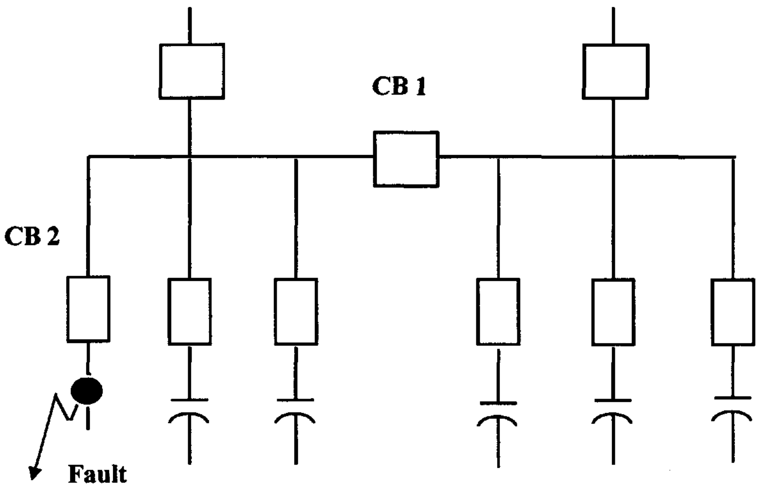

Figure 10.20 Diagram illustration of typical installation where the fault contribution of the capacitor banks may produce currents that exceed the capabilities of circuit breaker CB2.

The solution to this problem may the inclusion of pre-insertion and opening resistors into the circuit breakers or the installation of current limiting reactors in series either with the capacitor banks, or with the individual circuit breakers.

10.5.6.5 Switching Through Transformers

In a number of cases circuit breakers are required to switch capacitor banks, lines or cables through interposed transformers. Generally this type of operation is less demanding on the circuit breaker than when switching a capacitor that is connected directly to its terminals.

The current to be switched by the circuit breaker will be proportional to the number of turns ratio of the transformer times the original capacitive current of the component on the other side of the transformer. There is also the possibility that the transformer may go into saturation thus resulting in a lowered TRV. This relationships between the current and the voltage when the transformer is saturated are depicted in Figure 10.21.

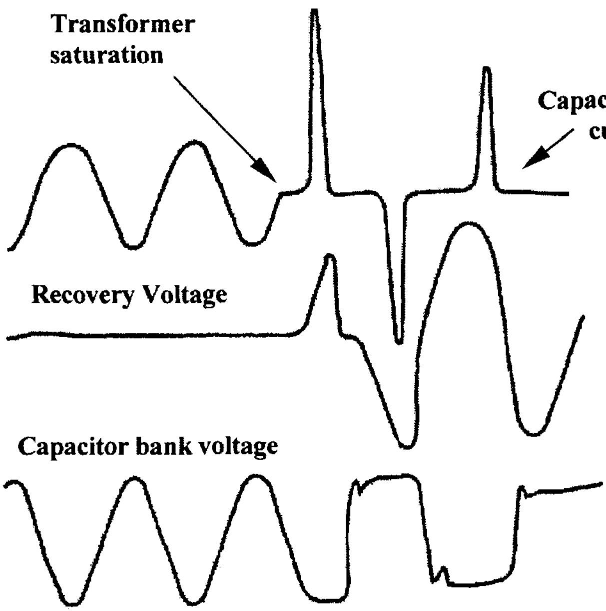

Figure 10.21 Capacitor bank switched through a transformer. Current and voltage waveforms.

10.5.7 Circuit Breaker Characteristics

Although all circuit breakers that have similar ratings, regardless of the type of interrupting media used, must meet the same performance standards there are some unique characteristics for each type of circuit breaker that sets them apart from each other and that should be taken into account whenever they are used for capacitance switching applications.

10.5.7.1 Oil Circuit Breakers

Oil circuit breakers are more sensitive than other types of circuit breakers to increased current levels and with these circuit breakers normally the restrike probability increases as the current increases. On the other hand the oil circuit breaker will not interrupt the high frequency restrike current and the high resistance characteristic of this type of circuit breaker will effectively damp the current oscillation. The result is a reduction of the risk for multiple restrikes.

A more dangerous condition is a prestrike during closing. Such a prestrike may generate shock waves in the oil, which could result in mechanical damage of the interrupter chamber. Close attention must be paid to the prospective inrush current whenever oil circuit breakers are used.

10.5.7.2 SF_6 Circuit Breakers

For puffer and self-blast type SF_6 circuit breakers there is very little chance that they will interrupt the high frequency currents and therefore the risk of voltage escalation due to multiple restrikes is practically non-existent.

Current magnitude and frequency of the inrush current are not critical. The inrush current magnitude that should not be exceeded is the rated close and latch corresponding to that particular circuit breaker. As far as frequency the limit will be that which is imposed by the current transformers and linear couplers that may be used.

In most cases higher than rated outrush currents are advantageous because higher currents tend to increase the minimum arcing time and thus develop a larger contact gap and consequently a greater dielectric withstand capability at the time when the current is interrupted.

10.5.7.3 Vacuum Circuit Breakers

Because in a vacuum interrupter the dielectric recovery is extremely fast and requires very short gap distances the restrike probability is very low and even in the event of a restrike the vacuum interrupter is capable of interrupting the high frequency restrike current without major consequences.

Prestrikes do not cause significant problems considering that vacuum has a high dielectric capability and at normal closing speeds the pre-arcing duration is likely that it would not exceed a millisecond or two.

10.6 REACTOR CURRENT SWITCHING, HIGH TRV APPLICATIONS

In general switching of reactor currents is associated with small magnitude of currents, high frequency transient recovery voltages, and high overvoltages. It is then conceivable that in some of those applications involving reactor switching, especially when current limiting reactors are connected in a close proximity to the circuit breaker, the resulting TRV may exceed the limits for which the circuit breakers have been designed and tested.

As it should be recalled SF_6 circuit breakers are likely to be more limited in their capability to withstand higher rates of recovery voltage than similarly rated vacuum circuit breakers. Consequently for these applications, and if available, a vacuum circuit breaker could be a better choice. Nevertheless, and since we also know that at voltages higher than 38 kV, the most likely choice would be an SF_6 circuit breaker. One solution to reduce the rate of rise of the recovery voltage, especially during the thermal recovery period which takes place during the first 2 microseconds after current interruption, is to add capacitors, either in parallel to the interrupter contacts, or connected from line to ground at the terminals of the circuit breaker. For this simplistic approach the size of the capacitor can be calculated by simply assuming that the TRV is produced by an equivalent series LC circuit and where the initial time delay (t_d), that is now required and has to be greater than 2 microseconds, is given approximately by:

$$t_d = Z\,C_m \quad \text{in microseconds}$$

where:

Z = Surge impedance
C_m = Externally added capacitance in microfarads

It is also possible, and this is a more realistic approach, especially when dealing with applications at the higher end of the voltage scale, to utilize circuit breakers that are equipped with opening resistors, or to use metal oxide surge arresters applied directly to the circuit breaker.

Opening resistors are connected in parallel to the main interrupting contacts of the circuit breaker and constitute an effective method for the reduction of overvoltages and for the modification of TRV. The value of the closing resistor should be approximately equal to the ohmic reactance of the reactor.

Another approach that can be used and which will be discussed in more detail in the next chapter is the synchronized opening of the circuit.

When the circuit breaker is used to switch shunt reactors that are connected to the bus its fault current interrupting capability should be determined in relation to the full requirement of the system, but if the circuit breaker is used to switch shunt reactors that are connected to transmission lines the full fault capability may not be required although the short time and the momentary capabilities of the circuit breaker should be at least equal to the ratings of the circuit breaker that is providing the primary fault protection to the circuit.

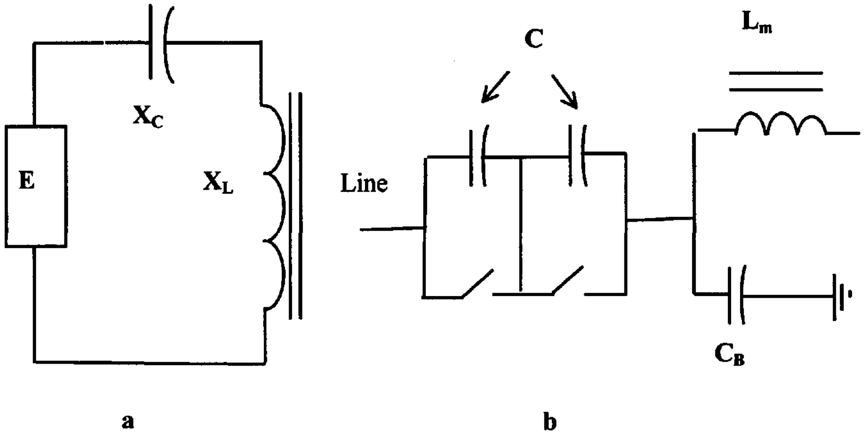

Figure 10.22 Relationship of circuit components for ferroresonance; (**a**) equivalent circuit and (**b**) single line diagram.

10.7 FERRORESONANCE

As described above the use of capacitors helps to improve the TRV withstand and therefore the interrupting capability of a circuit breaker. In other instances capacitors are also placed across the contacts on poles that have multiple interrupters with the purpose of equalizing the voltage distribution across the individual interrupters. In general, for these purposes the larger the capacitance the greater the improvement. However, the down side to the use of larger capacitors, aside from the cost and added complexity, is the possibility of creating a ferroresonant condition between the capacitor and the potential transformers that may be connected to lines that are de-energized.

This condition is created when there is a transformer connected to the bus, in which case there is a series connection of the capacitors and the transformer as illustrated in Figure 10.22.

The equivalent circuit basically represents a voltage divider (X_m / X_c - X_m) and when the capacitive reactance X_c equals the inductive reactance X_m of the transformer then, at least in theory, the voltage at the bus will become infinite. But in reality the voltage is limited due to the non-linear impedance of the transformer and its magnitude is determined by the intersection of the capacitive voltage with the transformer's saturation voltage and whenever the intersection point is below the knee of the saturation curve then the overvoltage could be severe and damage to the transformer can take place. An expeditious solution for this problem is to add a low ohmic resistor connected across the secondary of the transformer.

10.8 HIGH ALTITUDE DIELECTRIC CONSIDERATIONS

Application of a circuit breaker at elevations greater than 1000 meters (3300 ft) results in a reduction of the dielectric capabilities of the circuit breaker due to the lighter air density. For sealed interrupters the withstand capability across the contact gap is not affected and only those insulating structures which are exposed to the atmosphere should be considered for derating. Keeping in mind that what is desirable, but not always attainable, is that in case of a flashover produced by excessive overvoltages said flashover should occur externally to the contacts. Depending on the type of interrupter used and on the design of the circuit breaker it is possible that there is air dependent insulation located in a parallel path to the SF_6 or vacuum insulation across the circuit breaker contacts. This implies that in these cases the altitude derating must be considered.

In those cases where the design provides sufficient coordination between the non-atmospheric and the atmospheric paths it is conceivable that the possibility of applying the equipment either without derating or with a limited derating may also be considered. However, this approach must be carefully evaluated to assure that the insulation coordination with the rest of the equipment involved on the particular installation is not compromised in any way. Furthermore it will be necessary to provide adequate protection for the circuit breaker in the form of properly rated arresters located both at the line side and at the bus side and in some instances this may prove to be uneconomical when compared to a fully rated circuit breaker.

The applicable derating factor (K) is given by the following equation and is shown in Figure 10.23.

$$\mathrm{K} = e^{-\left((H-1000)/8150\right)}$$

where:

K = Derating factor
H = Altitude where circuit breaker is to be applied in meters

Once a correction factor has been determined, the next step is to calculate the operating voltage rating at the standard conditions. The selection of a circuit breaker that has a rating equal to or greater than that which has been calculated will generally take care of the power frequency and the impulse dielectric withstand requirements at the new altitude. For example, let us chose a circuit breaker for a 145 kV system to be used at 3000 meters above sea level.

The factor K is equal to $e^{-\left((3000-1000)/8150\right)} = 0.782$

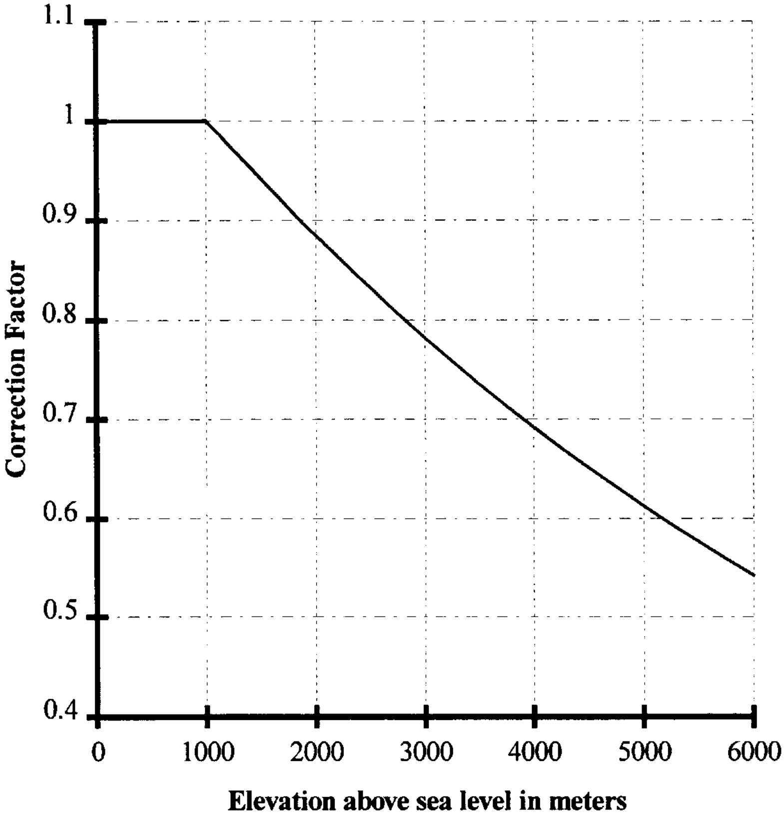

Figure 10.23 Correction factor for the dielectric withstand of the components of a circuit breaker exposed to air ambient at elevations other than sea level.

The maximum operating voltage rating at standard conditions for this application is equal to 1/ 0.782 x 145 = 185 kV. The closest higher standard rating is 242 kV.

Now let us suppose that the maximum voltage of the system is 121 kV instead of 145 kV. What we find with these new conditions is that the required maximum operating voltage is 155 kV. Now we are faced with a situation where it may be possible to use a 145 kV circuit breaker protected by properly sized arresters or to opt for selecting a 242 kV circuit breaker. If a dead tank circuit breaker is being considered and the system is grounded then the recommended choice should be the 145 kV rated circuit breaker.

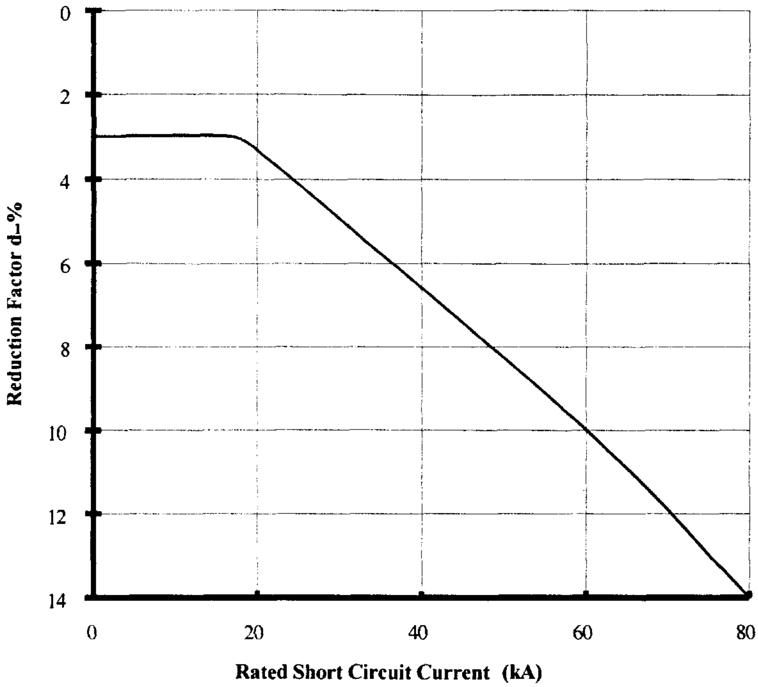

Figure 10.24 Reduction factor d_1 that is used for calculating derating factors for rapid reclosing and extended duty cycles.

10.9 RECLOSING DUTY DERATING FACTORS

The need for derating factors for applications involving rapid reclosing or extended duty cycles depends primarily on the type of circuit breaker that is being used. Being more specific, it should apply only to oil or air magnetic circuit breakers. This is due to the fact that following an interruption these circuit breakers need additional time to cool off and to regain their dielectric capability. SF_6 and vacuum circuit breakers generally do not need the extra time and therefore there should be no need for reducing their interrupting capability; nevertheless, there may be some cases where the manufacturer chooses to do so and consequently when the application of these circuit breakers involves either more operations or shorter time intervals between operations than what is established as the standard duty cycle it is advisable to consult with the manufacturer.

When a derating factor needs to be applied it can be calculated using the relationship that is given below, and which is applicable within the following constraints:

1. The duty cycle does not consist of more than five opening operations.
2. All operations taking place within a 15-minute period are to be part of the same duty cycle.
3. A period of 15 minutes between operations is considered to be sufficient for the initiation of a new duty cycle.

The derating factor is obtained by first calculating the total required percent reduction factor D which is found by adding the individual reductions that are obtained by multiplying the constant d_1 given in Figure 10.24 by the number of operations in excess of the two which are required by the standard duty cycle (CO + 15 sec + CO) and by the ratio of the time difference for each reclosure with a period that is less than 15 seconds. This is expressed mathematically by the relationship given below:

$$R = 100 - D$$

$$D = d_1(n-2) + d_1\frac{(15-t_1)}{15} + d_1\frac{(15-t_2)}{15} + \_\_\_\_\_$$

where:

R = Derating factor
D = Total reduction factor in percent
d_1 = Multiplier for the calculation of reducing factor
t_1 = First time interval which is less than 15 seconds
t_2 = Second time interval that is less than 15 seconds
n = Total number of contact openings

The following example should serve to illustrate the concept. Given a 245 kV, 20 kA circuit breaker that is going to be applied for a (O + CO + 10 sec + CO + 1 minute + CO) duty cycle.

The multiplier d_1 from Figure 10.13 is equal to 3.3 at 20 kA and the reduction factor D is

$$D = 3.3 \times (4-2) + 3.3 \times \frac{(15-0)}{15} + 3.3 \times \frac{(15-10)}{15} + 0$$

$$D = 6.6 + 3.3 + 1.1$$

D = 11% and R = 100 - 11 = 89% or 0.89

The short circuit rating of the circuit breaker is then reduced to 20 x .89 = 17,800 amperes.

10.10 VACUUM CIRCUIT BREAKER APPLICATIONS

Because of some of the unique characteristics of vacuum circuit breakers guidelines for their application are often being requested. The applications that generate the most concern are those involving the protection of transformers and rotating machinery where a non-uniform distribution of transient voltages may overstress the first coils or windings of the transformers or of the rotating machines.

Therefore, to insure the safe application of a vacuum circuit breaker the parameters that must be controlled are the magnitudes of the voltage transients and the frequency of the rate of rise of these transient voltages. The source of these transients is the system in itself and the characteristics of these transients are dictated by the resistive and reactive components of the system.

The role of the circuit breaker is only as an initiator of the sequences that will generate these transient responses. The mode by which the response is initiated is a consequence of some of the characteristics of the vacuum technology. Previously described phenomena such as current chopping, virtual current chopping, prestrikes, multiple re-ignitions, voltage escalation and delayed restrikes are the mechanisms of most concern that contribute to voltage surges during switching operations.

Although in most instances no special measures for additional protection of a system using vacuum interrupters are required in practice, due to the probabilistic nature of the switching over-voltages some steps may be taken to fully insure the safety of the system at all times.

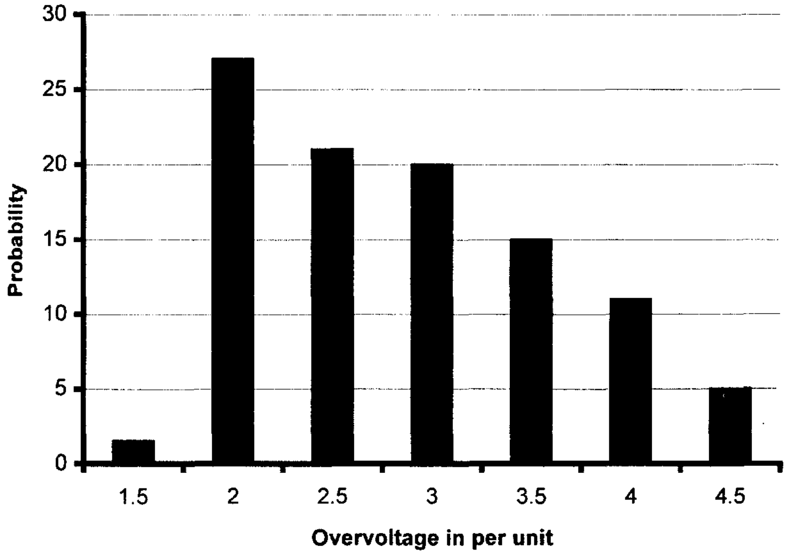

Figure 10.25 Switching surge probability for a 20 kV class transformer when interrupting an inrush current.

A detailed explanation of recommended protection for all possible individual applications would be unrealistic because of the number of variations in the values of the components in different systems. Instead, taking into account the possible interaction of the above listed transient generating mechanisms and the general characteristics of the connected equipment the following general recommendations can be offered. margin in this case, it would be advisable to provide surge protection.

10.10.1 Transformers Circuits

When using vacuum circuit breakers in conjunction with oil insulated transformers there is no need to add overvoltage transient protection. This type of transformer always has a high BIL insulation level. However, if these transformers are switched frequently in an unloaded condition or in applications such as arc furnace switching then surge protection is recommended.

Dry-type transformers have a lower insulation level than that of oil-type transformers and although it is not always absolutely necessary to add surge protection, it is considered to be a good insurance measure to do so. Therefore, it is highly recommended that some method of surge protection be applied.

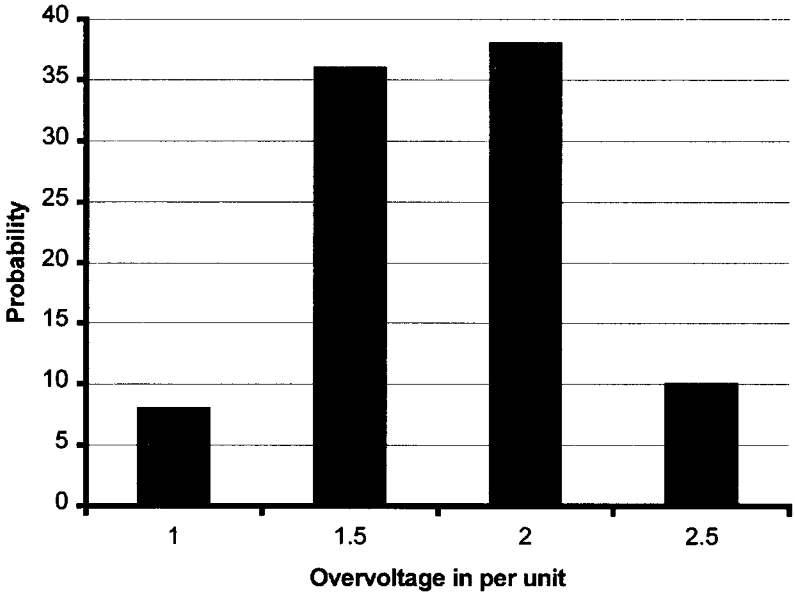

Figure 10.26 Switching surge probability for a 20 kV class transformer when interrupting exciting current

For example let us assume a 25 kV dry type transformer that has a 95 BIL rating and that is connected to a vacuum circuit breaker. The ratio between its withstand capability and the line to ground voltage is 4.6 per unit. From Figure 10.24 it is observed that when interrupting an inrush current a 5% probability exists of having a 4.5 per unit overvoltage and therefore, since there is not enough in this case, it would be advisable to provide surge protection.

Generally there is no need for surge protection when interrupting the exciting current of the transformer since, as it can be seem in Figure 10.26 the probability of an overvoltage greater than 2.5 per unit for all practical purposes does not exist.

10.10.2 Applications in Motor Circuits

Vacuum circuit breakers can be safely applied to rotating machinery circuits but as a general rule surge protection should always be added. Again this is primarily a form of insurance.

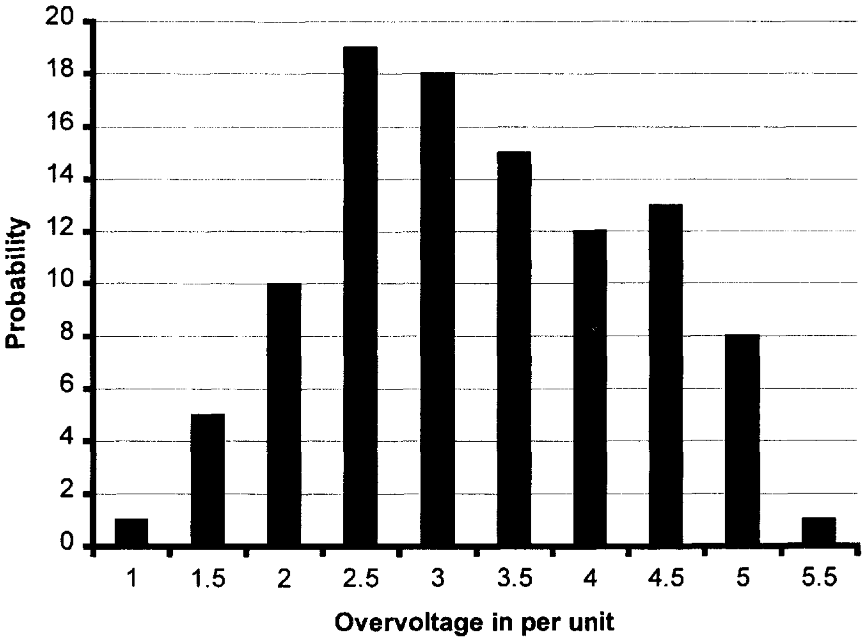

Figure 10.27 Overvoltage probabilities with a 5 kV 75 kW induction motor without surge protection.

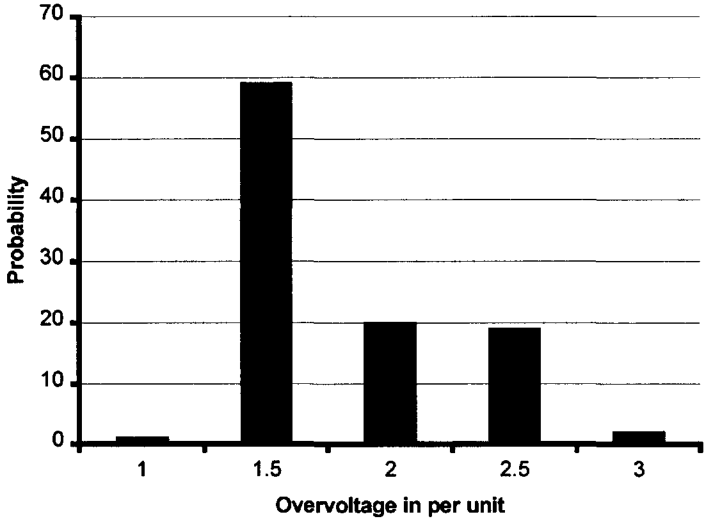

Figure 10.28 Overvoltage probabilities with a 5 kV 75 kW induction motor with capacitor (0.1 μF) protection installed.

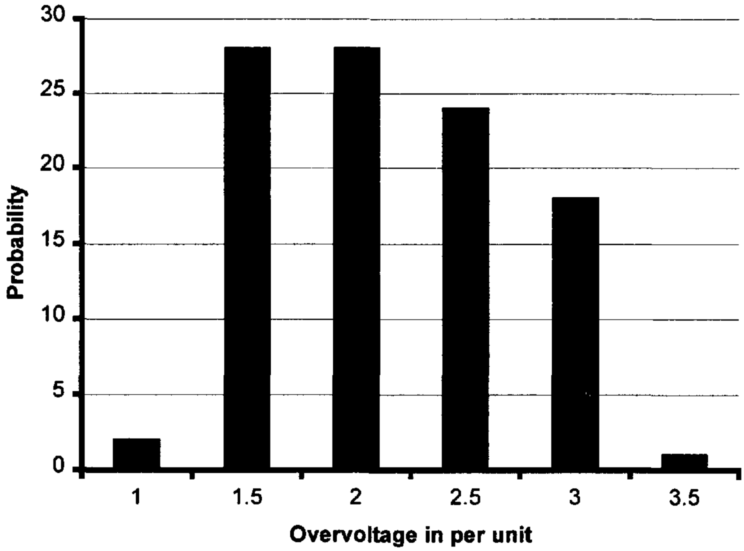

Figure 10.29 Overvoltage probabilities with a 5 kV 75 kW induction motor with capacitor-resistor surge suppresser installed.

For motor circuit applications it is rather difficult to precisely determine whether or not surge protection may be required. The reason for this ambiguity is that a definite reference value for the impulse insulation strength distribution between turns of the motor windings is not clearly defined nor specified.

Furthermore, as is shown in Figure 10.27 there are occasions, even though the probability is low (1 %), where a rather large voltage surge reaching magnitudes of as much as 5.5 per unit can be produced. These type of surges almost invariably will lead to insulation failures.

In Figures 10.28 and 10.29 the benefits that can be achieved by the use of a capacitor or a capacitor-resistor surge arrester are illustrated and as it can be seen a substantial reduction in the surge's magnitudes can be obtained.

10.10.3 Review of Surge Protection Methods

Surge protection devices can be viewed as those which protect against the magnitude of the surge voltage or those that modify the rate of rise of the transient voltage.

The first group is comprised of all types of surge arresters, from the conventional gapped station class and distribution class to the zinc oxide (ZnO) arresters and surge suppressers. ZnO arresters offer a better voltage versus current characteristic than standard silicon carbide (SiC) used in standard arresters. ZnO arresters and ZnO surge suppressers are basically the same device except that the surge suppresser is a lighter duty device with less absorption capability than that of the arrester.

Surge arresters preferably should be located at the load terminals to obtain maximum reduction of the transient voltage. If the arrester was to be installed at the circuit breaker terminals a higher voltage level will be observed due to the effect of the inductance between the suppressers and the load terminals.

Included in the second category are surge capacitors, capacitor-resistor (C-R) suppressers and series reactors.

Surge capacitors are widely used, and according to industry's established practices they should be placed as close as possible to the load terminals. There are some disadvantages if they were to be placed at the circuit breaker terminals. One of them is that in the event of a reignition the capacitor will discharge across the circuit breaker terminals thus potentially increasing the frequency and the magnitude of the reignition current.

Capacitor-resistor surge suppressers are not that popular in the US; nevertheless they are quite effective for controlling not only the frequency but also the magnitude of the overvoltage. This type of protection is especially suited for the protection of transformers connected to variable drives and uninterrupted power supply (UPS) systems.

10.11 CHOOSING BETWEEN VACUUM OR SF_6

A fair comparative assessment of vacuum or SF_6 circuit breakers can only be made for medium voltage circuit breakers where both types of technologies can be used interchangeably. The choice between vacuum and SF_6 is mostly a matter of preference. The basic performance of both technologies is essentially the same because both are designed and tested to meet the same performance standards. There may be however some specific applications where one technology may be deemed more appropriate.

Vacuum circuit breakers have a very long and relatively maintenance free life which represents a desirable attribute and a significant advantage for this technology. The main disadvantage for vacuum interrupters, on the other hand, is their noticeable propensity for initiating overvoltages, which may be harmful to other equipment. Although for most applications there is no need for concern, it is recommended that for applications involving the switching of transformers and/or rotating machinery due consideration be given to the use of surge arresters and better yet to the use of surge suppressors which consist of a resistor and a capacitor in series. This component combination not only reduces the frequency of the transient voltage but it also reduces the magnitude of the voltage. Another advantage of this protection is that it serves to detune the circuit and prevents the possibility of having a resonant circuit.

For applications where a large number of operations under load, or fault conditions, are required or where high rates of rise of recovery voltage are expected such as in the case of reactor switching, vacuum circuit breakers may be the better choice. But on the other hand for applications on capacitor switching or the switching of transformers SF_6 circuit breakers may be advantageous. In either of the last two mentioned applications the addition of capacitors or surge suppresser will serve to equalize the applicability of both technologies. Other factors that may influence the choice and which at the time of this writing are still unknown are the possible future environmental restrictions and liabilities that may be imposed on the use of SF_6.

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11

SYNCHRONOUS SWITCHING AND CONDITION MONITORING

11.0 INTRODUCTION

Synchronous switching and condition monitoring are two subjects that have gained a great deal of relevance not only because of their potential for increasing reliability and for making a contribution to improve the overall power quality of the electric systems, but also for economic reasons. These concepts can be instrumental in minimizing the use of auxiliary components, such as pre-insertion resistors, in reducing equipment wear and unnecessary maintenance and thus reducing the total cost of ownership throughout the full lifetime of the equipment.

Synchronous switching is not a recent idea and for at least the last 30 years the feasibility of synchronized switching has been studied; many concepts have been investigated and even some commercial equipment has been built and utilized [1], [2], [3].

Condition monitoring is a relatively newer concept that has came about primarily because of recent developments of electronic sensors and data acquisition equipment that have made this idea not only technically feasible but also economically attractive. Condition monitoring is an essential component for synchronous switching simply because a lot depends on how accurately the operating characteristics of the circuit breaker can be controlled. It is well know that the operating characteristics can be affected by extreme ambient temperatures, and by other prevailing conditions such as mechanism operating energy levels, control voltages, operating frequency of the equipment, its chronological age, and its maintenance history among others. Collecting information about these variations would provide a data source from where suitable correction factors may be selected to compensate for those operating deviations which are critical for accurate synchronous operation.

11.1 SYNCHRONOUS SWITCHING

Opening or closing the contacts of a circuit breaker is normally done in a totally random fashion and consequently, as it has been described before, transient current and voltage disturbances may appear in the electrical system. A typical way for controlling this transient behavior has been to add discrete components such as resistors, capacitors, reactors, surge arresters, or combinations of the above to the terminals of the circuit breaker. Nevertheless, in many cases it would be possible to control these transients without the addition of external components but by operating the circuit breaker in synchronism with either the current or the voltage oscillations, depending upon the type of switching operation at hand. This means that, for example, the opening of the contacts should occur at a current zero when interrupting short circuit currents or that the closing of the contacts should take place at voltage zero when energizing capacitor banks.

Operations that can benefit the most by synchronized switching are those involving the switching of unloaded transformers, capacitor banks, and reactors. Energizing transmission lines and opening the circuit breaker to interrupt short circuit currents are also good candidates for synchronous switching [4].

Ideally and to obtain the greatest benefits, synchronous switching should be done using circuit breakers that are capable of independent pole operation. Independent pole operation is already a standard feature in circuit breakers that are rated above 550 kV and it is also used, under special request, for applications as low as 145 kV. However, for those designs where all three poles are operated in unison the implementation of controlled switching concepts will require the development of specially designed circuit breakers which are provided with suitable methods for staggering the pole operating sequences.

Additionally, the success of a synchronized operation will depend upon the proper matching of the operating characteristics of the circuit breaker with the response of the system. Therefore in order to select the operating characteristics of a circuit breaker which have the most direct impact for synchronized switching requires a clear definition and understanding of the cause and effect relationship that exists between the mechanical operation of the circuit breaker and the behavior of the electric system. In every case it is indispensable to closely analyze the mechanical and electrical properties of the design including contact velocity, contact opening time, contact closing time, minimum arcing time for different interrupting duties and current levels and cold gap voltage withstand capability. Furthermore, and in relation to the operating times, the effects of control voltage fluctuations, ambient temperature, tolerances of the mechanism's stored energy and operating wear must also be considered.

11.1.1 Mechanical Performance Considerations

Consistency in the making and breaking times of the circuit breaker is absolutely essential for successful implementation of all types of synchronous switching.

However, considering the fact that a circuit breaker is a mechanical device and even though modern designs are highly reliable, further improvement still is necessary. Already mentioned were the influence of wear, aging, cold temperatures, and voltage control sources upon the operating consistency of the circuit breaker.

Of all the parameters that have been mentioned above the ones that have the greatest influence in the consistent timing of a circuit breaker are the ambient temperature, the level of energy stored in the operating mechanism and the control voltage level.

The effects of wear and aging upon the equipment presently in service, at least for now, are unpredictable. There are only scarce and incomplete data and furthermore there is a need for data obtained from actual field operating experiences to fully evaluate the influence of these conditions upon the life of a circuit breaker. Another condition that is difficult to evaluate and which may have a significant influence upon the repeatability of the operations is the effects of long periods of time when the circuit breaker has not been operated, especially when during the idle periods the equipment has been subjected to very low ambient temperatures.

As an illustration only and for future reference, the operating characteristics of what may be considered, from a qualitative point of view, typical of a SF_6 puffer high power circuit breaker are tabulated below in Table 11.1. Similar values for vacuum interrupters are given in Table 11.2.

In addition to the mechanical characteristics shown in Tables 11.1 and 11.2 the following electric attributes representing the minimum arcing times for different types of switching duties are given in Table 11.3.

For most synchronous switching applications the aggregate of all the variations in the operating times, corresponding to the worst condition, both in closing and in opening, should not exceed a maximum of plus or minus one millisecond.

For example, observing the operating times that are shown in Table 11.1, it is evident that the aggregate time of this circuit breaker, as shown below, far exceeds the maximum opening or closing time allowable deviation.

Maximum deviation in closing time

31.5 (min. volts) + 2.5 (min. temp) + 2.5 (min. force) = 36.5 ms

Maximum deviation in opening time

1.1 (min. volts) + 1.2 (min. temp) + 0.6 (min. force) = 2.9 ms

It is also quite evident that the control voltage exerts the greatest influence on the operating times. This parameter, in comparison to all the others offers better possibilities for enhancement and consequently it is where the major improvement would be expected. Possible solutions are the use a regulated power supply or capacitor discharge systems to provide the control power required for the supply of the control circuits energizing the operating coils. In addition the solenoid coils should be optimized to reduce the operating time range.

Table 11.1
Typical Operating Characteristics
of an EHV Puffer Circuit Breaker

	CLOSING		OPENING	
	Time m/s	Speed m/s	Time m/s	Speed m/s
Normal Control Volts	73.9	4.3	16.0	8.6
Min. Control Volts	105.4	4.0	17.1	8.4
Max. Control Volts	72.1	4.0	15.9	8.4
Min. Temp. -40°C	76.4	5.0	17.2	8.5
Min. Force Mech.	76.4	3.9	16.6	7.6
After 5000 Operations	73.9	4.3	16.0	8.6

Table 11.2
Typical Operating Characteristics
of a Vacuum Circuit Breaker

	CLOSING		OPENING	
	Time m/s	Speed m/s	Time m/s	Speed m/s
Normal Control Volts	45	0.9	25	1.25
Min. Control Volts	49	0.9	27	1.25
Max. Control Volts	43.5	0.9	23.5	1.25
Min. Temp. -40°C	46.5	0.85	26	1.2
Min. Force Mech.	46	.8	26	1.2
After 5000 Operations	47	.9	25	1.25

Table 11.3
Typical Minimum Arcing Times for SF_6 and Vacuum Circuit Breakers

Switching Operation	SF_6	Vacuum
Short Circuit Current Interruption	13 milliseconds	4 milliseconds
Capacitor Bank Current Interruption	2.5 milliseconds	1.5 milliseconds
Low Inductive Current Interruption	3 milliseconds	2 milliseconds

So far mention has only been made of the operating times without mention of the operating speeds, but these also are quite important for they are related to the minimum arcing time during opening and to the prestrike time during closing. The product of the velocity and the above mentioned parameters determines the minimum contact gap required for the respective operation.

11.1.2 Contact Gap Voltage Withstand

The contact gap voltage withstand capability is an arbitrary definition that relates to the change in gap distance in relation to the instantaneous voltage withstand capability across said gap during a normal closing operation. An approximate value can be obtained for an interrupter, but first, to minimize the variables, it is assumed that the interrupter has not been subjected to an electric arc immediately preceding the measurement. The voltage withstand thus obtained is somewhat on the optimistic side, since during normal service, and more so during a reclosing operation, it will be reasonable to expect that arcing has occurred. The effects of prior arcing must still be investigated, but it is expected that if there were a reduction in capabilities such reduction would be less than 10% of the cold gap withstand.

For SF_6 interrupters the contact gap withstand is a function of the gas pressure and of the geometry of the contacts; higher operating pressures and lower dielectric stresses in the field across the contacts would produce higher contact gap withstand values. Reported values [5] range from approximately 10 kV per millimeter to 25 kV per millimeter. While for vacuum interrupters the contact gap capability [6] is primarily a function of the electrode material and is in the range of 20 to 30 kV per millimeter.

11.1.3 Synchronous Capacitance Switching

For capacitance switching, the primary concern is not as much the interruption of capacitive currents because, due to the inherent characteristics of vacuum and SF_6 circuit breakers, the problems associated with restrikes, which were quite frequent with earlier technologies, have been greatly reduced and today indeed restrikes are a very rare occurrence.

On the other hand, failures are often reported which are the direct result of inrush currents and overvoltages that have propagated themselves into lower voltage networks causing damage especially to electronic equipment connected to the circuit. A comparison of the voltage transient for a non-synchronous operation is shown in Figure 11.1, and in Figure 11.2 the voltage response of a synchronized closing is shown. As it can be seen in the illustrations the higher frequency component of the voltage is practically eliminated when the contacts are closed at a nominal voltage zero condition.

11.1.3.1 Energizing a Capacitor Bank

In order to completely eliminate the overvoltages produced by the closure of a circuit breaker onto a capacitor bank it is required that there be a zero voltage difference across the contacts of the circuit breaker at the time where the contacts meet. Naturally this is not always possible simply because some deviation from the optimum operating conditions has to be expected.

There are a number of studies [7] that have shown that the overvoltages can be significantly reduced. It has been shown that the overvoltages can be kept within acceptable limits whenever the closing of the contacts is controlled so that it occurs within one millisecond either before or after the voltage zero point.

The significance of this requirement is better appreciated when the characteristics of the driving voltage is considered in conjunction with the dielectric withstand capability of the contact gap. This is illustrated in Figure 11.3 where the absolute value of a sinusoidal voltage has been plotted against the slope of an assumed gap voltage withstand characteristic. As it can be seen in the figure the point where the prestrike takes place corresponds to the intersection of the two curves.

In the figure, to better illustrate the concept several different times for the zero intersection of the gap withstand are shown. Ideally, for all circuit breaker designs, the rate of change of the gap withstand voltage should be at least 10% higher than the rate of change of the system voltage. This is required simply to assure that there would be proper coordination between the two rates.

To further investigate the concept let us consider a hypothetical circuit breaker whose characteristics are similar to those that are tabulated in Table 11.1. Let us furthermore assume that the gap withstand capability of this circuit breaker is 10 kV per millimeter and that its closing speed is 4.3 meters per second. The corresponding rate of withstand capability is then 43 kV per microsecond.

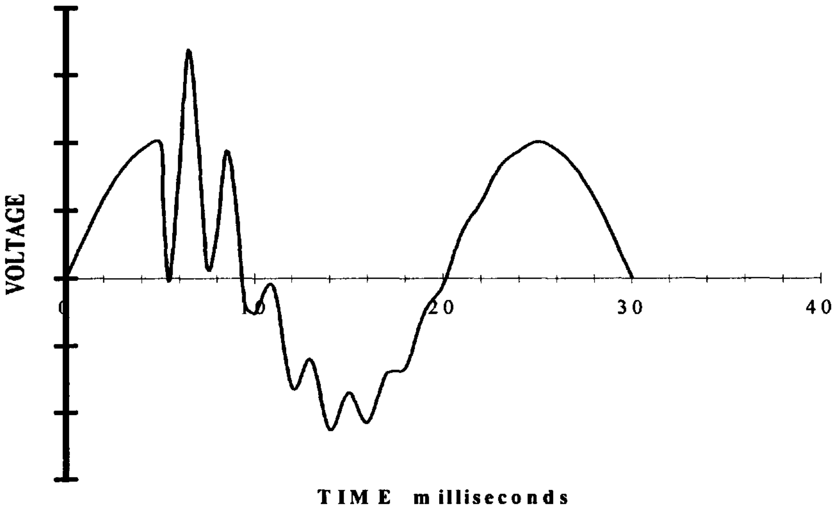


Figure 11.1 Voltage corresponding to a non-synchronous closing of a circuit breaker into a capacitor bank.

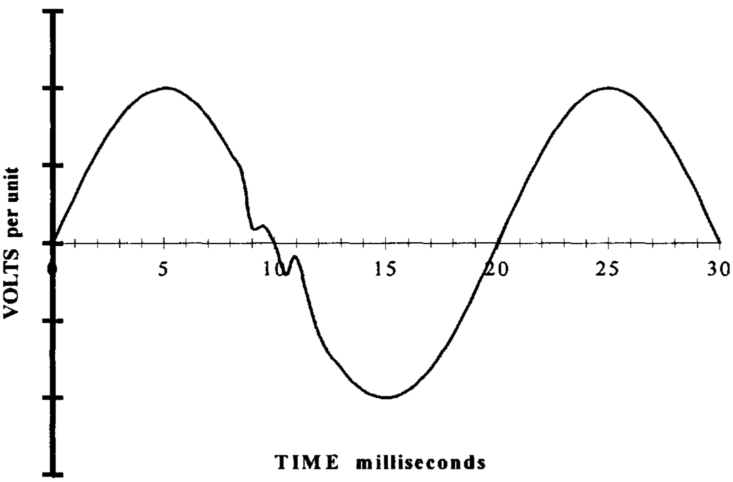


Figure 11.2 Voltage corresponding to a circuit breaker synchronous closing into a capacitor bank.

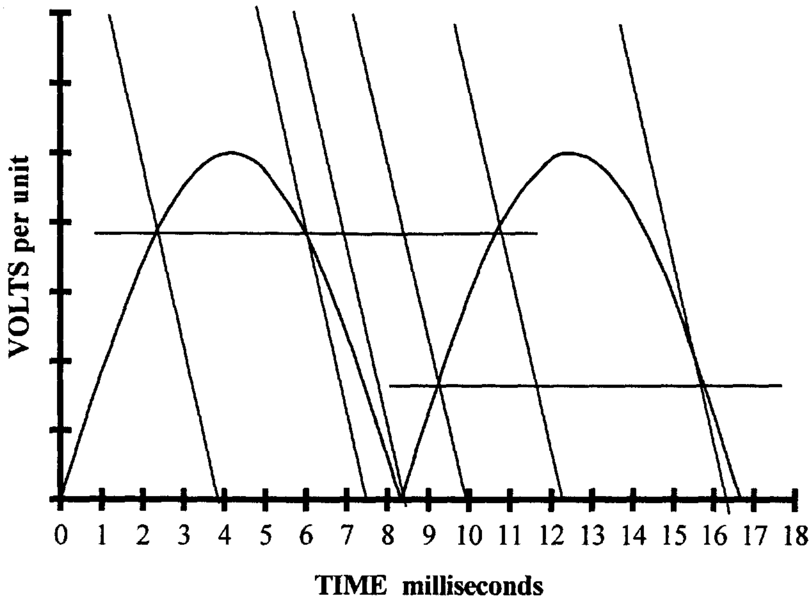


Figure 11.3 Relation between system voltage and interrupter gap withstand capability.

Assuming that the circuit breaker under consideration is intended for capacitance switching duty on a 72 kV ungrounded system. As we know, an ungrounded system represents the worst case in terms of voltage peak since this peak for the last phase to close is equal to 1.5 times the peak of the rated line to line system voltage.

The maximum rate of change of voltage with respect to time at the instant of voltage zero corresponding to the above phase is

For a grounded application

$$\frac{dE}{dt}=\frac{\sqrt{2}}{\sqrt{3}}Ex\omega = 0.82\times 72\times 377 = 22.2 \text{ kV per microsecond}$$

For an ungrounded application

$$\frac{dE}{dt}=1.5\times\frac{\sqrt{2}}{\sqrt{3}}E\omega = 1.225\times 72\times 377 = 33.2 \text{ kV per microsecond}$$

Comparing the two rates of change, the ones corresponding to the system voltage against the one related to the rate of change of the gap capability, as shown in Figure 11.4, it appears that the interrupter being considered in the example would be adequate for this application.

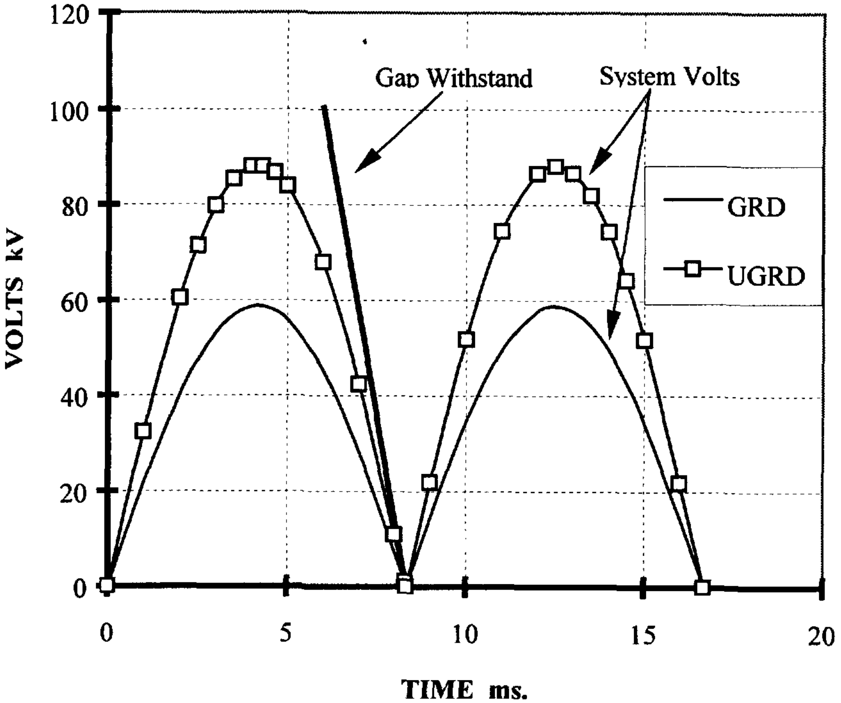


Figure 11.4 Rates of change of gap withstand capability for the circuit breaker of the given example and the rates of change of the system voltage for grounded and ungrounded applications.

Table 11.4
Rate of Change of Gap Withstand Capability

	Maximum rate of change of system Voltage kV/μs	
Rated Voltage	Grounded Bank	Ungrounded Bank
72	22	33
121	37	56
145	45	68
245	76	114
362	112	168
550	169	254

However, in the event that the example interrupter is considered for an application at 145 kV, after following the same procedure as before and using the tabulated values shown in Table 11.4 for the customary preferred rated system voltages it is evident that this interrupter is inadequate for the application. Nonetheless, if the gap withstand capability is increased to 25 kV per millimeter, assuming the same 4.3 meters per second speed, then the rate of change of the withstand capability becomes approximately 108 kV per microsecond. This suggests that it would be possible to consider the use of this interrupter for all grounded capacitor bank applications up to 245 kV and if two of these interrupters are connected in series it would also be possible to meet the 550 kV application requirements. For ungrounded banks a single interrupter is good only up to 145 kV, and even with two interrupters in series it would not be possible to meet the 550 kV rating.

To increase the rate of change of the withstand capability in an SF_6 circuit breaker any of the following three options either individually or in combination may be applied.

1. Increase the gas operating pressure.
2. Reduce the electric field stress in the contact region.
3. Increase the closing velocity of the circuit breaker contacts.

Increasing the gas operating pressure, in many cases, is not a viable solution because of the possibility of SF_6 liquefaction at low temperatures. Nevertheless, it should be kept in mind that at voltages above 362 kV the systems are grounded almost without exception and therefore our imaginary non-ideal circuit breaker may already be acceptable.

For vacuum circuit breakers, and since presently they are used almost exclusively at system voltages in the range of 15 kV to 38 kV, the minimum rate of change of the gap withstand does not present any problem. The minimum rate of gap dielectric may be assumed to be in the neighborhood of 30 kV per millisecond, while the maximum rate of change of voltage for a 38 kV ungrounded bank is 17.5 kV per millisecond.

The precise points where the contacts of each pole must close depend upon the system connections. When the capacitors and the system neutrals are grounded then the optimum point to close the contacts is each pole independently at the voltage zero of the corresponding phase.

When the capacitors are connected in an ungrounded system it is possible to close the first pole at random, since there will be no current flow with only one pole closed. The second pole and the third pole must then close at their respective voltage zero. Another alternative would be to close two poles simultaneously at a voltage zero and then close the third pole at its corresponding voltage zero.

When we speak of voltage zero what is meant is that the voltage difference across the contacts of the circuit breaker is zero. Because of the possibility of trapped charges in a capacitor it would then be necessary to monitor the ac voltage from the source side as well as the dc voltage in the capacitor at the load side of the circuit breaker.

11.1.3.2 De-Energizing a Capacitor Bank

Capacitive currents generally require very short arcing times which means that the actual contact gap is very short and in some cases, when the magnitude of the recovery voltage exceeds the dielectric capability of this small gap, it leads to restrikes.

It was indicated earlier that typical minimum arcing times for capacitance switching with SF_6 circuit breakers is about 2.5 milliseconds and 1.5 millisecond for vacuum interrupters. Since it is not indispensable that the opening of the contacts coincides with the minimum arcing time but rather that it should be longer than that which is considered minimum, a satisfactory choice would be to part the contacts at a point that is at least 4 milliseconds prior to the current zero. Consequently the controls for this type of application need not be that sophisticated. Again all that is needed is that the contacts separate sufficiently ahead of the current zero.

As it was said before, with the advent of the new technologies of high voltage circuit breakers there is basically no need for synchronous opening of the capacitor banks and that this mode of operation should only be considered in very special occasions when it is known that there is a real possibility of restriking.

11.1.4 Synchronous Reactor Switching

For reactor switching operations the basic needs are the opposite of those considered to be desirable for capacitance switching, that is closing the circuit is not as important as is opening.

11.1.4.1 Closing Control

Typically, most high voltage circuit breakers will experience a pre-strike during a closing operation and as a result of this pre-strike an overvoltage that generally is less than 1.5 per unit will be developed.

Since this overvoltage, by no means, should be considered to be excessive there is no pressing need to control its magnitude and consequently a controlled, or synchronized, closing from the point of view of switching overvoltages is considered to be unnecessary. Furthermore if the closing is synchronized with a voltage zero condition this would result in a high asymmetric current which may develop excessive mechanical stresses within the turns of the reactor being switched on.

Additionally, if in a grounded circuit the closing of the contacts takes place at a voltage zero it is possible that an excessive zero-sequence current may flow thus raising the possibility of the zero-sequence relays being activated. Consequently if synchronous closing were to be considered, it would be preferable to close the contacts at maximum voltage.

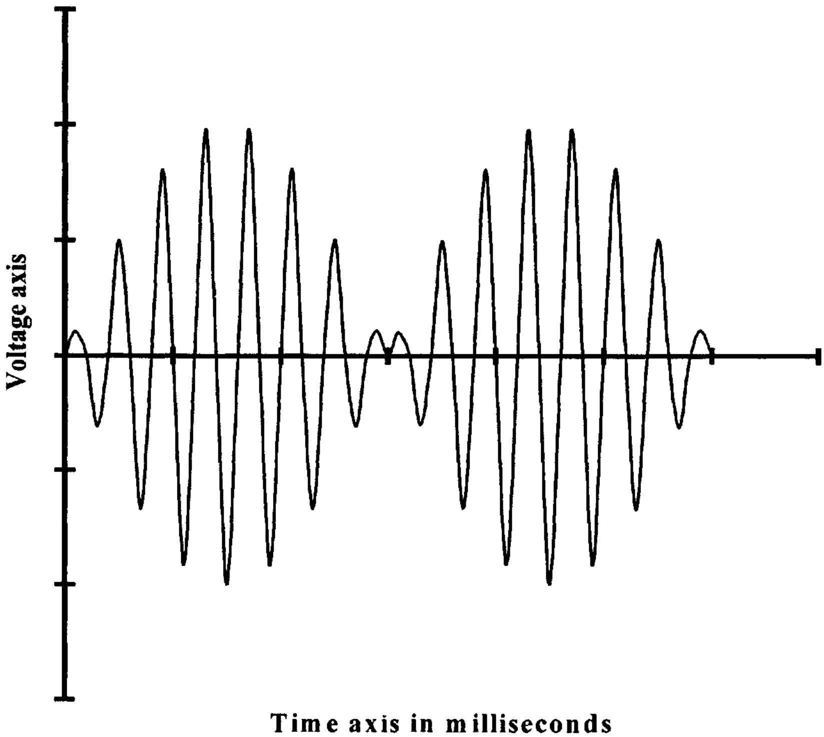


Figure 11.5 Representation of voltage appearing across the circuit breaker contacts when reclosing into a shunt compensated line.

This makes the task relatively easy since there is a natural tendency for the contacts to do just that, plus the fact that near the peak of the voltage its rate of change is basically zero and therefore there is room for a larger tolerance in the allowable variation of the closing time.

One simple way to accomplish controlled close would be to reduce the closing speed of the contacts so that the rate of change of the gap withstand becomes significantly lower than the maximum rate of change of the system voltage.

A unique condition that is worth mentioning because of the significant benefits that can be attained from synchronous closing is when rapid reclosing of a shunt reactor compensated line is required. Reclosing implies that current interruption has just taken place and since it follows interruption a trapped charge may be left on the unloaded line. In this case the voltage across the circuit breaker will show a significant beat, as illustrated in Figure 11.5, due to the frequency difference between the line and the load sides. At the source side of the circuit breaker the voltage oscillates with the power frequency while at the load side the frequency of the oscillation may be as low as one-half that of the power system frequency (60 Hz) or as high as to approach the power frequency. It only depends upon the degree of compensation; the higher the compensation, the lower the frequency.

Since synchronization should be made at a beat minimum, where the voltage across the contacts is relatively small, it is evident that the degree of complexity for detecting this zero voltage condition across the contacts has greatly increased, thus making this task extremely difficult. This is further complicated by the fact that the variable beat frequency creates a high degree of uncertainty for predicting the voltage zero across the circuit breaker contacts.

11.1.4.2 Opening Control

Synchronized opening of the contacts in an application involving the switching of reactors should be considered for the purpose of reducing overvoltages that may be generated as the result of current chopping or reignitions that may occur during a normal opening operation. One benefit of synchronous opening of reactor circuits, especially those that use reactors for shunt compensation, is that it substantially reduces switching surge overvoltages.

Synchronous control for opening reactor circuits is not difficult to achieve since it is only necessary to separate the contacts at a time which is larger than the minimum arcing time required for that operation by that particular circuit breaker design. What is important is that the contact gap be sufficient to withstand the recovery voltage and that the contact separation be close enough to the minimum arcing time to reduce the possibility of current chopping.

The likelihood of reignitions is greatly reduced by synchronized switching even when the three poles of the circuit breaker are gang operated. If the poles are operated independently of each other and each allows an arcing time of at least 4 milliseconds then any probability of reignitions is virtually eliminated.

It should be noticed that the synchronizing requirements for these types of applications are dependent primarily upon the characteristics of the circuit breaker, rather than the characteristics or the connections, grounded or ungrounded, of the system.

11.1.5 Synchronous Transformer Switching

Basically speaking, the switching of an unloaded transformer is no different than switching a reactor, that is the voltages and currents involved in opening and closing the circuit of the transformer generally have the same characteristics of those produced by the switching of reactors. However, for this application the most critical variable is the transformer's inrush current [8], which on some occasions can reach magnitudes that approach those of the short circuit current.

The magnitude of the inrush current depends on the transformer's impedance, on the magnetic characteristics of the core of the transformer and on the status of its magnetic flux remanence at the instant when the circuit is energized.

The severity of the energizing process is greater for transformers that have a high remanence than for those that are completely demagnetized. It follows then that for full synchronization it is necessary to detect the remanence level prior to the energizing of the transformer, or alternately that all openings of the transformer circuit be made synchronously so that the remanence conditions are controlled and can be well defined for the next closing operation. If remanence is not considered to be a problem then closing may be done satisfactorily at voltage peak with a tolerance of as much as ± 2 milliseconds.

11.1.6 Synchronous Short Circuit Current Switching

Synchronized switching, both opening and closing, of short circuit currents is a desirable feature from the point of view of reducing contact erosion. The reduction of the contact wear directly translates into an extension of the usable operating life of the circuit breaker. However, while the contact life may be extended there is the likelihood that the mechanical life may be reduced as a consequence of the operating speeds normally required for operating consistency and for performing the synchronizing function on itself. Furthermore, the benefits need to be weighed against the possible cost and the complexity of the task.

11.1.6.1 Synchronous Closing

The aim of synchronous closing would be to reduce contact erosion by reducing the arcing time during closing, which is due to pre-strikes across the contacts. The benefits that may be achieved by synchronous closing must be kept into perspective since contact erosion during a closing operation is significantly less than during interruption. Unless the rate of change of the gap dielectric capability is extremely slow the pre-arcing time is bound to be considerably shorter than the interrupting arcing time. Furthermore it should be considered that due to the low instantaneous values of current at closing the energy input will be significantly lower than that which is seen during interruption.

The optimum switching angle for reducing or eliminating prestrikes would be at voltage zero; nevertheless, this may present a problem because the maximum current peak is reached under these conditions due to the maximum asymmetry which is produced when the current flow, in an inductive circuit, is initiated at a voltage zero. As a consequence of the high current peak the electromechanical stresses imposed on the circuit breaker are the highest. This translates into higher output energy requirements for the operating mechanism and in general larger structures for the circuit breaker. An alternate possibility for semi-synchronism would be to choose an optimum switching angle, one which in most cases would be between 30 and 45 electrical degrees.

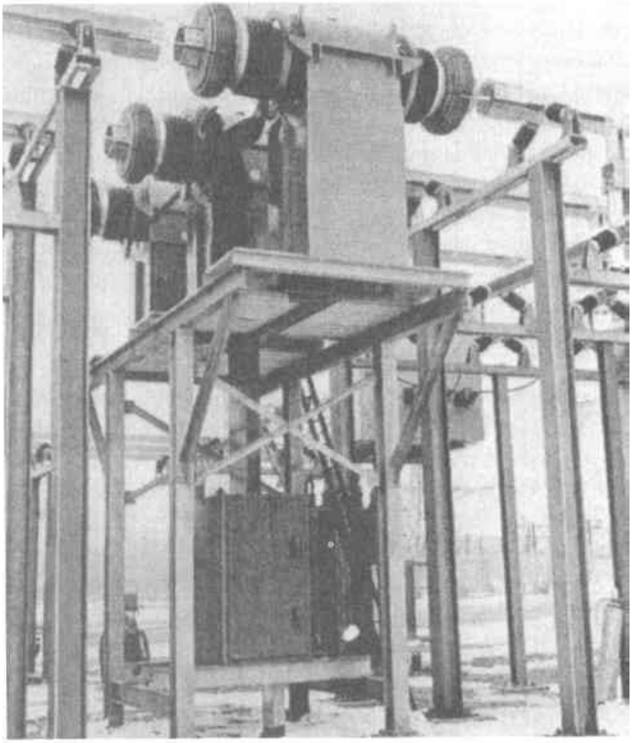


Figure 11.6 ITE synchronous interrupting circuit breaker installed by American Electric Power.

11.1.6.2 Synchronous Interruption

Theoretically a synchronous interrupter is one that changes instantaneously from a perfect conductor to a perfect isolator. This characteristic constitutes a physical impossibility for a mechanical device such as a conventional circuit breaker since a finite gap would have to be developed in essentially zero time.

Nevertheless, it is possible to design a quasi-synchronous interrupter, one that separates its contacts consistently at a predetermined time just ahead of current zero. However, in order to achieve this a high operating contact speed is needed so that a contact gap that is large enough to withstand the transient recovery voltage can be attained during the very short arcing period available. This approach has been successfully demonstrated in a number of experimental devices, for at least the last 30 years. A prototype design of a synchronous circuit breaker was installed and remained in service for over 15 years. A photograph of this prototype circuit breaker is shown in Figure 11.6.

In spite of the work that has been done and the knowledge that has been gained, there are still a number of practical problems associated with this concept. To reduce the mechanical stresses on the interrupter, due to the high operating forces which are required to accelerate the moving contacts, it would be desirable to reduce their mass but these lighter contacts may not be able to carry the rated continuous current. To regain this capability a parallel set of primary contacts may need to be provided, but in doing so the operating scheme of the circuit breaker becomes more complex. If two sets of contacts, each moving at a different speed, were used then a complicated mechanical scheme or two independent operating mechanisms would have to be provided for each pole assembly. A further complication arises, to a lesser extent with puffer SF_6 circuit breakers, but more definitely so with self pressure generating circuit breakers that utilize the arc energy to generate the interrupting pressure, from the fact that by minimizing the arcing time there may not be sufficient energy and stroke for the former and time for the latter to generate the required interrupting pressure.

The primary benefit to be derived from synchronous operation is a reduction in size and a decrease in the erosion of the arcing contacts. A relative comparison of the arc energy input for a non synchronous circuit breaker having a 12-millisecond arcing time and a synchronous interrupter with only a 1-millisecond arcing time is illustrated in Figures 11.7 and 11.8 respectively.

It is unlikely that synchronous interruption will produce a noticeable improvement in the interrupting capacity because as it was shown in Chapter 5 the recovery capability of an SF_6 interrupter is directly related to the rate of change of current at the instant of current interruption rather than to the magnitude of the current peak. With vacuum interrupters however some improvement may be expected because the duration of the coalescent arc mode may be significantly reduced and furthermore, depending upon the total magnitude of the current being interrupted, the arc may remain in its diffuse mode for the full duration of the arcing time period.

For circuit breakers that have a characteristically long arcing time the opening speed tends to reach levels that are considered to be impractical. To get a feel for the opening velocities that are required consider for example a 72 kV circuit breaker where its contacts move at 3 meters per second and the minimum arcing time is 10 milliseconds, thus the minimum contact gap can be assumed as being approximately 30 millimeters. If arcing is to be limited to only 1 millisecond then the required opening speed is 30 meters per second. Considering the mass of the contacts and the linkages involved attaining this speed would be a very difficult task. Since circuit breaker design almost invariably entails compromises, some reduction on the contact erosion may be sacrificed to gain some reduction in the operating speed and the likely mechanical wear. The decision must be based upon sound evaluation of the technical and economic advantages of the concept, taking into consideration the frequency of operations under fault conditions.

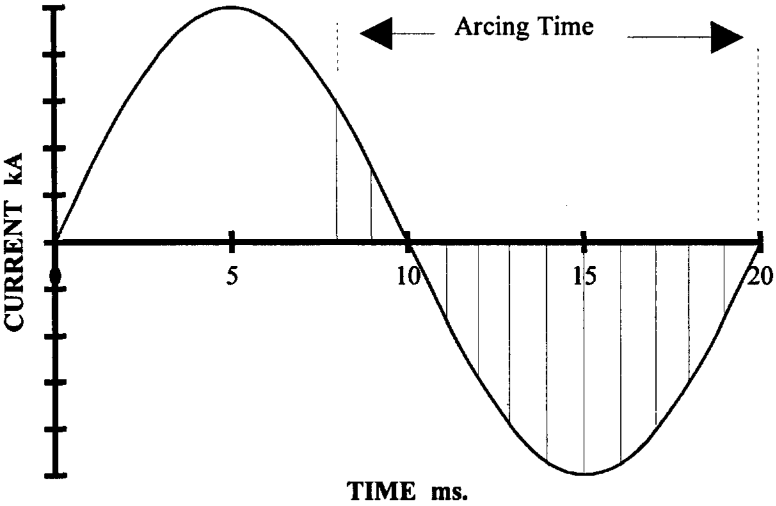


Figure 11.7 Arcing time for non-synchronous interruption.

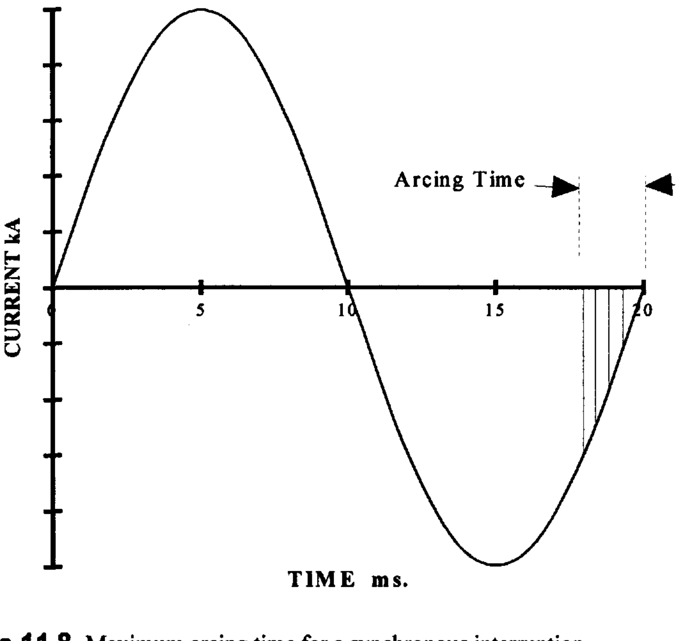


Figure 11.8 Maximum arcing time for a synchronous interruption.

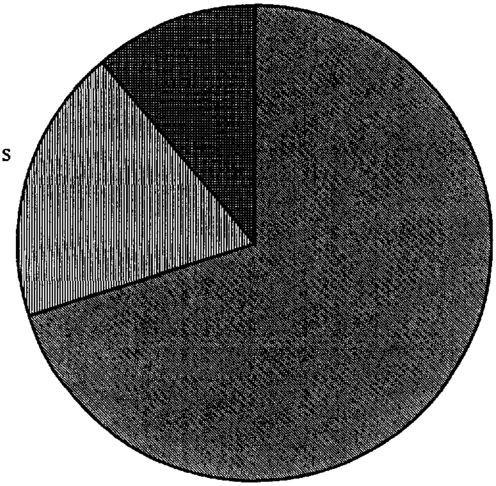


Figure 11.9 Types of circuit breaker failures by major components.

11.2 CONDITION MONITORING OF CIRCUIT BREAKERS

As it has been said before, circuit breakers constitute an important and critical component of the electric system, they are the last line of defense and consequently proper and reliable operation is paramount to the quality of power being delivered, to the promotion of customer satisfaction and most of all to the safety and integrity of the system [9].

To sustain the confidence level on this critical piece of equipment comprehensive maintenance programs have been established. These maintenance programs follow established standard guidelines and the recommendations of the manufacturer, which generally are based on their operating experience. This practice may not only be inefficient but it is also costly because of the down time required to perform these procedures. Additionally, it is not uncommon that problems develop following maintenance of otherwise satisfactorily performing equipment. A more logical approach may be to continually evaluate the condition of those components that through experience have been identified as being the most likely to fail and those whose failure could provoke a severe damage that would disrupt the service.

Historically, most of the circuit breaker failures that have been observed in the field can be attributed to mechanical problems and difficulties related to the auxiliary control circuits. A number of studies, such as those made by CIGRE [10], provide an excellent insight into the failure statistics of the components of a circuit breaker. The report indicates, as shown in Figure 11.9, that 70% of the major failures in circuit breakers are of a mechanical nature, 19% are related to auxiliary and control circuits and 11% can be attributed to electric problems involving the interrupters or the current path of the circuit breaker.

A further breakdown of the problems shows (Figure 11.10) that in the mechanical failure category approximately 16% involve compressors, pumps, motors, etc., 7% involve the energy storage elements, 10% are caused by control components, 7% are originated by actuators, shock absorbers, etc. and 3% result from failures of connecting rods and components of the power train.

In the group of electrical controls and auxiliary circuits, failure to respond to the trip and close commands account for 6% of the problems, 5% are due to faulty operation of auxiliary switches, 6% are caused by contactors, heaters etc. and 9% are attributed to deficiencies of the gas density monitors.

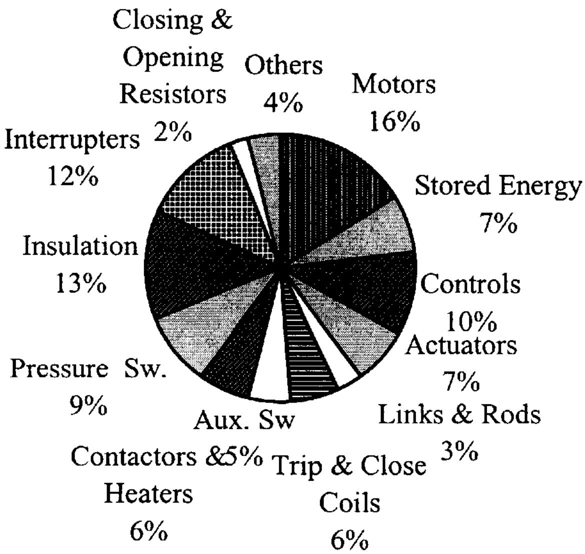


Figure 11.10 Percent of reported failures by components.

For those problems which are judged to be of electrical nature, 13% of them are due to failure of the insulation with respect to ground, 12% are due to the interrupters themselves and 2% are due to auxiliary interrupters or opening resistors or grading capacitors.

The just mentioned statistics can be used as a guideline for the selection of those components that should be monitored. Although the most desirable option would be to develop a system that constantly monitors critical components and which is able to detect any deterioration that may occur over time and to predict, in a proactive way, impending failures of mechanical components. This task, however, has proven to be rather elusive. A number of detection systems have been investigated, including the use of acoustic signatures [11], [12], [13], but at least at this time these systems have not yet been translated into a viable product and they still remain mostly in a laboratory environment. Furthermore its reliability may be questioned primarily because of its complexity and its high sensitivity, which makes it vulnerable to noise and to the influence of extraneous sources. Simpler schemes may provide adequate protection, but naturally a final choice should be based on an evaluation of the benefits against the complexity and the difficulty of implementing the specifically required monitoring function.

The information that is gathered by the monitoring system does not have to be limited exclusively to evaluating the condition of the circuit breaker, but it also may be used to enhance the accuracy of the controls for synchronous operation, if such operating option is available. It is entirely possible to use the data to adjust the initiation of the closing or opening operation so as to compensate for variations in the making or breaking times that are due to the influence of the parameters that are being monitored.

The benefits offered by condition monitoring are not solely restricted to provide information for future use or to develop trends about the well being of the circuit breaker that will be applicable to future planned actions. Monitoring of a number of parameters on a regular basis, as is already being done now, is essential for the immediate proper operation of the circuit breaker. Additional monitored parameters may not directly reflect as an improvement in the operation but taken as a whole will serve to increase the reliability of the equipment.

11.2.1 Choice of Monitored Parameters

There are a significant number of parameters that can be chosen for monitoring. There are as well a variety of methods each having varying degrees of complexity for executing the monitoring function. The optimum system would be one that selects the most basic and important functions and thus minimizes the number of parameters that are to be monitored and yet it maximizes the effectiveness of the evaluation of the system that is being monitored.

In addition to optimizing the number of monitored parameters, the methods used to do the monitoring should be kept as simple and straightforward as possible. It will be desirable, if not essential, from the point of view of availability, cost and operating experience, that commercially available transducers that are used in any related industry should be given preference and used where at all feasible.

It must also be recognized that continuous monitoring of some parameters is not possible and that a proper systematic program for periodic monitoring of essential parameters may have to be implemented.

11.2.2 Mechanical Parameters

The most likely parameters to be monitored because of their significance and the simplicity of the monitoring scheme are given below. The list of likely candidates for monitoring and the possible methods that can be used are given only as a suggestion. Other parameters may be deemed to be as important and therefore they should be added to the list while others may be disregarded. The methodology may vary to suit the conditions of the application. What is important is to be able to have an indication or warning if something is changing in the circuit breaker.

1. charging motors
2. contact travel distance and velocity
3. point of contact separation and contact touch
4. space heaters condition
5. trip coils and close coils
6. mechanism stored energy
7. circuit breaker number of operations
8. ambient temperature

11.2.2.1 Charging Motors

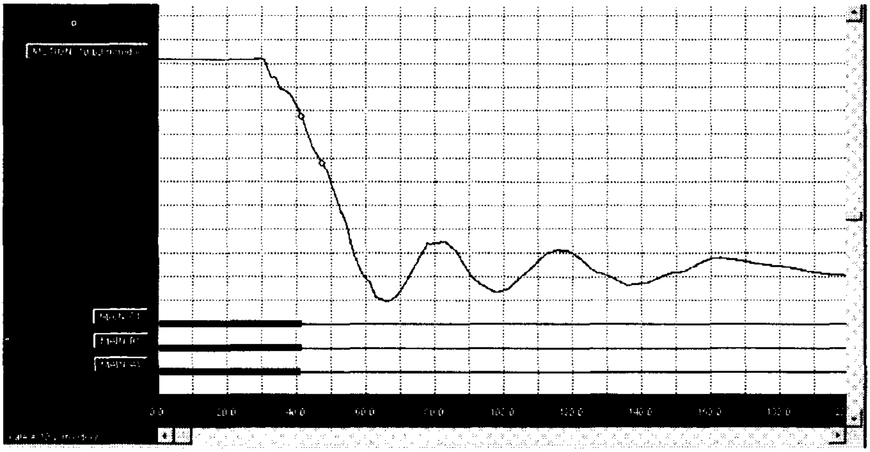
Encompassed under this denomination are all motors that are used for driving a gas compressor, a hydraulic pump, or for compressing a set of operating springs. Monitoring them is important since, from available statistics, motors, compressors and pumps exhibit the biggest share of failures.

A convenient way to monitor the condition of a motor would be to measure the starting and the running currents. These current values can then be used to calculate the torque of the motor. The torque value then may be used to judge the condition of the equipment or components that are being driven by the motor. For example, unusual increases in either the starting or the running torque may indicate added friction, which may be possible indication of deteriorating bearings or galling of the motor shaft. It may also suggest possible seal migration into the shaft.

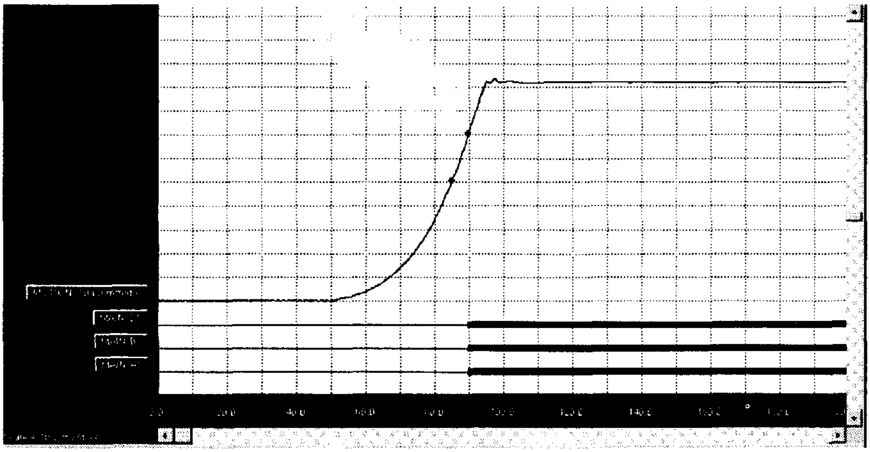
If the running time and the frequency of operation of the motor are compared to baseline data that have been established under standard operating conditions then a noticeable increase in running times may be an indication of possible leaks that may have developed in the pneumatic or hydraulic system.

11.2.2.2 Contact Travel and Velocity

This could easily be considered as the most important function being monitored. It provides dynamic information about the operating components of the circuit breaker as a whole including not only mechanical links but also the interrupter contacts. Typical curves for an opening and a closing operation are shown in Figures 11.11 (a) and (b). The information that can be extracted from these measurements is always extremely valuable for judging the overall status of the circuit breaker and fortunately this is probably one of the simplest and easiest functions to monitor.



(a)



(b)

Figure 11.11 Circuit breaker typical open and close travel curves, (a) open, (b) close.

From the measured travel characteristics and comparing the new data to a baseline signature for an specific circuit breaker it should be possible to infer not only deterioration of linkages, but increased friction that could mean lack of proper lubrication and or deterioration of bearings for example.

For puffer circuit breakers the travel characteristics, when used in conjunction with the magnitude of the short circuit current being interrupted, would serve to indicate the degree of ablation of the interrupter's nozzle.

A possible deviation that may suggest changes in performance and how to interpret these records is illustrated in Figures 11.12 and 11.13.

In 11.12 (a) through (d) the dotted lines represent the variance in the trace. Curve (a) shows that the contact separation occurred sooner than before, this may suggest contact wear in (b). A faster circuit breaker stroke is observed and this may suggest that the stored kinetic energy on the mechanism is above its upper limit; (c) shows that there is no damping at the end of the opening operation, a condition that can be attributed to shock absorber failure, and finally in (d) a reduction in the total travel distance is illustrated which may be caused by binding or stalling of the mechanism or due to insufficient driving stored energy.

In Figure 11.13 the change in velocity during the opening stroke of a SF_6 puffer circuit breaker is shown. To compare these curves it must be assumed that the second curve is recorded under the same operating conditions as those of the first. This is especially important in regards to the magnitude of the fault current that is being interrupted. By comparing the two traces it may be possible to detect a possible enlargement of the nozzle throat. Trace 1 corresponds to the original reference trace where the slow-down or pause period that is due to the clogging action of the nozzle is a little longer. In trace 2 the pause is shorter thus indicating that there may be increased gas flow through the nozzle due to an enlargement of its throat diameter.

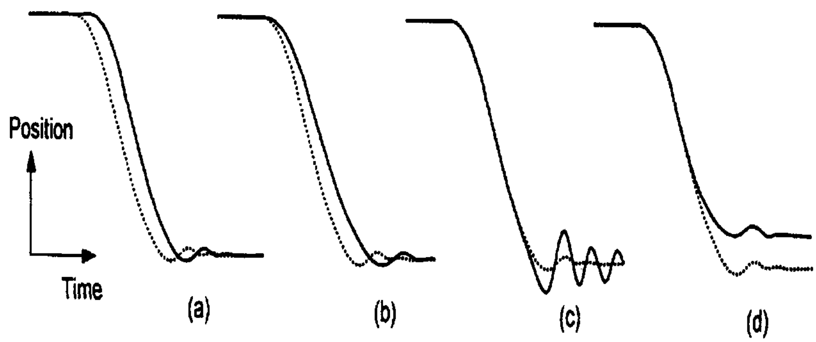


Figure 11.12 Comparison of circuit breaker travel curves.

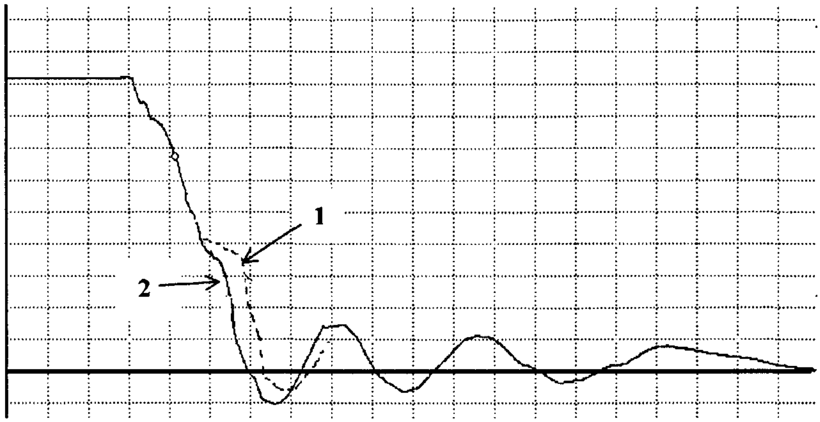


Figure 11.13 Travel curve for a puffer circuit breaker showing possible nozzle ablation: (a) is original base trace, (b) is latest trace being evaluated.

The contact, or circuit breaker, travel measurement can be easily attained by monitoring the displacement or the rotation of the output shaft of the operating mechanism. The closing or opening velocities then can be obtained by finding the derivative with respect to time of the displacement measurement. This mathematical manipulation most likely would be done electronically with the assistance of a central processing unit where all the signals would be collected for evaluation and data storage.

The displacement measurement can be made using either contact or non-contact transducers.

Sliding resistors, linear or rotating resistor potentiometers, step travel recorders, etc. are considered to be contact type transducers because there is an actual, physical connection between the transducer and the component being measured. Non-contact transducers are those such as optical motion sensors, proximity sensors, LTV sensors, etc. that do not require a physical connection between the sensor and the moving part. In all cases it is highly desirable that non-contact transducers be used to minimize errors that may be caused by the inherent inertia of the moving parts of a mechanical contact transducer.

It has been mentioned that it may be possible to compare the monitored instantaneous velocity to a pre-defined velocity for a particular circuit breaker operating under different sets of conditions, such as short circuit interruption, reduced energy from the mechanism, reduced ambient temperatures, etc. The evaluation of this comparison process would then be the criterion that is used to judge the condition of the circuit breaker.

11.2.2.3 Contact Make and Contact Break

Contact break and contact make indications can be obtained either by direct or indirect methods. If a direct indication is desired it can be obtained when the measurement is made under load conditions by monitoring the voltage across the contacts. Additionally for a closing operation the measurement of the initiation of current flow provides an approximate indication of contact touch. The current indication can be used in conjunction with the no load travel measurement to compensate for normal prestriking.

For no load operations, or when indirect measurements are made, the methods that are used to determine contact displacement are applicable. The major drawback of this approach is that it fails to take into account the changes in the making or breaking of the contacts that may occur as a result of possible contact erosion.

11.2.2.4 Mechanism Spring Charge

The function referred to as spring charge is in reality a measurement of the kinetic energy that is stored in the operating mechanism. The measurement can be made by measuring the spring compression, in terms of its change of length, or the gas pressure of pneumatic accumulators used in conjunction with hydraulic mechanisms. The same type of measurements are also applicable for spring or pneumatic mechanisms.

The displacement measurement is made using the same type of instrumentation as that which is used for measuring the travel of the contacts of the circuit breaker. In general it is only necessary to detect the extreme limits of the displacement which corresponds to the limits for the required spring deflection that covers the specified range of operating forces.

11.2.2.5 Operations Counter

This is a seemingly elementary piece of information and yet it is very significant especially on those circuit breakers where the operating characteristics show variations that are related to the accumulated number of operations. This measurement is not something new and in most circuit breakers it has been routinely made if nothing else to keep a tally in order to perform maintenance at the next recommended maintenance interval.

11.2.2.6 Space Heaters

Their function is simple and yet their failure may cause significant problems. Monitoring the integrity of the heater elements is a rather trivial task that can be done by simply circulating continuously a very small current. Another alternative is to use thermostats that are strategically located in close proximity to the heaters, one disadvantage of this method is that heaters are not energized all the time but only when the ambient temperature drops below a certain level and consequently a logic circuit that relates ambient temperature to heater temperature should be provided but still it does not provide continuous monitoring of the continuity of the heater element itself.

11.2.2.7 Trip and Close Coils

Monitoring of these components is a relatively simple task, although caution must be used to prevent the creation of parasitic current paths that could create misoperations and problems with control relays.

In its most simple version the monitoring system would only require either a continuous or an intermittent high frequency signal to determine the electrical continuity of the coils.

Monitoring the current drawn by the coils as they are energized and subsequently comparing their signatures can provide another bit of useful information. In Figure 11.14 and 11.15 the current traces of a trip and a close coil are shown. On both of these traces there are two especially significant reference points. One is the inflection on the current curve of the coil, which shows the instant when the latch is released and the other is the point where the current is cut off by a contact on the auxiliary switch. Changes that may occur in the timing of these points would indicate possible impending problems on the mechanical drive system.

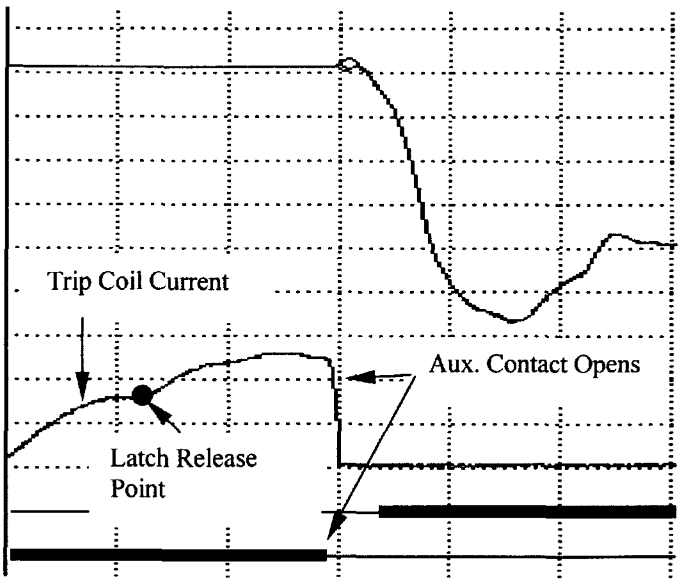


Figure 11.14 Trip coil current, typical curve.

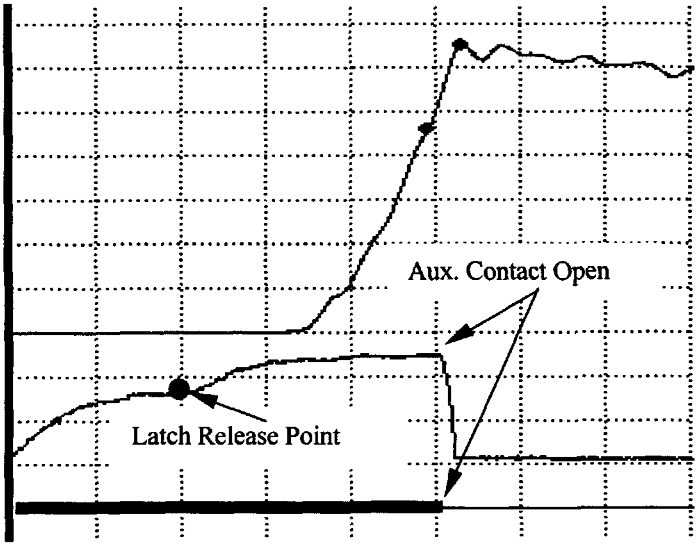


Figure 11.15 Close coil current, typical curve.

11.2.2.8 Ambient Temperature

Monitoring the ambient temperature may also be considered as an elementary or trivial piece of information, but this information is needed to detect deviations from the historical operating characteristics of the circuit breaker under similar conditions to those being monitored. The measurement can also be useful to compensate for variations in the operating time in synchronous switching applications.

11.2.3 Electrical Parameters

Dielectric failures and interrupter failures represent a high percentage of the listed reasons for circuit breaker problems. Although many of these failures would take place without any prior warning, there are some cases where it would be possible to anticipate an impending failure based on some conditions which are generally well known and predictable as is the case with high levels of corona, high leakage currents, high moisture content and low insulating gas density. While some of these parameters can be monitored with only reasonable efforts, there are others which are difficult to monitor while the circuit breaker is energized and in service. What follows is again only a suggested list of significant electrical components that could be monitored.

11.2.3.1 Contact Erosion and Interrupter Wear

Monitoring contact erosion and interrupter wear has a strong, direct influence upon the required maintenance frequency. Therefore, it is not only desirable but beneficial to accurately evaluate the condition of the interrupters rather than to rely on the presently used method of simply adding the interrupted currents until the estimated accumulated duty that is given by applicable standards, or by the manufacturers recommendations, is reached.

Measurements of contact erosion or interrupter wear can not be made directly, but it can be done conveniently by indirect methods using measurements of current and arcing time. The interrupted current can me measured using conventional instrumentation, such as current transformers, which are generally available in circuit breaker as a standard component. The arcing time, depending on the desired degree of sophistication, can be determined by optical detection of the arc, by measurement of the arc voltage, or simply by estimating the point of contact separation using the information given by the contact travel transducer and the duration of current flow from this time until it is interrupted. Figure 11.16 shows a measurement of the arc voltage, from these records the arcing time for each, the arcing contact and the main contact can be obtained.

The product of the current and the elapsed time from contact separation to current extinction gives a parameter to which the interrupter wear can be related. It is assumed that sufficient data have been collected during development tests relating contact erosion and nozzle ablation to ampere-seconds of arcing, and therefore by keeping track of the accumulated ampere seconds an adequate appraisal of the interrupter condition can be made.

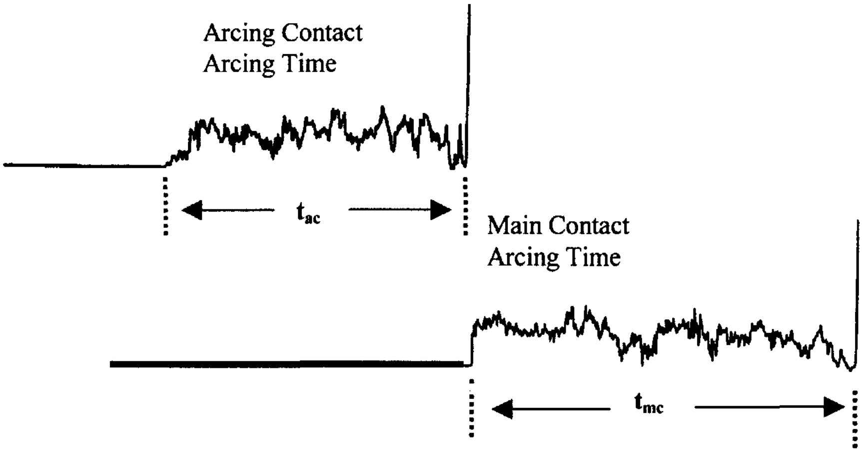


Figure 11.16 Arc voltage across arcing and main contacts.

11.2.3.2 Gas Density

For SF_6 circuit breakers gas density rather than gas pressure is the parameter that should be monitored. To do this, it is possible to use commercially available temperature compensated pressure switches or, alternatively, the density may be determined by electronically processing separate pressure and temperature signals. An algorithm representing the well-known equation-of-state for the gas can be the used to combine these signals. Any deviation from a constant density line will indicate that there is a gas leak in the system and unless a massive catastrophic failure occurs, slow leaks can be alarmed and protective actions can then be implemented. The selection of the corresponding constant density line depends on the initial filling conditions of the circuit breaker.

11.2.3.3 Gas Moisture

Dielectric failures constitute one of the highest percentage modes of failure. A possible cause for these failures is high moisture content in the insulating gas, which may lead to tracking along the surfaces of the insulating materials used in the interrupter assembly. To prevent moisture related problems monitoring the moisture content of the gas should be a high priority.

Checking for moisture content in a gas is an easier task when done during routine maintenance, when the circuit breaker is out of service. In most cases this routine inspection is all that should be needed because it is a standard practice to install inside of the interrupter moisture absorbing materials such as activated alumina. Furthermore, for a circuit breaker which has been properly dried and evacuated prior to filling, there is no reason for any significant amount of moisture to migrate inside of the interrupter unless there is a gas leak and the interrupter is then incorrectly refilled. Nevertheless, if it is desired to monitor the moisture content while the circuit breaker is in service, it is possible to do so using commercially available moisture monitoring instrumentation that can be readily connected to the gas system of any circuit breaker.

11.2.3.4 Partial Discharges

The type and rate of deterioration of insulation and the time required for a breakdown of the insulation depends on the thickness of the insulating material, on its chemical and thermal stability, on the applied stress and on the ambient temperature and humidity. Ultimate failure is usually caused by cumulative heating of the discharges or by tracking across the material surfaces. Although there is no absolute basis for predicting the life of materials in the presence of electrical discharges, it has been demonstrated that insulation just can not be reliably operated above the discharge inception voltage. It is then desirable to detect the onset as well as the magnitude of the discharges.

Measurement of these two characteristics is rather difficult even under carefully controlled conditions, such as in a test laboratory. The problem lies in the low magnitude of the signals involved, since the discharge pulses may be as low as one microvolt [14], [15]. An alternate solution would be to use acoustic or optical detectors. These methods can provide a reasonably accurate indication but mostly only as a qualitative evaluation of the discharges at or near the surface of the insulation.

11.2.3.5 Contact Temperature

The temperature at or near the main contacts can be a good indicator for a number of possible potential problems with the circuit breaker. Large changes in contact temperature may be due to broken contact fingers, excessive burning of the main contacts, material degradation, oxide formation, weak contact springs, or even an improperly or not fully closed circuit breaker.

The temperature of the contacts or the conducting parts can be measured using optical methods, or else it can be approximated by measuring the temperature of the surrounding gas, of the ambient temperature and of the continuous current that is being carried. Knowing the normal temperature rise of the circuit breaker the corresponding temperature at these particular conditions can be calculated. The results then can be compared with what is expected from this circuit breaker based on previously obtained development data.

11.3 MONITORED PARAMETERS SELECTION ANALYSIS

Using as a reference a recent guide on condition monitoring prepared and published by CIGRE [16] the need for the selection of parameters that should be monitored can be quantified. The applied numerical values are 5 for those parameters that are considered to be essential, 3 for those that have a high significance and 1 for the ones with a lower level of importance.

Three main areas of benefit are considered. The first weights the importance of the monitored parameters with respect to the actual on-going operation. The second evaluates the value of the same parameters to detect changes and possible trends in those changes that may affect the future operating reliability of the circuit breaker. In the third category the objective is to evaluate the condition to determine the need for equipment maintenance and to possibly estimate the additional operating life that may left in the circuit breaker.

The ability to do maintenance on an as needed basis is very desirable not only from the economic point of view, eliminating periodic and often unneeded maintenance, but also for reducing outage times and the risk of developing operating problems after completion of the maintenance work. In Table 11.5 a summary of the findings is tabulated and in reality this is similar to the group of essential parameters that was suggested earlier in this chapter.

Table 11.5
Weighed Value of Monitored Parameters

Function Monitored		Normal Operation	Failure Prevention	Life assess-ment	Total	RANK
INSULATION						
SF_6	Density	5	5	1	11	**3**
	Moisture	5	5	3	13	**2**
AIR	Pressure	5	5	1	11	**3**
	Moisture	5	5	3	13	**2**
OIL	Contamination	3	5	3	11	**3**
	Moisture	3	5	5	13	**2**
VAC	Pressure	5	5	5	15	**1**
ALL	Partial disch.	3	5	5	13	**2**
CURRENT CARRYING PATH						
Contact resistance		5	5	5	15	**1**
Contact temperature		5	5	5	15	**1**
Load current		3	3	1	7	**3**
Contact position		5	5	1	11	**2**
Contact force		5	5	5	15	**1**
SWITCHING						
Operating times		5	5	5	15	**1**
Pole discrepancy		5	5	5	15	**1**
Arcing times		3	3	3	9	**3**
Contact speed		5	5	5	15	**1**
Contact position		5	5	1	11	**2**
Contact wear		5	5	5	15	**1**
Mechanical						
Number of operations		3	3	5	11	**2**
Stored energy		5	3	3	11	**2**
Velocity		5	5	5	15	**1**
Starts motors, pumps		3	5	1	9	**3**
Current motor		3	5	1	9	**3**
Controls and Auxiliary Circuits						
Supply voltage		5	3	1	9	**3**
Insulation resistance		5	5	5	15	**1**
Circuit continuity		5	5	1	11	**2**
Coil currents		3	5	3	11	**2**
Auxiliary switch status		5	3	1	9	**3**
Ambient in control box		3	3	3	9	**3**
Heater		5	5	1	11	**2**

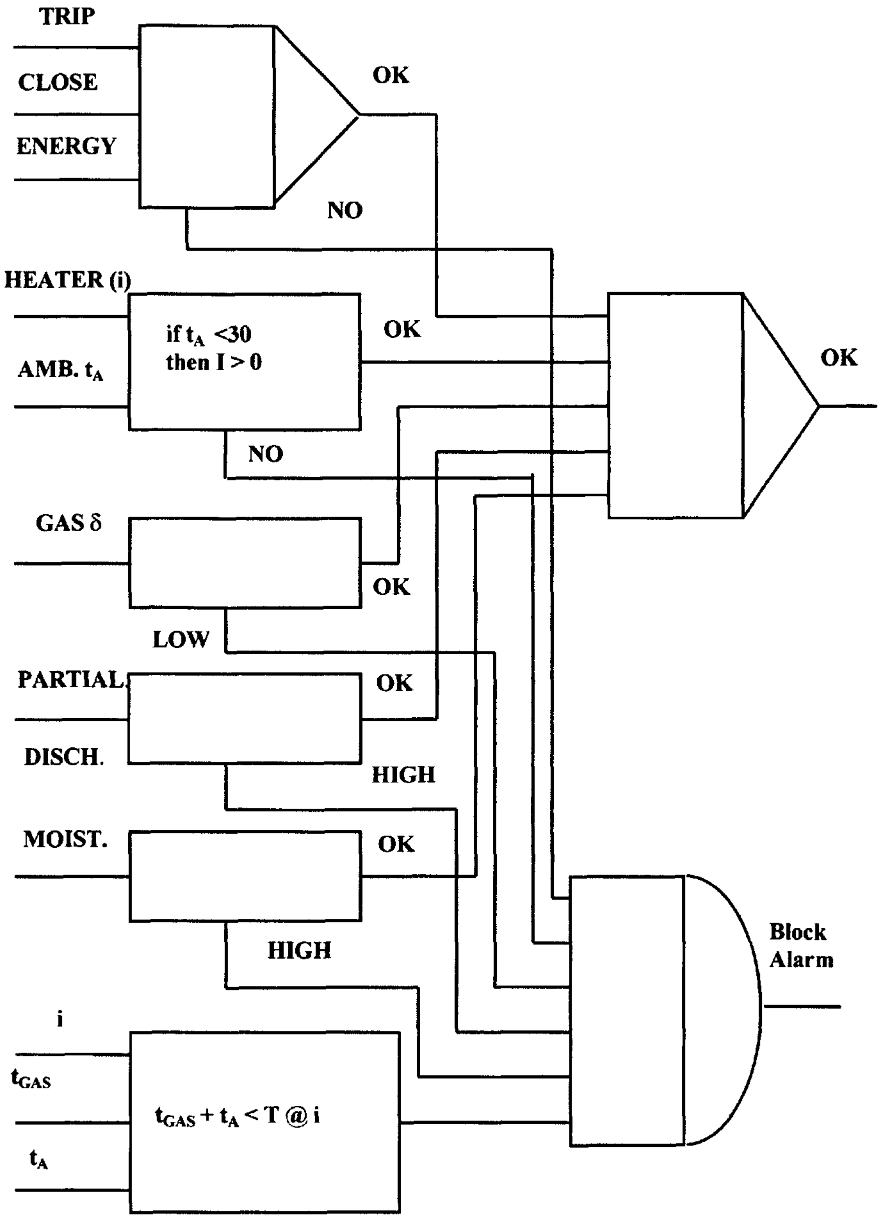


Figure 11.17 Logic diagram for action to be taken based on proactive signals.

11.4 MONITORED SIGNALS MANAGEMENT

Considering the operating conditions under which the monitoring is done and the actions taken as a result of the information being obtained it would be possible to characterize these signals as being proactive or reactive.

Proactive signals would be those which do not depend on the circuit breaker being operated before the condition of certain parameters could be determined. On the other hand reactive signals are those that can only be measured during a dynamic condition such as the opening or closing of the circuit breaker contacts.

Proactive signals truly fulfill the intent of condition monitoring by giving the opportunity to take action either by sending an alarm or by preventing the operation of the circuit breaker when one of the components being monitored has failed.

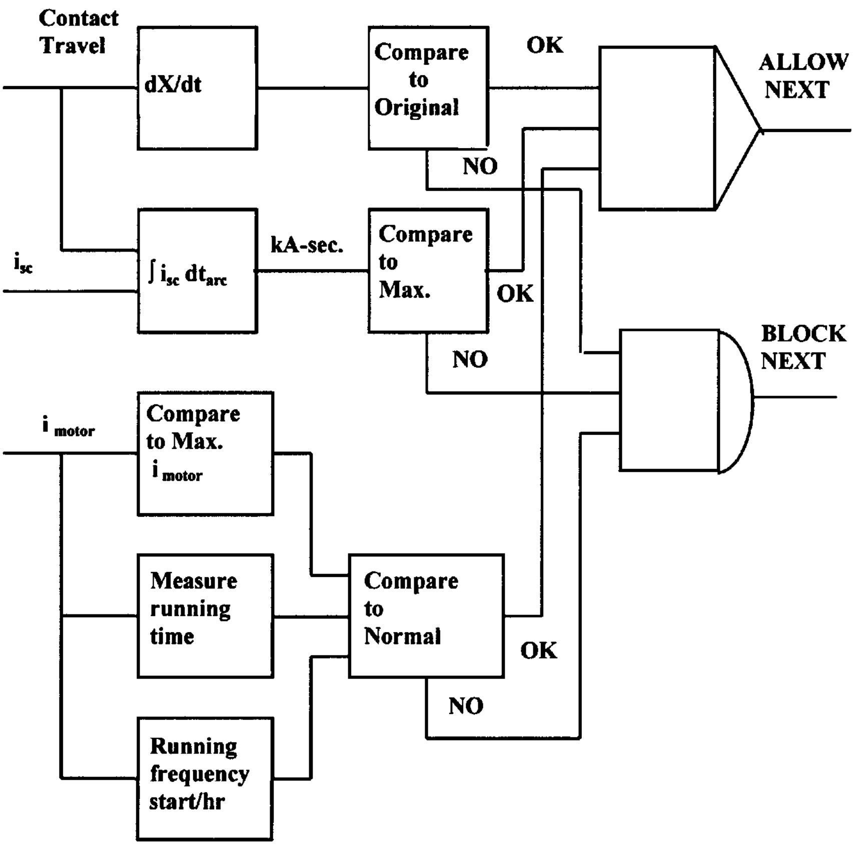


Figure 11.18 Logic diagram for action to be taken based on reactive signals.

One thing that should be avoided is sending information continuously while all the conditions are normal. Decisions should be made at the circuit breaker level as to what action must be taken.

To accomplish this objective it is possible to set up a switching logic scheme such as those shown in Figures 11.17 and 11.18 for the proactive and the reactive signals respectively. In the case of a reactive signal, if deviation from the maximum acceptable limits is observed, the action most likely to be taken would be to send an alarm accompanied by blocking of the next operation.

The actual schemes will vary, depending upon the established local operating philosophies and consequently a number of widely diversified schemes may be found. As the technology further develops it may be possible to use neural networks and fuzzy logic to make more complex decisions once the networks have been properly trained and sufficient operational data are available that justifies the programmed actions.

11.5 COST-BENEFIT ANALYSIS

Justification for implementing a condition monitoring (CM) process has to be an individual decision not only for each user but also for each specific application. It should be based on the needs of the user, the technology of the equipment that is presently in service and on the operating duties of the equipment. But in most cases above all it must justify the benefits that can derived. The need and benefit of condition monitoring programs would be to optimize the life cycle and to increase the dependability of the equipment, and not necessarily in that order.

Some methods for quantifying the benefits have been described in the CIGRE Guide [16] and in an IEEE guide [17] and a Canadian Electricity Association reports [18].

The three methods described in these references are the analytic method, the synthesis method and the resources method.

Basically the first two methods are similar on their approach. The basic difference between them lies in the degree of complexity that is required from the required input data.

The analytic method lists every source of cost and evaluates the possible savings that may be achieved by monitoring. It considers in detail the costs of failures and maintenance during the life span of the circuit breaker. When properly applied this approach will yield the most accurate estimates but it must be emphasized that the accuracy will only be as good as that of the data.

The second method is known as the synthesis approach. This is actually only a simplified version of the previous method. Instead of using the detail cost for each event only the average for each group of events taken over a long period of time is used.

The last method is undoubtedly the easiest to apply. It is based on an evaluation of significant failure modes, the risk of such failures occurring and the cost benefit that may be obtained by reducing the costs of inspection and of failure repair and maintenance by employing condition monitoring to prevent such failures. The method is predicated upon the assumption that data obtained from failure mode analysis and risk assessment studies are available.

Consideration is also given to the potential consequences of failure and a weight factor is assigned to each severity level.

According to the IEEE guide [17] and the Canadian report [18] calculations to arrive to a Cost of Failure (CF) per component per year can be made using the following definitions, parameter nomenclature and relationships.

Table 11.6
Parameter Nomenclature

Parameter	Minor Failure	Major Failure	Explosive Failure
Rate of failure (failure / year)	mfr	MFR	EFR
Repair cost (cost / failure)	cr	CR	ECR
Repair time (hours / failure)	rf	RF	RE
Planned outage cost (cost / hour)	co	CO	ECO

$$\text{CF (\$/component/year)} = \text{MFR} \times \text{CR} + \text{mfr} \times \text{cr} + \text{EFR} \times \text{ECR} + \text{MFR} \times \text{CO} \times \text{RF} + \text{mfr} \times \text{co} \times \text{rf} + \text{EFR} \times \text{ECO} \times \text{RE}$$

The total cost of failures (TCF) for a particular type of circuit breaker can be expressed as:

$$\text{TCF (\$/year)} = \text{CF} \times (\text{\# of components of a given type})$$

In the CIGRE report [16] the calculating procedure is slightly modified and the following new parameters are introduced

UOC = Unplanned outage cost (cost / failure)
Pd = Probability of detecting an impending failure

Pc = Percentage of cost still needed to repair an impending failure

An efficiency value is established and is defined as:

$$E = Pd \times (1\text{-}Pc)$$

Next the values for each failure type with and without condition monitoring are calculated individually and then the final benefit is established by comparing the sums of the two conditions.

Minor failures without CM

$$m1 = mfr \times (cr + rf \times co)$$

Minor failures with CM

$$m2 = mfr \times (cr + rf \times co)$$

Observing the results for the minor failure comparison it is evident that early detection in this instance has no beneficial effects since a minor failure is considered to be one that does not alter the fundamental protective functions of the circuit breaker.

Major failures without CM

$$M1 = MFR \times (CR + RF \times UOC)$$

Major failures with CM

$$M2 = Pd \times MFR \times (Pc \times CR + Pc \times RF \times CO) + (1 - Pd) \times MFR \times (CR + RF \times UCO)$$

Explosive failures without CM

$$E1 = EFR \times (ECR + RE \times UOC)$$

Explosive failures with CM

$$E2 = Pd \times EFR\ (Pc \times ECR + Pc \times RE \times ECO) + (1 - Pd) \times EFR \times (ECR + RE \times UOC)$$

The final benefit value is equal to:

$$B = (m1 + M1 + E1) - (m2 + M2 + E2)$$

$$B = Pd \times MFR\ [(1\text{-}Pc)\ CR + RF \times (UOC - Pc \times RF \times CO)] + Pd \times EFR\ [(ECR - Pc \times CR) + (ERT \times UOC - Pc \times RF \times ECO)]$$

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APPENDIX: CONVERSION TABLES

TABLE I

CONVERSION TABLE FOR UNITS OF PRESSURE

	Pascal (Pa) N/m^2	**bar 0.1 MPa**	**psi lbs/in^2**	**atmospheres kg_{force}/cm^2**	**Torr 1/760 atm**
1 Pa	1	10^{-5}	$1.45x10^{-4}$	$10.2x10^{-6}$	$7.5x10^{-3}$
1 bar	10^5	1	14.5	1.02	750
1 psi	6895	$68.96x10^{-3}$	1	$70.27x10^{-3}$	51.7
1 atm	98100	0.981	14.23	1	736
1 Torr	133	$1.33x10^{-3}$	$19.34x10^{-3}$	$1.36x10^{-3}$	1

TABLE II

CONVERSION TABLE FOR UNITS OF
WORK ENERGY AND QUANTITY OF HEAT

	joule (1.m=1Ws)	**kWh**	**kcal**	**ft-lb**
1 joule	1	0.278×10^{-6}	0.239×10^{-3}	0.7376
1 kWh	3.6×10^{6}	1	860	0.3672×10^{6}
1 kcal	4187	1.1628×10^{-3}	1	427
1 ft-lb	1.3558	0.3766×10^{-6}	0.3238×10^{-3}	0.1383

TABLE III

CONVERSION TABLE FOR UNITS OF VOLUME

	cu. in.	cu. ft	gallon	liter	cu. cm
1 cu. in.	1	5.79×10^{-4}	4.33×10^{-3}	16.39×10^{-3}	16.39
1 cu. ft	1728	1	7.48	28.32	28.32×10^{3}
1 gallon	231	.134	1	3.79	3.79×10^{3}
1 liter	61	35.3×10^{-3}	264×10^{-3}	1	1×10^{3}
1 cu cm	.061	35.3×10^{-6}	264×10^{-6}	1×10^{-3}	1

TABLE IV

CONVERSION TABLE FOR UNITS OF DENSITY

	lb/cu. ft	**lb/gallon**	**g/cu. cm**	**kg/cu. m**
1 lb/cu.ft	1	.1337	.0160	16.02
1 lb/gallon	7.479	1	.1197	119.8
1 g/cu. cm	62.43	8.347	1	1000
1 kg/cu. m	.06243	8.347×10^{-3}	1×10^{-3}	1

TABLE V

CONVERSION TABLE FOR UNITS OF THERMAL CONDUCTIVITY

	Btu/ft hr °R	cal/cm sec °K	joule/cm sec °K	watt/cm °K	watt/m °K
Btu/ft hr °R	1	4.134×10^{-3}	.0173	.0173	1.73
cal/cm sec °K	241.9	1	4.18	4.18	418.49
joule/cm sec °K	57.8	238.9×10^{-3}	1	1	100
watt/cm °K	57.8	238.9×10^{-3}	1	1	100
watt/m °K	.578	2.389×10^{-3}	.01	.01	1

TABLE VI

COMMON PREFIXES AND SYMBOLS FOR
MULTIPLES AND SUB-MULTIPLES OF 10

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{18}	exa	E	10^{-1}	deci	d
10^{15}	peta	P	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	mili	m
10^{9}	giga	G	10^{-6}	micro	μ
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10^{1}	deca	da	10^{-18}	atto	a

Appendix 1

A Quiz on Boilers and HRSGs

[*The answers to all of these questions can be found in the book. However, email me for the list of answers or clarifications if required. My email is*: v_ganapathy@yahoo.com.]

1. If boiler efficiency for a typical natural gas fired boiler is 83% on higher heating value basis, what is it approximately on lower heating value basis?
   a. 73% b. 83% c. 92%
2. If NOx in a natural gas fired boiler is 50 ppmv (3% oxygen dry), what is it in lb/MM Btu (HHV) basis?
   a. 0.06 b. 0.10 c. 0.20
3. 1 in. WC of additional gas pressure drop in a 100,000 lb/h packaged boiler is worth about how many kW of fan power consumption?
   a. 5 b. 20 c. 50
4. If boiler water concentration in a boiler drum is 1000 ppm and steam purity is 1 ppm, what is the percent steam quality?
   a. 99.9 b. 99 c. 99.99
5. Boilers of the same capacity are located at different sites, whose ambient conditions and elevation are as follows. Which case requires the biggest fan?
   a. 80°F and sea level b. 100°F and 3000 ft c. 10°F and 7000 ft

6. In a boiler plant if the conductivity of the condensate, makeup, and feedwater are 800, 40, and 150 μmho/cm, respectively, what is the percent condensate returns in the feedwater?
a. 5 b. 50 c. 15
7. A 20°F change in exit gas temperature of an oil-fired boiler changes boiler efficiency by approximately what percent?
a. 1 b. 0.5 c. 2.0
8. Approximate air flow (acfm) required in a packaged boiler firing 100 MM Btu/h (HHV) of natural gas is:
a. 19,000 b. 30,000 c.12,000
9. The steam pressure drop in a boiler superheater is 50 psi when generating 600 psig, 650°F steam. What is it likely to be at 400 psig, 600°F with the same flow?
a. 70 b. 30 c. 50
10. Which is the worst case scenario for an economizer from the viewpoint of sulfuric acid condensation? Assume that the oil-fired boiler flue gas contains 12% water vapor and 0.03% SO_2.
a. Flue gas at 680°F and feedwater at 200°F b. Flue gas at 320°F and feedwater at 275°F.
11. If vol% of oxygen (dry) in a natural gas fired boiler is 2.0%, what is the excess air used?
a. 15 b. 5 c. 10
12. If boiler casing heat loss is 0.2% at 100% load, what is it at 25% load, assuming that wind velocity and ambient temperature are unchanged?
a. 1.0 b. 2.0 c. 0.8
13. Plant management decides to change the tube inner diameter of an existing superheater from 1.7 in. to 1.5 in. The steam-side pressure drop for the same steam conditions will go up by what percent?
a. 87 b. 65 c. 29
14. The heat transfer coefficient in a finned tube bundle is higher than in a bare tube exchanger for the same gas velocity, temperature, tube size, and geometry.
a. True b. False
15. In a fire tube waste heat boiler, a small diameter tube has a higher tube side heat transfer coefficient and higher heat flux than a larger tube for the same gas velocity.
a. True b. False
16. Superheated steam temperature from a boiler firing oil will be higher than when firing natural gas at the same steam generation rate (assuming steam temperature is uncontrolled).
a. True b. False
17. More flue gas is generated in a boiler while firing oil than while firing

natural gas at the same excess air and steam generation.

a. True b. False

18. The maximum possible fuel (natural gas/distillate oil) that can be fired in an HRSG with exhaust gas flow = 200,000 lb/h and 14% oxygen wet in MM Btu/h (LHV) is:

a. 100 b. 150 c. 50

19. Surface area gives a good indication of whether a boiler or HRSG design is adequate or not.

a. True b. False

20. An uncooled soot blower lance is located in a boiler convection bank at 1700°F gas temperature. Its temperature will be:

a. > 1700°F b. 1700°F c. < 1700°F

21. (a) A fire tube waste heat boiler using small diameter tubes will be longer than the design using larger diameter tubes for the same duty and gas pressure drop.

a. True b. False

(b) A fire tube waste heat boiler using small diameter tubes requires less surface area than the design using larger diameter tubes for the same duty and gas pressure drop.

a. True b. False

22. For the same mass flow and gas temperature drop, a flue gas containing 16% water vapor will transfer more energy than a gas stream having 5% water vapor.

a. True b. False

23. Design of tubular air heaters in steam generators can be improved if finned tubes are used instead of plain tubes.

a. True b. False c. Depends on fuel used

24. In a crossflow heat transfer situation, an in-line arrangement of plain tubes is better than a staggered one.

a. True b. False

25. For the same casing insulation thickness and ambient conditions, aluminium casing will run hotter than carbon steel.

a. True b. False

26. If additional steam is required in a cogeneration plant, supplementary firing the HRSG rather than using a packaged boiler will be more prudent.

a. True b. False

27. Required thickness of a boiler tube subjected to external pressure will be less than when the same tube is subjected to the same internal pressure at the same temperature.

a. True b. False

28. Which is a better choice for fin density for a superheater in a HRSG?

a. 5 fins/in. b. 2 fins/in.

29. The exit gas temperature in a single-pressure unfired HRSG generating steam at 600 psig, 700°F can be less than 300°F. (Assume exhaust gas at 950°F and feedwater at 230°F.)
a. True b. False
30. A boiler designed for 1000 psig, 800°F steam can be operated at the same steam flow at 300 psig without modifications.
a. True b. False
31. A gas turbine HRSG economizer is likely to steam at which ambient temperature in unfired mode?
a. 40°F b. 90°F
32. More energy can be transferred to a boiler evaporator if the circulation ratio is higher.
a. True b. False
33. Heat flux will be higher in a packaged boiler furnace for which fuel? Assume same steam generation.
a. Fuel oil b. Natural gas
34. For the same excess air and exit gas temperature, an oil-fired boiler will have a higher efficiency on HHV basis than a gas-fired boiler.
a. True b. False
35. For the same mass flow per tube and length of tube, superheated steam at 600 psig, 800°F will have a higher pressure drop than 150 psig saturated steam.
a. True b. False
36. Gas-side fouling increases the tube wall temperature in a waste heat boiler.
a. True b. False c. Depends on whether it is a fire tube or water tube boiler
37. The feed pump requires more power to generate a given amount of steam at a given pressure and temperature in a once-through HRSG than in a natural circulation HRSG.
a. True b. False
38. The volumetric heat release rate is more important in a gas-fired packaged boiler than the area heat release rate.
a. True b. False
39. Large margins on flow and head should not generally be used while selecting the fan for a packaged boiler.
a. True b. False
40. If an economizer with counterflow arrangement is experiencing low temperature corrosion problems, then re-piping it with a parallel flow arrangement can fix the problem.
a. True b. False
41. Exit gas temperature from a single-pressure HRSG having a superheater, evaporator, and economizer increases as steam generation increases.
a. True b. False

42. It is better to preheat condensate or feedwater using extraction steam from the steam turbine rather than use the energy in the HRSG exhaust gases.
a. True b. False
43. Steam for deaeration should preferably be taken from the boiler outlet rather than from an extraction point in the steam turbine.
a. True b. False
44. The maldistribution of steam flow through superheater tubes will be the worst at a boiler load of:
a. 20% b. 50% c. 100%
45. Which fuel generates the maximum amount of carbon dioxide per MM Btu fired?
a. Oil b. Natural gas c. Coal
46. Is it possible to predict the off-design performance of an HRSG without knowing its mechanical constructional features?
a. Yes b. No
47. Can we have more surface area in an HRSG and yet transfer less duty?
a. Yes b. No
48. Can we use finned tubes for the evaporator or superheater of a gas-fired packaged boiler?
a. Yes b. No
49. What happens to the pinch and approach points of the evaporator in an HRSG as we increase the supplementary firing rate?
a. Both increase b. Both decrease c. Pinch point increases while approach point decreases d. They are unchanged
50. In a packaged boiler, the furnace performance and circulation are more critical in oil firing than in gas firing.
a. True b. False
51. Can a superheater be located between the evaporator and economizer in a packaged boiler?
a. Yes b. No
52. Good steam-separating devices cannot prevent carryover of silica from boiler water into steam at high pressures.
a. True b. False
53. Superheated steam for use in turbines should have better steam purity than saturated steam.
a. True b. False
54. Feedwater used for attemperation in a desuperheater for steam temperature control should preferably have low to zero solids.
a. True b. False
55. Tube-side heat flux will be higher in a plain tube evaporator than in a finned tube evaporator for the same gas- and steam-side conditions.
a. True b. False

56. In a waste heat boiler containing hydrogen chloride gas, a low steam temperature (say 700°F vs 850°F) is preferred.
    a. True b. False
57. A higher steam pressure requires a higher steam temperature to minimize wetness in steam after expansion in a steam turbine.
    a. True b. False
58. An ammonia–water mixture has a varying boiling point and hence is a better fluid for energy recovery from waste flue gases than steam.
    a. True b. False
59. The cross section of a 100,000 lb/h packaged boiler will be much smaller than that of an unfired gas turbine HRSG generating the same amount of steam.
    a. True b. False
60. Gas conditions being the same, as steam pressure increases, the steam generation in an unfired HRSG:
    a. increases b. decreases c. is unchanged
61. The cross section of a forced circulation HRSG and its surface area will be much different from a natural circulation HRSG for the same duty and pressure drop.
    a. True b. False c. Can't say
62. A fire tube waste heat boiler generally responds faster to load changes than an equivalent water tube design.
    a. True b. False
63. The amount of deaeration steam is impacted by the conductivity of boiler feedwater.
    a. True b. False
64. In a boiler or HRSG evaporator, the allowable steam quality to avoid DNB conditions decreases as the heat flux increases.
    a. True b. False
65. A natural circulation HRSG using vertical evaporator tubes can handle higher heat flux than a forced circulation or once-through unit using horizontal tubes.
    a. True b. False
66. A gas turbine plant has two options: a supplementary-fired HRSG and an unfired HRSG. The cross section of the supplementary-fired HRSG generating twice the amount of steam as the unfired HRSG should be much larger.
    a. True b. False

Think About It!

1. Why is multiple pressure steam generation often required in HRSGs but not in a packaged boiler?

2. Explain how surface areas can be different in steam generators (or HRSGs) and yet the duty transferred is the same.
3. Why is supplementary firing very efficient in HRSGs?
4. Why is an economizer preferred to an air heater in oil- and gas-fired packaged boilers? Give at least two reasons.
5. Why is steaming in the economizer often a concern in HRSGs and not in packaged boilers?
6. Why can we achieve a low exit gas temperature in a packaged boiler at any steam pressure, whereas it is difficult in a single-pressure unfired HRSG?
7. Why is the superheated steam temperature generally lower with oil firing than with gas firing in a packaged boiler?
8. Why is a low fin density, say 2 fins/in., preferred in a HRSG superheater over, say, 5 fins/in.?
9. Why does raising the gas temperature at the economizer alone not help minimize low temperature corrosion problems?
10. Compute typical operating costs of fuel and electricity for various boilers and HRSGs in your plant and suggest how to lower these costs.
11. Is a supplementary-fired HRSG a better choice than an unfired HRSG in a combined cycle plant?
12. Why do we not worry about pinch and approach points in a packaged boiler, whereas they are very important in an HRSG?
13. What are the advantages of a convective superheater in a packaged boiler over a radiant design?
14. What are the various factors to be considered while modifying an existing packaged boiler to meet lower emissions of NOx and CO?
15. In a packaged boiler, why is interstage attemperation for steam temperature control generally preferred to attemperation at the superheater exit?
16. A single-pressure unfired HRSG generates 600 psig steam at 750°F using 230°F feedwater with an exit gas temperature of 380°F. To lower the exit gas temperature, is it more prudent to add a condensate heater rather than increase the surface area of the evaporator significantly?
17. Explain why rules of thumb relating surface areas with steam generation can be misleading.
18. An economizer has been removed from a packaged boiler for maintenance. Can the plant generate the same amount of steam as before? What are the concerns?

Appendix 2

Conversion Factors

Metric to American, Metric to Metric	American to Metric, American to American
AREA	
1 mm^2 = 0.00155 $in.^2$ = 0.00001076 ft^2	1 $in.^2$ = 645.2 mm^2 = 6.452 cm^2 = 0.0006452 m^2
1 cm^2 = 0.155 $in.^2$ = 0.001076 ft^2	1 ft^2 = 92,903 mm^2 = 929.03 cm^2 = 0.0929 m^2
1 m^2 = 1550 $in.^2$ = 10.76 ft^2	1 acre = 43,560 ft^2
	1 circular mil = 0.7854 square mil = 5.067×10^{-10} m^2 = 7.854×10^{-6} $in.^2$
DENSITY and SPECIFIC GRAVITY	
1 g/cm^3 = 0.03613 $lb/in.^3$ = 62.43 lb/ft^3 = 1000 kg/m^3 = 1 kg/liter = 62.43 lb/ft^3 = 8.345 lb/U.S. gal	1 $lb/in.^3$ = 27.68 g/cm^3 = 27,680 kg/m^3
1 $\mu g/m^3$ = 136 $grains/ft^3$ (for particulate pollution)	1 lb/ft^3 = 0.0160 g/cm^3 = 16.02 kg/m^3 = 0.0160 kg/liter
1 kg/m^3 = 0.06243 lb/ft^3	Specific gravity relative to water: SGW of 1.00 = 62.43 lb/ft^3 at 4°C or 39.2 °F[†]
	Specific gravity relative to dry air: SGA of 1.00 = 0.0765 lb/ft^3[‡] = 1.225 kg/m^3
	1 lb/U.S. gal = 7.481 lb/ft^3 = 0.1198 kg/liter
	1 g/ft^3 = 35.3×10^6 $\mu g/m^3$
	1 lb/1000 ft^3 = 16×10^6 $\mu g/m^3$

[†]62.35 lb/ft^3 at 60°F, 15.6°C; 8.335 lb/U.S. gal.
[‡]0.0763 lb/ft^3 for moist air.

Metric to American, Metric to Metric	American to Metric, American to American

ENERGY, HEAT, and WORK

1 cal = 0.003968 Btu
1 kcal = 3.968 Btu = 1000 cal = 4186 J
= 0.004186 MJ
1 J = 0.000948 Btu = 0.239 cal = 1 W sec
= 1 N m = 10^7 erg = 10^7 dyn cm
1 W h = 660.6 cal

3413 Btu = 1 kWh
1 Btu = 0.2929 Whr
= 252.0 cal = 0.252 kcal
= 778 ft lb
= 1055 J = 0.001055 MJ
1 ft lb = 0.1383 kg m = 1.356 J
1 hp hr = 1.98×10^6 ft lb
1 therm = 1.00×10^5 Btu
1 BHP (boiler horsepower) = 33,475 Btu/hr
= 8439 kcal/hr = 9.81 kW

HEAT CONTENT and SPECIFIC HEAT

1 cal/g = 1.80 Btu/lb = 4187 J/kg
1 cal/cm^3 = 112.4 Btu/ft^3
1 kcal/m^3 = 0.1124 Btu/ft^3 = 4187 J/m^3
1 cal/g °C = 1 Btu/lb °F = 4187 J/kg K

1 Btu/lb = 0.5556 cal/g = 2326 J/kg
1 Btu/ft^3 = 0.00890 cal/cm^3
= 8.899 kcal/m^3 = 0.0373 MJ/m^3
1 Btu/U.S. gal = 0.666 kcal/liter
1 Btu/lb °F = 1 cal/g °C = 4187 J/kg K

HEAT FLOW, POWER

1 N·m/s = 1 W = 1 J/s
= 0.001341 hp = 0.7376 ft lb/sec
1 kcal/h = 1.162 J/s = 1.162 W
= 3.966 Btu/hr
1 kW = 1000 J/s = 3413 Btu/hr
= 1.341 hp

1 hp = 33 000 ft lb/min = 550 ft lb/sec
= 745.7 W = 745.7 J/s
= 641.4 kcal/h
1 Btu/hr = 0.2522 kcal/h
= 0.0003931 hp
= 0.2931 W = 0.2931 J/s

HEAT FLUX and HEAT TRANSFER COEFFICIENT

1 cal/cm^2·s = 3.687 Btu/ft^2 sec
= 41.87 kW/m^2
1 cal/cm^2·h = 1.082 W/ft^2 = 11.65 W/m^2
1 kW/m^2 = 317.2 Btu/ft^2 hr
1 kW/m^2°C = 176.2 Btu/ft^2 hr °F

1 Btu/ft^2 sec = 0.2713 cal/cm^2s
1 Btu/ft^2 hr = 0.003 153 kW/m^2
= 2.713 kcal/m^2 h
1 kW/ft^2 = 924.2 cal/cm^2 h
1 Btu/ft^2 hr °F = 4.89 kcal/m^2 h °C

LENGTH

1 mm = 0.10 cm = 0.03937 in.
= 0.003281 ft
1 m = 100 cm = 1000 mm = 39.37 in.
= 3.281 ft
1 km = 0.6214 mile

1 in. = 25.4 mm = 2.54 cm = 0.0254 m
1 ft = 304.8 mm = 30.48 cm = 0.3048 m
1 mile = 5280 ft
1 μm = 10^{-6} m
1 Angstrom unit = 1 Å = 10^{-10} m

PRESSURE

1 N · m^2 = 0.001 kPa = 1.00 Pa
1 mm H_2O = 0.0098 kPa
1 mm Hg = 0.1333 kPa = 13.60 mm H_2O
= 1 torr = 0.01933 psi
1 kg/cm^2 = 98.07 kPa = 10,000 kg/m^2

1 in. H_2O = 0.2488 kPa = 25.40 mm H_2O
= 1.866 mm Hg
= 0.00254 kg/cm^2 = 2.54 g/cm^2
1 in. Hg = 3.386 kPa = 25.40 mm Hg
= 345.3 mm H_2O = 13.61 in. H_2O

Metric to American, Metric to Metric	American to Metric, American to American
= 10,000 mm H_2O = 394.1 in. H_2O	= 7.858 oz/in.^{2} = 0.491 psi
= 735.6 mm Hg = 28.96 in. Hg	= 25.4 torr
= 227.6 oz/in.^{2} = 14.22 psi	1 psi = 6.895 kPa = 6895 N/m^2
= 0.9807 bar	= 703.1 mm H_2O = 27.71 in. H_2O
1 bar = 100.0 kPa = 1.020 kg/cm^2	= 51.72 mm Hg = 2.036 in. Hg
= 10,200 mm H_2O = 401.9 in. H_2O	= 16.00 oz/in.^{2}
= 750.1 mm Hg = 29.53 in. Hg	= 0.0703 kg/cm^2 = 70.31 g/cm^2
= 232.1 oz/in.^{2} = 14.50 psi	= 0.068 97 bar
= 100,000 N/m^2	1 oz./in.^{2} = 0.4309 kPa
1 g/cm^2 = 0.014 22 psi	= 43.94 mm H_2O = 1.732 in. H_2O
= 0.2276 oz/in.^{2}	= 3.232 mm Hg
= 0.3937 in. H_2O	= 0.004 39 kg/cm^2 = 4.394 g/cm^2
(For rough calculations,	1 atm† = 101.3 kPa = 101,325 N/m^2
1 bar = 1 atm = 1 kg/cm^2	= 10,330 mm H^2O = 407.3 in. H_2O
= 10 m H_2O = 100 kPa)	= 760.0 mm Hg = 29.92 in. Hg
	= 235.1 oz/in.^{2} = 14.70 psi
	= 1.033 kg/cm^2
	= 1.013 bar

TEMPERATURE

°C = 5/9 (°F − 32)
°F = (9/5°C) + 32
K = °C + 273.15
°R = °F + 459.67

THERMAL CONDUCTIVITY

1 W/m K = 0.5778 Btu ft/ft^2 hr °F	1 Btu ft/ft^2 hr °F = 1.730 W/m K
= 6.934 Btu in./ft^2 hr °F	= 1.488 kcal/m h K
1 cal cm/cm^2·s·°C = 241.9 Btu ft/ft^2 hr °F	1 Btu in./ft^2 hr °F = 0.1442 W/m K
= 2903 Btu in./ft^2 hr °F	1 Btu ft/ft^2 hr °F = 0.004139 cal cm/cm^2 s °C
= 418.7 W/m K	1 Btu in./ft^2 hr °F = 0.0003445 cal cm/cm^2 s °C

THERMAL DIFFUSIVITY

1 m^2/s = 38 760 ft^2/hr	1 ft^2/hr = 0.0000258 m^2/s = 0.0929 m^2/h
1 m^2/h = 10.77 ft^2/hr	

VELOCITY

1 cm/s = 0.3937 in./sec = 0.032 81 ft/sec	1 in./sec = 25.4 mm/s = 0.0254 m/s
= 10.00 mm/s = 1.969 ft/min	= 0.0568 mph

†Normal atmosphere = 760 torr (mm Hg at 0°C)—not a "technical atmosphere," which is 736 torr or 1 kg/cm^2. Subtract about 0.5 psi for each 1000 ft above sea level.

Metric to American, Metric to Metric	American to Metric, American to American
VELOCITY (*continued*)	
1 m/s = 39.37 in./sec = 3.281 ft/sec	1 ft/sec = 304.8 mm/s = 0.3048 m/s
= 196.9 ft/min = 2.237 mph	= 0.6818 mph
= 3.600 km/h = 1.944 knot	1 ft/min = 5.08 mm/s = 0.00508 m/s
	= 0.0183 km/h
	1 mph = 0.4470 m/s = 1.609 km/h
	= 1.467 ft/sec
	1 knot = 0.5144 m/s
	1 rpm = 0.1047 radian/sec
VISCOSITY, absolute, μ	
0.1 Pa · s = 1 dyne s/cm^2 = 360 kg/h m	1 lb$_m$/hr · ft = 0.000008634 lb$_f$ sec/ft^2
= 1 poise = 100 centipoise (cP)	= 0.413 cP = 0.000413 Pa · s
= 242.1 lb$_m$/hr ft	1 lb$_f$ sec/ft^2 = 115,800 lb$_m$/hr ft
= 0.002089 lb/$_f$ sec/ft^2	= 47,880 cP
1 kg/h · m = 0.672 lb/hr/ ft = 0.00278 g/s cm	= 47.88 Pa s
= 0.00000581 lb$_f$ sec/ft^2	1 reyn = 1 lb$_f$ sec/in.^{2}
	= 6.890 × 10^6 cP
μ of water[†] = 1.124 cP	μ of air[†] = 0.0180 cP
= 2.72 lb$_m$/hr ft	= 0.0436 lb/hr ft
= 2.349 × 10^{-5} lb sec/ft^2	= 3.763 × 10^{-7} lb sec/ft
VISCOSITY, kinematic, ν	
1 cm^2/s = 0.0001 m^2/s	1 ft^2/sec = 3600 ft^2/hr = 92,900 cS
= 1 stokes = 100 centistokes (cS)	= 0.0929 m^2/s
= 0.001076 ft^2/sec	1 ft^2/h = 0.000278 ft^2/sec = 25.8 cS
= 3.874 ft^2/hr	= 0.0000258 m^2/s
1 m^2/s = 3600 m^2/h	
= 38,736 ft^2/hr = 10.76 ft^2/sec	
ν of water[†] = 1.130 centistokes	ν of air[†] = 14.69 cS
= 32 SSU	= 1.581 × 10^{-4} ft^2/sec
= 1.216 × 10^{-5} ft^2/sec	
VOLUME	
1 cm^3 (cc) = 0.000 001 00 m^3	1 in.^{3} = 16.39 cm^3 = 0.0001639 m^3
= 0.0610 in.^{3} = 0.0338 U.S. fluid oz.	= 0.01639 liter
1 liter (dm^3) = 0.0010 m^3 = 1000 cm^3	1 ft^3 = 1728 in.^{3} = 7.481 U.S. gal
= 61.02 in.^{3} = 0.03531 ft^3	= 6.229 Br gal
= 0.2642 U.S. gal	= 28,320 cm^3 = 0.02832 m^3 = 28.32 liters
	= 62.427 lb of 39.4°F (4°C) water
	= 62.344 lb of 60°F (15.6°C) water

[†]Viscosity at STP.

Metric to American, Metric to Metric	American to Metric, American to American
$1\ m^3 = 1000$ liter $= 1 \times 10^6\ cm^3$	1 U.S. gal $= 3785\ cm^3 = 0.003785\ m^3$
$= 61{,}020\ in.^3 = 35.31\ ft^3$	$= 3.785$ liters $= 231.0\ in.^3$
$= 220.0$ Br gal	$= 0.8327$ Br gal $= 0.1337\ ft^3$
$= 6.290$ bbl	$=$ sp gr $\times$ 8.335 lb
$= 264.2$ U.S. gal	$= 8.335$ lb of water
$= 1.308\ yd^3$	$= 1/42$ barrel (oil)
	1 Br gal $= 277.4\ in.^3$
	$= 0.004\ 546\ m^3 = 4.546$ liters
	$= 1.201$ U.S. gal
	1 bbl, oil $= 9702\ in.^3 = 5.615\ ft^3$
	$= 0.1590\ m^3 = 159.0$ liters
	$= 42.00$ U.S. gal
	$= 34.97$ Br gal
VOLUME FLOW RATE	
$1\ cm^3/s = 1 \times 10^{-6}\ m^3/8$	1 gpm (gal/min) $= 60.0$ gph (gal/hr)
1 liter/s $= 1 \times 10^{-3}\ m^3/s$	$= 0.01667$ gps (gal/sec)
$1\ m^3/h = 4.403$ U.S. gpm (gal/min)	$= 0.00223$ cfs (ft^3/sec)
$= 0.5887\ ft^3/min$	$= 0.1337$ cfm (ft^3/min)
	$= 0.8326$ Br gpm
	$= 0.227\ m^3/h$
	$= 1.429$ bbl/hr
	$= 34.29$ bbl/day
	1 gph (gal/hr) $= 0.00105$ liter/s
	$= 0.000037\ 1$ cfs (ft^3/sec)
	1 cfm (ft^3/min) $= 6.18$ Br gpm
	$= 0.000471\ m^3/s$
	1 cfs (ft^3/sec) $= 448.8$ gpm
	$= 22{,}250$ Br gph
WEIGHT, FORCE, MASS	
1 g $= 0.03527$ oz avdp mass	1 oz avdp mass $= 28.35$ g $= 0.02835$ kg
1 kg mass $= 1000$ g mass	1 lb avdp mass $= 453.6$ g $= 0.4536$ kg
$= 35.27$ oz. avdp mass	$= 4.536 \times 10^6\ \mu g$
$= 2.205$ lb avdp mass	1 lb avdp force $= 0.4536$ kg force
1 kg force $= 1000$ g force $= 9.807$ N	$= 4.448$ N
$= 2.205$ lb avdp force	1 lb $= 7000$ grains
1 metric ton $= 1000$ kg $= 2205$ lb	1 short ton $= 2000$ lb $= 907.2$ kg
	1 long ton $= 2240$ lb $= 1015.9$ kg

Appendix 3

Tables

TABLE A1 Thermodynamic Properties of Dry Saturated Steam—Pressure Table

Abs press., psi	Temp. °F	Specific volume		Enthalpy			Entropy			Internal energy		Abs press., psi
		Sat. liquid	Sat. vapor	Sat. liquid	Evap.	Sat. vapor	Sat. liquid	Evap.	Sat. vapor	Sat. liquid	Sat. vapor	
p	*t*	*vf*	*he*	*hf*	*hfe*	*he*	*sf*	*sfe*	*se*	*uf*	*ue*	*p*
1.0	101.74	0.01614	333.6	69.70	1036.3	1106.0	0.1326	1.8456	1.9782	69.70	1044.3	1.0
2.0	126.08	0.01623	173.73	93.99	1022.2	1116.2	0.1749	1.7451	1.9200	93.98	1051.9	2.0
3.0	141.48	0.01630	118.71	109.37	1013.2	1122.6	0.2008	1.6855	1.8863	109.36	1056.7	3.0
4.0	152.97	0.01636	90.63	120.86	1006.4	1127.3	0.2198	1.6427	1.8625	120.85	1060.2	4.0
5.0	162.24	0.01640	73.52	130.13	1001.0	1131.1	0.2347	1.6094	1.8441	130.12	1063.1	5.0
6.0	170.06	0.01645	61.98	137.96	996.2	1134.2	0.2472	1.5820	1.8292	137.94	1065.4	6.0
7.0	176.85	0.01649	53.64	144.76	992.1	1136.9	0.2581	1.5586	1.8167	144.74	1067.4	7.0
8.0	182.86	0.01653	47.34	150.79	988.5	1139.3	0.2674	1.5383	1.8057	150.77	1069.2	8.0
9.0	188.28	0.01656	42.40	156.22	985.2	1141.4	0.2759	1.5203	1.7962	156.19	1070.8	9.0
10	193.21	0.01659	38.42	161.17	982.1	1143.3	0.2835	1.5041	1.7876	161.14	1072.2	10
14.696	212.00	0.01672	26.80	180.07	970.3	1150.4	0.3120	1.4446	1.7566	180.02	1077.5	14.696
15	213.03	0.01672	26.29	181.11	969.7	1150.8	0.3135	1.4415	1.7549	181.06	1077.8	15
20	227.96	0.01683	20.089	196.16	960.1	1156.3	0.3356	1.3962	1.7319	196.10	1081.9	20
25	240.07	0.01692	16.303	208.42	952.1	1160.6	0.3533	1.3606	1.7139	208.34	1085.1	25
30	250.33	0.01701	13.746	218.52	945.3	1164.1	0.3680	1.3313	1.6993	218.73	1087.8	30
35	259.28	0.01708	11.898	227.91	939.2	1167.1	0.3807	1.3063	1.6870	227.80	1090.1	35
40	267.25	0.01715	10.498	236.03	933.7	1169.7	0.3919	1.2844	1.6763	235.90	1092.0	40
45	274.44	0.01721	9.401	243.36	928.6	1172.0	0.4019	1.2650	1.6669	243.22	1093.7	45
50	281.01	0.01727	8.515	250.09	924.0	1174.1	0.4110	1.2474	1.6585	249.93	1095.3	50
55	287.07	0.01732	7.787	256.30	919.6	1175.9	0.4193	1.2316	1.6509	256.12	1096.7	55
60	292.71	0.01738	7.175	262.09	915.5	1177.6	0.4270	1.2168	1.6438	261.90	1097.9	60
65	297.97	0.01743	6.655	267.50	911.6	1179.1	0.4342	1.2032	1.6374	267.29	1099.1	65
70	302.92	0.01748	6.206	272.61	907.9	1180.6	0.4409	1.1906	1.6315	272.38	1100.2	70
75	307.60	0.01753	5.816	277.43	904.5	1181.9	0.4472	1.1787	1.6259	277.19	1101.2	75
80	312.03	0.01757	5.472	282.02	901.1	1183.1	0.4531	1.1676	1.6207	281.76	1102.1	80
85	316.25	0.01761	5.168	286.39	807.8	1184.2	0.4587	1.1571	1.6158	286.11	1102.9	85
90	320.27	0.01766	4.896	290.56	894.7	1185.3	0.1641	1.1471	1.6112	290.27	1103.7	90
95	324.12	0.01770	4.652	294.56	891.7	1186.2	0.4692	1.1376	1.6068	294.25	1104.5	95
100	327.81	0.01774	4.432	298.40	888.8	1187.2	0.4740	1.1286	1.6026	298.08	1105.2	100
110	334.77	0.01782	4.049	303.66	883.2	1188.9	0.4832	1.1117	1.5948	305.80	1106.5	110

120	341.25	0.01789	3.728	312.44	877.9	1190.4	0.4916	1.0962	1.5878	312.05	1107.6	120
130	347.32	0.01796	3.455	318.81	879.9	1191.7	0.4995	1.0817	1.5812	318.38	1108.6	130
140	353.02	0.01802	3.220	324.82	868.2	1193.0	0.6069	1.0682	1.5751	324.35	1109.6	140
150	358.42	0.01809	3.015	330.51	863.6	1194.1	0.5138	1.0556	1.5094	330.01	1110.5	150
160	363.53	0.01815	2.834	333.93	859.2	1195.1	0.5204	1.0436	1.5640	335.39	1111.2	160
170	368.41	0.01822	2.675	341.09	854.9	1196.0	0.5266	1.0324	1.5590	340.52	1111.9	170
180	373.06	0.01827	2.532	346.03	850.8	1196.9	0.5325	1.0217	1.5542	345.42	1112.5	180
190	377.51	0.01833	2.404	350.79	846.8	1197.6	0.5381	1.0116	1.5497	350.15	1113.1	190
200	381.79	0.01839	2.288	355.36	843.0	1198.4	0.5435	1.0018	1.5453	354.68	1113.7	200
250	400.95	0.01865	1.8438	376.00	825.1	1201.1	0.5675	0.9588	1.5263	375.14	1115.8	250
300	417.33	0.01890	1.5433	393.84	809.0	1202.8	0.5879	0.9225	1.5104	392.79	1117.1	300
350	431.72	0.01913	1.3260	409.69	794.2	1203.9	0.6056	0.8910	1.4966	408.45	1118.0	350
400	444.59	0.0193	1.1613	424.0	780.5	1204.5	0.6214	0.8630	1.4844	422.6	1118.5	400
450	456.28	0.0195	1.0320	437.2	767.4	1204.6	0.6356	0.8378	1.4734	435.5	1118.7	450
500	467.01	0.0197	0.9278	449.4	755.0	1204.4	0.6487	0.8147	1.4634	447.6	1118.6	500
550	476.94	0.0199	0.8424	460.8	743.1	1203.9	0.6608	0.7934	1.4542	458.8	1118.2	550
600	486.21	0.0201	0.7698	471.6	731.6	1203.2	0.6720	0.7734	1.4454	469.4	1117.7	600
650	494.90	0.0203	0.7083	481.8	720.5	1202.3	0.6826	0.7548	1.4374	479.4	1117.1	650
700	503.10	0.0205	0.6554	491.5	709.7	1201.2	0.6925	0.7371	1.4296	488.8	1116.3	700
750	510.86	0.0207	0.6092	500.8	699.2	1200.0	0.7019	0.7204	1.4223	598.0	1115.4	750
800	518.23	0.0209	0.5687	509.7	688.9	1198.6	0.7108	0.7045	1.4153	506.6	1114.4	800
850	525.26	0.0210	0.5327	518.3	678.8	1197.1	0.7194	0.6891	1.4085	515.0	1113.3	850
900	531.98	0.0212	0.5006	526.6	668.8	1195.4	0.7275	0.6744	1.4020	523.1	1112.1	900
950	536.43	0.0214	0.4717	534.6	659.1	1193.7	0.7355	0.6602	1.3957	530.9	1110.8	950
1000	544.61	0.0216	0.4456	542.4	649.4	1191.8	0.7430	0.6467	1.3897	538.4	1109.4	1000
1100	556.31	0.0220	0.4001	557.4	630.4	1187.8	0.7575	0.6205	1.3780	552.9	1106.4	1100
1200	567.22	0.0223	0.3619	571.7	611.7	1183.4	0.7711	0.5956	1.3667	566.7	1103.0	1200
1300	577.46	0.0227	0.3293	585.4	593.2	1178.6	0.7840	0.5719	1.3559	580.0	1099.4	1300
1400	587.10	0.0231	0.3012	598.7	574.7	1173.4	0.7963	0.5491	1.3454	592.7	1095.4	1400
1500	596.23	0.0235	0.2765	611.6	556.3	1167.9	0.8082	0.5269	1.3351	605.1	1091.2	1500
2000	635.82	0.0257	0.1878	671.7	463.4	1135.1	0.8619	0.4230	1.2849	662.2	1065.6	2000
2500	668.13	0.0287	0.1307	730.6	360.5	1091.1	0.9126	0.3197	1.2322	717.3	1030.6	2500
3000	695.36	0.0346	0.0858	802.5	217.8	1020.3	0.9731	0.1885	1.1615	783.4	972.7	3000
3206.2	705.40	0.0503	0.0503	902.7	0	902.7	1.0580	0	1.0580	872.9	872.9	3206.

Source: Abridged from Joseph H. Keenan and Frederick G. Keyes, *Thermodynamic Properties of Steam*, John Wiley & Sons, Inc., New York, 1937.

TABLE A2 Thermodynaic Properties of Dry Saturated Steam—Temperature Table

Temp., °F	Abs press., psi	Specific volume			Enthalpy			Entropy			Temp., °F
		Sat. liquid	Evap.	Sat. vapor	Sat. liquid	Evap.	Sat. vapor	Sat. liquid	Evap.	Sat. vapor	
t	p	vf	vfe	ve	hf	hfe	he	sf	afe	se	t
32	0.08854	0.01602	3306	3306	0.00	1075.8	1075.8	0.0000	2.1877	2.1877	32
35	0.09995	0.01602	2947	2947	3.02	1074.1	1077.1	0.0061	2.1709	2.1770	35
40	0.12170	0.01602	2444	2444	8.05	1071.3	1079.3	0.0162	2.1435	2.1597	40
45	0.14752	0.01602	2036.4	2036.4	13.06	1068.4	1081.5	0.0262	2.1167	2.1429	45
50	0.17811	0.01603	1703.2	1703.2	18.07	1065.6	1083.7	0.0361	2.0903	2.1264	50
60	0.2563	0.01604	1206.6	1206.7	28.06	1059.9	1088.0	0.0555	2.0393	2.0948	60
70	0.3631	0.01606	867.8	867.9	38.04	1054.3	1092.3	0.0745	1.9902	2.0647	70
80	0.5069	0.01608	633.1	633.1	48.02	1048.6	1096.6	0.0932	1.9428	2.0360	80
90	0.6982	0.01610	468.0	468.0	57.99	1042.9	1100.0	0.1115	1.8972	2.0087	90
100	0.9492	0.01613	350.3	350.4	67.97	1037.2	1105.2	0.1295	1.8531	1.9826	100
110	1.2748	0.01617	265.3	265.4	77.94	1031.6	1109.5	0.1471	1.8106	1.9577	110
120	1.6924	0.01620	203.25	203.27	87.92	1025.8	1113.7	0.1645	1.7694	1.9339	120
130	2.2225	0.01625	157.32	157.34	97.90	1020.0	1117.9	0.1816	1.7296	1.9112	130
140	2.8886	0.01629	122.99	123.01	107.89	1014.1	1122.0	0.1984	1.6910	1.8894	140
150	3.718	0.01634	98.06	97.07	117.89	1008.2	1126.1	0.2149	1.6537	1.8685	150
160	4.741	0.01639	77.27	77.29	127.89	1002.3	1130.2	0.2311	1.6174	1.8485	160
170	5.992	0.01645	62.04	62.06	137.90	996.3	1134.2	0.2472	1.5822	1.8293	170
180	7.510	0.01651	50.21	50.23	147.92	990.2	1138.1	0.2630	1.5480	1.8109	180
190	9.339	0.01657	40.94	40.96	157.95	984.1	1142.0	0.2785	1.5147	1.7932	190
200	11.526	0.01663	33.62	33.64	167.99	977.9	1145.9	0.2938	1.4824	1.7762	200
210	14.123	0.01670	27.80	27.82	178.05	971.6	1149.7	0.3090	1.4508	1.7598	210
312	14.696	0.01672	26.78	26.80	180.07	970.3	1150.4	0.3120	1.4446	1.7566	212
220	17.186	0.01677	23.13	23.15	188.13	965.2	1153.4	0.3239	1.4201	1.7440	220
230	20.780	0.01684	19.365	19.382	198.23	958.8	1157.0	0.3387	1.3901	1.7288	230
240	24.969	0.01692	16.306	16.323	208.34	952.2	1160.5	0.3531	1.3609	1.7140	240
250	29.825	0.01700	13.804	13.821	216.48	945.5	1164.0	0.3675	1.3323	1.6998	250
260	35.429	0.01709	11.746	11.763	228.64	938.7	1167.3	0.3817	1.3043	1.6860	260
270	41.858	0.01717	10.044	10.061	238.84	931.8	1170.6	0.3958	1.2769	1.6727	270
280	49.203	0.01726	8.628	8.645	249.06	924.7	1173.8	0.4096	1.2501	1.6597	280

290	57.556	0.01735	7.444	7.461	259.31	917.5	1176.8	0.4234	1.2238	1.6472	290
300	67.013	0.01745	6.449	6.466	269.59	910.1	1179.7	0.4369	1.1980	1.6350	300
310	77.68	0.01755	5.609	5.626	279.92	902.6	1182.5	0.4504	1.1727	1.6231	310
320	89.66	0.01765	4.896	4.914	290.28	894.9	1185.2	0.4637	1.1478	1.6115	320
330	103.06	0.01776	4.289	4.307	300.68	887.0	1187.7	0.4769	1.1233	1.6002	330
340	118.01	0.01787	3.770	3.788	311.13	879.0	1190.1	0.4900	1.0992	1.5891	340
350	134.63	0.01799	3.324	3.342	321.63	870.7	1192.3	0.5029	1.0754	1.5783	350
360	153.04	0.01811	2.939	2.957	332.18	862.2	1194.0	0.5158	1.0519	1.5677	360
370	173.37	0.01823	2.606	2.625	342.79	853.5	1196.3	0.5286	1.0287	1.5573	370
380	195.77	0.01836	2.317	2.335	353.45	844.6	1198.1	0.5413	1.0059	1.5471	380
390	220.37	0.01850	2.0651	2.0836	364.17	835.4	1199.6	0.5539	0.9832	1.5371	390
400	247.31	0.01864	1.8447	1.8633	374.97	826.0	1201.0	0.5664	0.9608	1.5272	400
410	276.75	0.01878	1.6312	1.6700	385.83	816.2	1202.1	0.5788	0.9386	1.5174	410
420	308.83	0.01894	1.4811	1.5000	396.77	806.3	1203.1	0.5912	0.9166	1.5078	420
430	343.72	0.01910	1.3308	1.3499	407.79	796.0	1203.8	0.6035	0.8947	1.4982	430
440	381.59	0.01926	1.1979	1.2171	418.90	785.4	1204.3	0.6158	0.8730	1.4887	440
450	422.6	0.0194	1.0799	1.0993	430.1	774.5	1204.6	0.6280	0.8513	1.4793	450
460	466.9	0.0196	0.9748	0.9944	441.4	763.2	1204.6	0.6402	0.8298	1.4700	460
470	514.7	0.0198	0.8811	0.9009	452.8	751.5	1204.3	0.6523	0.8083	1.4606	470
480	566.1	0.0200	0.7972	0.8172	464.4	739.4	1203.7	0.6645	0.7868	1.4513	480
490	621.4	0.0202	0.7221	0.7423	476.0	726.8	1202.8	0.6766	0.7653	1.4419	490
500	680.8	0.0204	0.6545	0.6749	487.8	713.9	1201.7	0.6887	0.7438	1.4325	500
520	812.4	0.0209	0.5385	0.5594	511.9	686.4	1198.2	0.7130	0.7006	1.4136	520
540	962.5	0.0215	0.4434	0.4649	536.6	636.6	1193.2	0.7374	0.6568	1.3942	540
560	1133.1	0.0221	0.3647	0.3868	562.2	624.2	1186.4	0.7621	0.6121	1.3742	560
580	1325.8	0.0228	0.2989	0.3217	588.9	588.4	1177.3	0.7872	0.5659	1.3532	580
600	1542.9	0.0236	0.2432	0.2668	617.0	548.5	1165.5	0.8131	0.5176	1.3307	600
620	1786.6	0.0247	0.1955	0.2201	646.7	503.6	1130.3	0.8398	0.4664	1.3062	620
640	2059.7	0.0260	0.1538	0.1798	678.6	452.0	1130.5	0.8679	0.4110	1.2789	640
660	2365.4	0.0278	0.1165	0.1442	714.2	390.2	1104.4	0.8987	0.3485	1.2472	660
680	2708.1	0.0305	0.0810	0.1115	757.3	309.9	1067.2	0.9351	0.2719	1.2071	680
700	3093.7	0.0369	0.0392	0.0761	823.3	172.1	993.4	0.9905	0.1484	1.1359	700
705.4	3206.2	0.0503	0	0.0503	902.7	0	902.7	1.0580	0	1.0580	706.1

Source: Abridged from Joseph H. Keenan and Frederick G. Keyes, *Thermodynamic Properties of Steam*, John Wiley & Sons, New York, 1937.

TABLE A3 Thermodynamic Properties of Superheated Steam

Abs press., psi (sat temp)		Temp. °F 200	300	400	500	600	700	800	900	1000	1100	1200	1400	1600
	v....	392.6	452.3	512.0	571.6	631.2	690.8	750.4	809.9	869.5	929.1	988.7	1107.8	1227.0
1	h....	1150.4	1195.8	1241.7	1288.3	1335.7	1383.8	1432.8	1482.7	1533.5	1585.2	1637.7	1745.7	1857.5
(101.74)	s....	2.0612	2.1153	2.1720	2.2233	2.2702	2.3137	2.3542	2.3923	2.4283	2.4625	2.4952	2.5566	2.6137
	v....	78.16	90.25	102.26	114.22	126.16	138.10	150.03	161.95	173.87	185.79	197.71	221.6	245.4
5	h....	1148.8	1195.0	1241.2	1288.0	1335.4	1383.6	1432.7	1482.6	1533.4	1585.1	1637.7	1745.7	1857.5
(163.24)	s....	1.8718	1.9370	1.9942	2.0456	2.0927	2.1361	2.1767	2.2148	2.2509	2.2851	2.3178	2.3792	2.4363
	v....	38.85	45.00	51.04	57.05	63.03	69.01	74.98	80.95	86.92	92.88	98.84	110.77	122.69
10	h....	1146.6	1193.9	1240.6	1287.5	1335.1	1383.4	1432.5	1482.4	1533.2	1555.0	1637.6	1745.6	1857.3
(193.21)	s....	1.7927	1.8595	1.9172	1.9689	2.0160	2.0596	2.1002	2.1383	2.1744	2.2086	2.2413	2.3028	2.3598
	v....	......	30.53	34.68	38.78	42.56	46.94	51.00	55.07	59.13	63.19	67.25	75.37	83.48
14.096	h....	......	1192.8	1239.9	1287.1	1334.8	1383.2	1432.3	1482.3	1533.1	1584.8	1637.5	1745.5	1857.3
(212.00)	s....	......	1.8160	1.8743	1.9261	1.9734	2.0170	2.0676	2.0958	2.1319	2.1662	2.1989	2.2603	2.3174
	v....	......	22.36	25.43	28.46	31.47	34.47	37.46	40.45	43.44	46.42	49.41	55.37	61.34
20	h....	......	1191.6	1239.2	1286.6	1334.4	1382.9	1432.1	1482.1	1533.0	1684.7	1637.4	1745.4	1857.2
(237.96)	s....	......	1.7808	1.8396	1.8918	1.9392	1.9829	2.0235	2.0618	2.0978	2.1321	2.1648	2.2243	2.2834
	v....	......	11.040	12.628	14.168	15.688	17.198	18.702	20.20	21.70	23.20	24.69	27.68	30.86
40	h....	......	1186.8	1236.5	1234.8	1333.1	1381.9	1431.3	1481.4	1532.4	1584.3	1637.0	1745.1	1857.0
(267.25)	s....	......	1.6994	1.7006	1.8140	1.8619	1.9058	1.9467	1.9650	2.0212	2.0555	2.0883	2.1498	2.2069
	v....	......	7.259	8.357	9.403	10.427	11.441	12.449	13.452	14.454	15.453	16.451	18.446	20.44
60	h....	......	1181.8	1233.6	1283.0	1331.8	1380.9	1430.5	1480.8	1531.9	1583.3	1636.6	1744.8	1856.7
(292.71)	s....	......	1.6492	1.7135	1.7678	1.8162	1.8605	1.9015	1.9400	1.9762	2.0106	2.0434	2.1049	2.1621
	v....	......	......	6.220	7.020	7.797	8.562	9.322	10.077	10.830	11.582	12.232	13.830	15.325
80	h....	......	......	1230.7	1281.1	1330.5	1379.9	1429.7	1480.1	1531.3	1583.4	1636.2	1744.5	1856.5
(312.03)	s....	......	......	1.6791	1.7346	1.7836	1.8281	1.8694	1.9079	1.9442	1.9787	2.0115	2.0731	2.1303
	v....	......	......	4.937	5.589	6.218	6.835	7.446	8.052	8.656	9.259	9.860	11.060	12.268
100	h....	......	......	1227.6	1279.1	1329.1	1378.9	1428.9	1479.5	1530.8	1582.9	1635.7	1744.2	1866.2
(337.81)	s....	......	......	1.6518	1.7085	1.7581	1.8029	1.8443	1.8829	1.9193	1.9538	1.9867	2.0484	2.1056
	v....	......	......	4.081	4.636	5.165	5.683	6.195	6.702	7.207	7.710	8.212	9.214	10.213
120	h....	......	......	1224.4	1277.2	1327.7	1377.8	1428.1	1478.8	1530.2	1582.4	1635.3	1743.9	1856.0
(341.25)	s....	......	......	1.6287	1.6869	1.7370	1.7822	1.8237	1.8625	1.8990	1.9335	1.9663	2.0281	2.0664
	v....	......	......	3.468	3.954	4.413	4.861	5.301	5.738	6.172	6.604	7.035	7.895	8.752

140	h....	......	......	1221.1	1275.2	1326.4	1376.8	1427.3	1476.2	1529.7	1581.9	1634.9	1743.5	1855.7
(353.02)	s....	......	......	1.6087	1.6683	1.7190	1.7645	1.8063	1.8151	1.8817	1.9163	1.9493	2.0110	2.0683
	v....	......	......	3.008	3.443	3.849	4.244	4.631	5.015	5.396	5.775	6.152	6.906	7.656
160	h....	......	......	1217.6	1273.1	1325.0	1375.7	1426.4	1477.5	1529.1	1581.4	1634.5	1743.2	1855.5
(363.53)	s....	......	......	1.5908	1.6519	1.7033	1.7491	1.7911	1.8301	1.8667	1.9014	1.9344	1.9962	2.0535
	v....	......	......	2.649	3.044	3.411	3.764	4.110	4.452	4.792	5.129	5.466	6.136	6.804
180	h....	......	......	1214.0	1271.0	1323.5	1374.7	1425.6	1476.8	1528.6	1581.0	1634.1	1742.9	1855.2
(373.06)	s....	......	......	1.5745	1.6373	1.6894	1.7355	1.7776	1.8167	1.8534	1.8882	1.9212	1.9831	2.0404
	v....	......	......	2.361	2.726	3.040	3.380	3.693	4.002	4.309	4.613	4.917	5.521	6.123
200	h....	......	......	1210.3	1268.9	1322.1	1373.6	1424.8	1476.2	1528.0	1580.5	1633.7	1742.6	1855.0
(381.79)	s....	......	......	1.5594	1.6240	1.6767	1.7232	1.7655	1.8048	1.8415	1.8763	1.9094	1.9713	2.0287
	v....	......	......	2.125	2.465	2.772	3.066	3.352	3.634	3.913	4.191	4.467	5.017	5.565
200	h....	......	......	1206.5	1266.7	1320.7	1372.0	1424.0	1475.5	1527.5	1580.0	1633.3	1742.3	1854.7
(300.86)	s....	......	......	1.5453	1.6117	1.6652	1.7120	1.7545	1.7939	1.8308	1.8656	1.8987	1.9607	2.0181
	v....	......	......	1.9276	2.247	2.533	2.804	3.068	3.327	3.584	3.839	4.093	4.597	5.100
240	h....	......	......	1202.5	1264.5	1319.2	1371.5	1423.2	1474.8	1526.9	1579.6	1632.9	1742.0	1854.5
(397.37)	s....	......	......	1.5219	1.6003	1.6546	1.7017	1.7444	1.7839	1.8209	1.8553	1.8889	1.9510	2.0064
	v....	......	......	......	2.062	2.330	2.552	2.827	3.067	3.305	3.541	3.776	4.242	4.707
260	h....	......	......	......	1262.3	1317.7	1370.4	1422.3	1474.2	1526.3	1579.1	1632.5	1741.7	1854.2
(404.42)	s....	......	......	......	1.5897	1.6447	1.6923	1.7362	1.7748	1.8118	1.8467	1.8799	1.9420	1.9905
	v....	......	......	......	1.9047	3.156	2.392	2.621	2.845	3.066	3.286	3.504	3.938	4.370
280	h....	......	......	......	1360.0	1316.2	1360.4	1421.5	1473.5	1525.8	1578.6	1632.1	1741.4	1854.0
(411.08)	s....	......	......	......	1.5796	1.6354	1.6834	1.7365	1.7662	1.8033	1.8383	1.8716	1.9337	1.9912
	v....	......	......	......	1.7675	2.005	2.227	2.442	2.652	2.859	3.065	3.269	3.674	4.078
300	h....	......	......	......	1257.6	1314.7	1368.3	1420.6	1472.8	1525.2	1578.1	1631.7	1741.0	1853.7
(417.33)	s....	......	......	......	1.5701	1.6268	1.6751	1.7184	1.7582	1.7954	1.8305	1.8638	1.9260	1.9835
	v....	......	......	......	1.4923	1.7036	1.8980	2.084	2.366	2.445	2.623	2.798	3.147	3.493
350	h....	......	......	......	1251.5	1310.9	1365.5	1418.5	1471.1	1523.8	1577.0	1630.7	1740.3	1853.1
(431.72)	s....	......	......	......	1.5481	1.6070	1.6563	1.7002	1.7403	1.7777	1.8130	1.8463	1.9065	1.9662
	v....	......	......	......	1.2851	1.4770	1.6508	1.8161	1.9767	2.134	2.290	2.445	3.751	3.055
400	h....	......	......	......	1245.1	1304.9	1362.7	1416.4	1469.4	1522.4	1575.8	1629.6	1739.5	1852.5
(444.59)	s....	......	......	......	1.5281	1.5894	1.6398	1.6842	1.7247	1.7623	1.7977	1.8311	1.8936	1.9513

Source: Abridged from *Thermodynamic Properties of Steam*, by Joseph H. Keenan and Frederick G. Keyes, John Wiley & Sons, New York, 1937.

TABLE A3 Continued

Abs press., psi (sat temp)		Temp. °F													
		500	550	600	620	640	660	680	700	800	900	1000	1200	1400	1600
	v....	1.1231	1.2155	1.3005	1.3332	1.3652	1.3967	1.4276	1.4384	1.6074	1.7616	1.8928	2.170	2.443	2.714
450	h ...	1238.4	1272.0	1302.8	1214.6	1326.2	1337.5	1348.8	1359.9	1414.3	1467.7	1521.0	1628.6	1738.7	1861.9
(456.28)	s....	1.5095	1.5437	1.5735	1.5845	1.5951	1.6054	1.6153	1.6250	1.6099	1.7106	1.7486	1.8177	1.9803	1.9381
	v....	0.9927	1.0600	1.1591	1.1883	1.2186	1.2478	1.2763	1.3044	1.4405	1.5715	1.6096	1.9504	2.197	2.442
500	h....	1231.3	1266.8	1298.6	1310.7	1322.6	1334.2	1345.7	1357.0	1412.1	1466.0	1519.6	1627.6	1737.9	1851.3
(467.01)	s....	1.4919	1.5280	1.5588	1.5701	1.5810	1.5915	1.6016	1.6115	1.6571	1.6962	1.7363	1.8056	1.8683	1.9262
	v....	0.8852	0.9686	1.0431	1.0714	1.0969	1.1259	1.1533	1.1783	1.3068	1.4241	1.5414	1.7704	1.9957	2.219
550	h....	1223.7	1261.2	1294.3	1306.8	1318.9	1330.8	1342.5	1354.0	1409.9	1464.3	1518.2	1626.6	1737.1	1850.6
(476.94)	s....	1.4751	1.5131	1.5451	1.5568	1.5680	1.5787	1.5890	1.5991	1.6452	1.6868	1.7250	1.7946	1.8575	1.9156
	v....	0.7947	0.8753	0.9463	0.9729	0.9988	1.0241	1.0489	1.0732	1.1899	1.3013	1.4096	1.6208	1.8279	2.033
600	h....	1215.7	1255.5	1289.9	1302.7	1315.2	1327.4	1339.3	1351.1	1407.7	1462.5	1516.7	1625.5	1736.3	1850.0
(486.21)	s....	1.4596	1.4990	1.5323	1.5443	1.5558	1.5667	1.5773	1.5875	1.6342	1.6762	1.7147	1.7846	1.8476	1.9068
	v....	......	0.7277	0.7934	0.8177	0.8411	0.8639	0.8860	0.9077	1.0108	1.1082	1.2024	1.3853	1.5641	1.7405
700	h....	......	1243.2	1280.6	1294.3	1307.5	1320.3	1332.8	1345.0	1403.2	1459.0	1515.9	1623.5	1734.8	1848.8
(503.10)	s....	......	1.4722	1.5064	1.5212	1.5223	1.5449	1.5559	1.5665	1.6147	1.6572	1.6962	1.7666	1.8299	1.8881
	v....	......	0.6154	0.6779	0.7006	0.7223	0.7433	0.7635	0.7833	0.8763	0.9623	1.0470	1.2066	1.3662	1.5214
800	h....	......	1229.8	1270.7	1285.4	1299.4	1312.9	1325.9	1235.6	1398.6	1455.4	1511.0	1621.4	1733.2	1847.5
(518.23)	s....	......	1.4467	1.4863	1.5000	1.5129	1.5250	1.5366	1.5476	1.5972	1.6407	1.6801	1.7510	1.8146	1.8729
	v....	......	0.5264	0.5873	0.6089	0.6294	0.6491	0.6680	0.6863	0.7716	0.8506	0.9262	1.0714	1.2124	1.3509
900	h....	......	1215.0	1250.1	1275.9	1290.9	1305.1	1318.8	1332.1	1393.9	1451.8	1508.1	1619.3	1731.6	1846.2
(531.98)	s....	......	1.4216	1.4653	1.4800	1.4938	1.5066	1.5187	1.5303	1.5814	1.6257	1.6656	1.7371	1.8009	1.8595
	v....	......	0.4533	0.5140	0.5350	0.5546	0.5733	0.5912	0.6084	0.6878	0.7604	0.8294	0.9615	1.0893	1.2146
1000	h....	......	1196.3	1248.8	1265.9	1281.9	1297.0	1311.4	1325.3	1389.2	1448.2	1505.1	1617.3	1730.0	1845.0
(544.61)	s....	......	1.3961	1.4450	1.4610	1.4757	1.4893	1.5021	1.5141	1.5670	1.6121	1.6525	1.7245	1.7886	1.8474
	v....	......	......	0.4532	0.4738	0.4929	0.5110	0.5281	0.5445	0.6191	0.6866	0.7503	0.8716	0.9885	1.1031
1100	h....	......	......	1236.7	1255.3	1272.4	1288.5	1303.7	1318.3	1384.3	1444.5	1502.2	1615.2	1728.4	1843.8
(556.31)	s....	......	......	1.4251	1.4425	1.4583	1.4728	1.4862	1.4989	1.5535	1.5995	1.6406	1.7130	1.7775	1.8262
	v....	......	......	0.4016	0.4222	0.4410	0.4586	0.4752	0.4909	0.5617	0.6250	0.6843	0.7967	0.9046	1.0101
1200	h....	......	......	1223.5	1243.9	1262.4	1279.6	1295.7	1311.0	1379.3	1440.7	1499.2	1613.1	1726.9	1842.5
(567.22)	s....	......	......	1.4052	1.4243	1.4413	1.4568	1.4710	1.4843	1.5409	1.5879	1.6293	1.7025	1.7672	1.8263
	v....	......	......	0.3174	0.3390	0.3580	0.3753	0.3912	0.4062	0.4714	0.5281	0.5805	0.6789	0.7727	0.8640

1400	k....	......	......	1193.0	1218.4	1240.4	1260.3	1278.5	1295.5	1369.1	1433.1	1493.2	1606.9	1723.7	1840.0
(587.10)	s....	......	......	1.3639	1.3877	1.4079	1.4258	1.4419	1.4567	1.5177	1.5666	1.6093	1.6836	1.7489	1.8063
	v....	......	......	......	0.3733	0.2936	0.3112	0.3271	0.3417	0.4034	0.4553	0.5027	0.5906	0.6728	0.7545
1600	h....	......	......	......	1187.8	1215.2	1238.7	1259.6	1278.7	1358.4	1425.3	1487.0	1604.6	1720.5	1837.5
(604.90)	s....	......	......	......	1.3489	1.3741	1.3952	1.4137	1.4303	1.4964	1.5476	1.5914	1.6669	1.7328	1.7926
	v....	......	......	......	......	0.2407	0.2597	0.2760	0.2907	0.3502	0.3986	0.4421	0.5218	0.5968	0.6093
1800	h....	......	......	......	......	1185.1	1214.0	1238.5	1260.3	1347.2	1417.4	1480.8	1600.4	1717.3	1835.0
(621.03)	s....	......	......	......	......	1.3377	1.3628	1.3855	1.4044	1.4765	1.5301	1.5752	1.6520	1.7185	1.7766
	v....	......	......	......	......	0.1936	0.2161	0.2337	0.2489	0.3074	0.3532	0.3935	0.4668	0.5252	0.6011
2000	h....	......	......	......	......	1145.6	1184.9	1214.8	1240.0	1336.5	1409.2	1474.5	1596.1	1714.1	1622.5
(635.82)	s....	......	......	......	......	1.2945	1.3300	1.3564	1.3782	1.4576	1.5139	1.5602	1.6384	1.7065	1.7886
	v....	......	......	......	......	......	......	0.1484	0.1686	0.2294	0.2710	0.3061	0.3678	0.4244	0.4784
2500	h....	......	......	......	......	......	......	1132.3	1176.8	1303.6	1387.8	1458.4	1585.3	1706.1	1826.2
(668.13)	s....	......	......	......	......	......	......	1.2687	1.3073	1.4127	1.4772	1.5273	1.6088	1.6775	1.7389
	v....	......	......	......	......	......	......	......	0.0964	0.1760	0.2159	0.2476	0.3018	0.3505	0.3966
3000	h....	......	......	......	......	......	......	......	1060.7	1267.2	1365.0	1441.8	1574.3	1698.0	1819.9
(495.36)	s....	......	......	......	......	......	......	......	1.1966	1.3690	1.4439	1.4984	1.5837	1.6540	1.7163
	v....	......	......	......	......	......	......	......	......	0.1583	0.1961	0.2288	0.2806	0.3267	0.3703
3286.2	h....	......	......	......	......	......	......	......	......	1250.5	1355.2	1434.7	1569.8	1694.6	1817.2
(706.40)	s....	......	......	......	......	......	......	......	......	1.3506	1.4309	1.4874	1.5742	1.6452	1.7080
	v....	......	......	......	......	......	......	......	0.0806	0.1364	0.1762	0.2058	0.2546	0.2977	0.3381
3500	h....	......	......	......	......	......	......	......	780.5	1224.9	1340.7	1424.5	1563.3	1689.8	1813.6
	s....	......	......	......	......	......	......	......	0.9515	1.3241	1.4127	1.4723	1.5615	1.6336	1.6968
	v....	......	......	......	......	......	......	......	0.0287	0.1062	0.1462	0.1743	0.2192	0.2581	0.2943
4000	h....	......	......	......	......	......	......	......	763.8	1174.8	1314.4	1406.8	1562.1	1681.7	1807.2
	s....	......	......	......	......	......	......	......	0.9347	1.2757	1.3827	1.4482	1.5417	1.6154	1.6795
	v....	......	......	......	......	......	......	......	0.0276	0.0798	0.1226	0.1500	0.1917	0.2273	0.2602
4500	h....	......	......	......	......	......	......	......	753.5	1113.9	1286.5	1388.4	1540.8	1673.5	1800.9
	s....	......	......	......	......	......	......	......	0.9235	1.2204	1.3529	1.4253	1.5235	1.5990	1.6040
	v....	......	......	......	......	......	......	......	0.0268	0.0593	0.1036	0.1302	0.1696	0.2027	0.2329
5000	h....	......	......	......	......	......	......	......	746.4	1047.1	1256.5	1369.5	1629.5	1665.2	1794.5
	s....	......	......	......	......	......	......	......	0.9152	1.1622	1.3231	1.4034	1.5066	1.5839	1.6499
	v....	......	......	......	......	......	......	......	0.0262	0.0463	0.0880	0.1143	0.1516	0.1825	0.2106
5500	h....	......	......	......	......	......	......	......	741.3	985.0	1224.1	1349.3	1518.2	1657.0	1788.1
	s....	......	......	......	......	......	......	......	0.9090	1.1093	1.2930	1.3821	1.4908	1.5699	1.6309

Source: Abridged from *Thermodynamic Properties of Steam*, by Joseph H. Keenan and Frederick G. Keyes, John Wiley & Sons, New York, 1937.

TABLE A4 Enthalpy of Compressed Water

p (t Sat.)	0				580 (467.13)				1000 (544.75)			
t	v	u	h	s	v	u	h	s	v	u	h	s
Sat.					.019748	447.70	449.53	.64904	.021591	538.39	542.38	.743
32	.016022	-.01	-.01	-.00003	.015994	.00	1.49	.00000	.015967	.03	2.99	.000
50	.016024	18.06	18.06	0.3687	.015998	18.02	19.50	.03599	.015972	17.99	20.94	.035
100	.016130	68.05	68.05	.12963	.016106	67.87	69.36	.12932	.016082	67.70	70.68	.129
150	.016343	117.95	117.95	.21504	.016318	117.66	119.17	.21457	.016293	117.38	120.40	.214
200	.016635	168.05	168.05	.29402	.016608	167.65	169.19	.29341	.016580	167.28	170.32	.292
250	.017003	218.32	218.32	.36777	.016972	217.99	219.56	.36702	.016941	217.47	220.61	.366
300	.017453	269.61	269.61	.43732	.017416	268.92	270.53	.43641	.017379	268.24	271.46	.435
350	.018000	321.59	321.59	.50359	.017954	320.71	322.37	.50249	.017909	319.83	323.15	.501
400	.018668	374.85	374.85	.56740	.018608	373.68	375.40	.56604	.018550	372.55	375.98	.564
450	.019503	429.96	429.96	.62970	.019420	428.40	430.19	.62798	.019340	426.89	430.47	.626
500	.02060	488.1	488.1	.6919	.02048	485.9	487.8	.6896	.02036	483.5	487.5	.68
510	.02087	500.3	500.3	.7046	.02073	497.9	499.8	.7021	.02060	495.6	499.4	.695
520	.02116	512.7	512.7	.7173	.02190	530.1	512.0	.7146	.02086	507.6	511.5	.712
530	.02148	525.5	525.5	.7303	.02130	522.6	524.5	.7273	.02114	519.9	523.8	.724
540	.02182	538.6	538.6	.7434	.02162	535.3	537.3	.7402	.02144	532.4	536.3	.737
550	.02221	552.1	552.1	.7569	.02198	548.4	550.5	.7532	.02177	545.1	549.2	.749
560	.02265	566.1	566.1	.7707	.02237	562.0	564.0	.7666	.02213	558.3	562.4	.763
570	.02315	580.8	580.8	.7851	.02281	576.0	578.1	.7804	.02253	571.8	576.0	.776
580					.02332	590.8	592.9	.7946	.02298	585.9	590.1	.789
590					.02392	606.4	608.6	.8096	.02349	600.6	604.9	.894
600									.02409	616.2	620.6	.818
610									.02482	632.9	637.5	.834

p (t Sat.)	1500 (596.39)				2000 (636.00)				2500 (668.31)			
t	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	.023461	604.97	611.48	.80824	.025649	662.40	671.89	.86227	.028605	717.66	730.89	.9130
32	.015939	.05	4.47	.00007	.015912	.06	5.95	.00008	.015885	.08	7.43	.0000
50	.015946	17.95	22.38	.03584	.015920	17.91	23.81	.03575	.015895	17.88	25.23	.0356
100	.016058	67.53	71.99	.12870	.016034	67.37	73.30	.12839	.016010	67.20	74.61	.1280
150	.016268	117.10	121.62	.21364	.016244	116.83	122.84	.21318	.016220	116.56	124.07	.2127
200	.016554	166.87	171.46	.29221	.016527	166.49	172.60	.29162	.016501	166.11	173.75	.2910
250	.016910	216.96	221.65	.36554	.016880	216.46	222.70	.36482	.016851	215.96	223.75	.3641
300	.017343	267.58	272.39	.43463	.017308	266.93	273.33	.43376	.017274	266.29	274.28	.4329
350	.017865	318.98	323.94	.50034	.017822	318.15	324.74	.49929	.017780	317.33	325.56	.4982
400	.018493	371.45	376.59	.56343	.018439	370.38	377.21	.56216	.018386	369.34	377.84	.5609
450	.019264	425.44	430.79	.62470	.019191	424.04	431.14	.62313	.019120	422.68	431.52	.6216
500	.02024	481.8	487.4	.6853	.02014	479.8	487.3	.6832	.02004	478.0	487.3	.681?
510	.02048	493.4	499.1	.6974	.02036	491.4	498.9	.6953	.02025	489.4	498.8	.693?
520	.02072	505.3	511.0	.7096	.02060	503.1	510.7	.7073	.02048	501.0	510.4	.7051
530	.02099	517.3	523.1	.7219	.02085	514.9	522.6	.7195	.02072	512.6	522.2	.7171
540	.02127	529.6	535.5	.7343	.02112	527.0	534.8	.7317	.02098	524.5	534.2	.7292
550	.02158	542.1	548.1	.7469	.02141	539.2	547.2	.7440	.02125	536.6	546.4	.7413
560	.02191	554.9	561.0	.7596	.02172	551.8	559.8	.7565	.02154	548.9	558.8	.7536
570	.02228	568.0	574.2	.7725	.02206	564.6	572.8	.7691	.02186	561.4	571.5	.7659
580	.02269	581.6	587.9	.7857	.02243	577.8	586.1	.7820	.02221	574.3	584.5	.7785
590	.02314	595.7	602.1	.7993	.02284	591.3	599.8	.7951	.02258	587.4	597.9	.7913
600	*.02366*	*610.4*	*616.9*	*.8134*	.02330	605.4	614.0	.8066	.02300	601.0	611.6	.8043
610	*.02426*	*625.8*	*432.6*	*.8281*	.02382	620.0	628.8	.8225	.02346	615.0	625.9	.8177
620	*.02498*	*642.5*	*649.4*	*.8437*	.02443	635.4	644.5	.8371	.02399	629.6	640.7	.8315
630	*.02590*	*660.8*	*668.0*	*.8609*	.02514	651.9	661.2	.8525	.02459	644.9	656.3	.8459
640					*.02603*	*669.8*	*679.4*	*.8691*	.02530	661.2	672.9	.8610
650					*.02724*	*690.3*	*700.4*	*.8881*	.02616	678.7	690.8	.8773
660									.02729	698.4	711.0	.8954
670									*.02895*	*722.1*	*735.3*	*.9172*

TABLE A5 Specific Heat, Viscosity, and Thermal Conductivity of Some Common Gases at Atmospheric Pressure[a]

Temp. (°F)	Carbon dioxide			Water vapor			Nitrogen		
	C_p	μ	k	C_p	μ	k	C_p	μ	k
200	.2162	.0438	.0125	.4532	.0315	.0134	.2495	.0518	.0189
400	.2369	.0544	.0177	.4663	.0411	.0197	.2530	.0608	.0219
600	.2543	.0645	.0227	.4812	.0506	.0261	.2574	.0694	.0249
800	.2688	.0749	.0274	.4975	.0597	.0326	.2624	.0776	.0279
1000	.2807	.0829	.0319	.5147	.0687	.0393	.2678	.0854	.0309
1200	.2903	.0913	.0360	.5325	.0773	.0462	.2734	.0927	.0339
1400	.2980	.0991	.0400	.5506	.0858	.0532	.2791	.0996	.0369
1600	.3041	.1064	.0435	.5684	.0939	.0604	.2846	.1061	.0399
1800	.3090	.1130	.0468	.5857	.0119	.0678	.2897	.1122	.0429
2000	.3129	.1191	.0500	.6019	.1095	.0753	.2942	.1178	.0459

Temp. (°F)	Oxygen			Sulfur dioxide			Hydrogen chloride		
	C_p	μ	k	C_p	μ	k	C_p	μ	k
200	.2250	.0604	.0186	.1578	.0386	.0074	.1907	.0412	.0113
400	.2332	.0716	.0229	.1704	.0493	.0109	.1916	.0534	.0143
600	.2404	.0823	.0272	.1806	.0595	.0143	.1936	.0655	.0175
800	.2468	.0924	.0313	.1887	.0692	.0175	.1965	.0774	.0209
1000	.2523	.1021	.0352	.1950	.0784	.0205	.2002	.0892	.0245
1200	.2570	.1111	.0389	.1997	.0871	.0234	.2043	.1009	.0283
1400	.2611	.1197	.0425	.2030	.0954	.0261	.2086	.1124	.0327
1600	.2647	.1278	.0460	.2054	.1030	.0286	.2128	.1239	.0364
1800	.2678	.1353	.0492	.2069	.1103	.0310	.2168	.1351	.0407
2000	.2705	.1423	.0523	.2079	.1170	.0332	.2203	.1463	.0452

C_p = gas specific heat, Btu/lb °F; μ = viscosity, lb/ft hr; k = thermal conductivity, Btu/ft hr °F.

[a]From heat transfer considerations, the pressure effect becomes significant above 250 psig and at gas temperatures below 400°F.

TABLE A6a Specific Heat, Viscosity, and Thermal Conductivity of Products of Combustion of Natural Gas, Fuel Oil, and Ambient Air

Temp, °F	Natural gas			Fuel oil			Air		
	C_p	μ	k	C_p	μ	k	C_p	μ	k
2000	0.3326	0.1174	0.0511	0.3206	0.1178	0.0497	0.2906	0.1232	0.0475
1600	0.3203	0.1050	0.0437	0.3094	0.1055	0.0427	0.2817	0.1108	0.0414
1200	0.3059	0.0908	0.0362	0.2959	0.0915	0.0356	0.2712	0.0967	0.0351
800	0.2907	0.0750	0.0287	0.2812	0.0757	0.0284	0.2602	0.0807	0.0287
400	0.2757	0.0575	0.0211	0.2660	0.0583	0.0211	0.2498	0.0631	0.0221

Analysis of natural gas–15% excess air vol%: $CO_2 = 8.29$, $H_2O = 18.17$, $N_2 = 71.08$, $O_2 = 2.46$.
Fuel oil–15% excess air vol%: $CO_2 = 11.57$, $H_2O = 12.29$, $N_2 = 73.63$, $O_2 = 2.51$.
Air vol%: $H_2O = 1$, $N_2 = 78$, $O_2 = 21$, C_p = specific heat, Btu/lb°F. μ = viscosity, lb/ft h; k = thermal conductivity, Btu/ft h °F.

TABLE A6b Gas Turbine Exhaust Gases

Temp, °F	C_p	μ	k
1000	0.2768	0.087	0.0321
800	0.2704	0.0789	0.0287
600	0.2643	0.0702	0.0252
400	0.2584	0.0612	0.0217
200	0.2529	0.0517	0.0182

Gas analysis vol%: $CO_2 = 3$, $H_2O = 7$, $N_2 = 75$, $O_2 = 15$.

TABLE A7a Enthalpy of Gases[a]

Temp, (°F)	*A*	*B*	*C*	*D*
200	34.98	31.85	35.52	33.74
400	86.19	78.57	87.83	83.00
600	138.70	126.57	141.79	133.42
800	192.49	175.77	197.35	184.91
1000	247.56	226.2	254.47	237.52
1400		330.15	372.93	345.77
1800		437.86	496.42	457.82

[a]

	Content (vol%)				
	CO_2	H_2O	N_2	O_2	SO_2
A Gas turbine exhaust	3	7	75	15	—
B Sulfur combustion	—	—	81	10	9
C Flue gas	12	12	70	6	—
D Dry air			79	21	—

TABLE A7b Enthalpy of Products of Combustion of Natural Gas and Fuel Oil[a] (Btu/lb)

Temp (°F)	Natural gas	Fuel oil
3000	928.6	894.9
2600	787.1	759.5
2200	649.5	627.3
1800	516.3	498.8
1400	387.9	374.8
1000	264.9	255.8
600	147.9	142.6
200	37.1	35.7

[a] Same fuel analysis as in Table A6a.

TABLE A8 Correlation for Superheated Steam Properties

$C_1 = 80{,}870/T^2$

$C_2 = (-2641.62/T) \times 10^{C_1}$

$C_3 = 1.89 + C_2$

$C_4 = C_3(P^2/T^2)$

$C_5 = 2 + (372420/T^2)$

$C_6 = C_5C_2$

$C_7 = 1.89 + C_6$

$C_8 = 0.21878T - 126{,}970/T$

$C_9 = 2C_6C_7 - (C_5/T)(126{,}970)$

$C_{10} = 82.546 - 162{,}460/T$

$C_{11} = 2C_{10}C_7 - (C_5/T)(162{,}460)$

$v = \{[(C_8C_4C_3 + C_{10})(C_4/P) + 1]C_3 + 4.55504$
$\quad (T/P)\}0.016018$

$H = 775.596 + 0.63296T + 0.000162467T^2 + 47.3635 \log T$
$\quad + 0.043557\{C_7P + 0.5C_4[C_{11} + C_5(C_{10} + C_9C_4)]\}$

$S = 1/T\{[(C_8C_3 - 2C_9)C_3C_4/2 - C_{11}]C_4/2 + (C_3 - C_7)P\}$
$\quad \times (-0.0241983) - 0.355579 - 11.4276/T + 0.00018052T$
$\quad - 0.253801 \log P + 0.809691 \log T$

where

P = pressure, atm
T = temperature, K
v = specific volume, ft^3/lb
H = enthalpy, Btu/lb
S = entropy, Btu/lb °F

TABLE A9 Coefficients to Estimate Properties of Dry, Saturated Steam with Equation[a]

$$Y = Ax + B/x + cx^{1/2} + D \ln x + Ex^2 + Fx^3 + G$$

Property	A	B	C
Temperature, °F	-0.17724	3.83986	11.48345
Liquid specific volume, ft^3/lb	-5.280126×10^{-7}	2.99461×10^{-5}	1.521874×10^{-4}
Vapor specific volume, ft^3/lb			
1–200 psia	-0.48799	304.717614	9.8299035
200–1,500 psia	2.662×10^{-3}	457.5802	-0.176959
Liquid enthalpy, Btu/lb	-0.15115567	3.671404	11.622558
Vaporization enthalpy, Btu/lb	0.008676153	-1.3049844	-8.2137368
Vapor enthalpy, Btu/lb	-0.14129	2.258225	3.4014802
Liquid entropy, Btu/lb °R	-1.67772×10^{-4}	4.272688×10^{-3}	0.01048048
Vaporization entropy,			
Btu/lb °R	3.454439×10^{-5}	-2.75287×10^{-3}	-7.33044×10^{-3}
Vapor entropy, Btu/lb °R	-1.476933×10^{-4}	1.2617946×10^{-3}	3.44201×10^{-3}
Liquid internal energy, Btu/lb	-0.1549439	3.662121	11.632628
Vapor internal energy, Btu/lb	-0.0993951	1.93961	2.428354

[a] y = property, x = pressure, psia.

TABLE A9

D	E	F	G
31.1311	8.762969×10^{-5}	-2.78794×10^{-8}	86.594
6.62512×10^{-5}	8.408856×10^{-10}	1.86401×10^{-14}	0.01596
-16.455274	9.474745×10^{-4}	-1.363366×10^{-8}	19.53953
0.826862	-4.601876×10^{-7}	6.3181×10^{-11}	-2.3928
30.832667	8.74117×10^{-5}	-2.62306×10^{-8}	54.55
-16.37649	-4.3043×10^{-5}	9.763×10^{-9}	1,045.81
14.438078	4.222624×10^{-5}	-1.569916×10^{-8}	1,100.5
0.05801509	9.101291×10^{-8}	-2.7592×10^{-11}	0.11801
-0.14263733	-3.49366×10^{-8}	7.433711×10^{-12}	1.85565
-0.06494128	6.89138×10^{-8}	-2.4941×10^{-11}	1.97364
30.82137	8.76248×10^{-5}	-2.646533×10^{-8}	54.56
10.9818864	2.737201×10^{-5}	-1.057475×10^{-8}	1,040.03

TABLE A10 Saturation Line; Specific Heat Capacity and Transport Properties

t (°F)	t_c (°C)	p (lb ft/in.^{2})	C_{pf} (Btu/lb °F)	$\mu_f \times 10^6$ (lb/ft s)	$\nu_f \times 10^6$ (ft^2/s)	$\lambda_f \times 10^3$ (Btu/ft h °F)	$(Pr)_f$	C_{pg} (Btu/lb °F)	$\mu_g \times 10^6$ (lb/ft s)	$\nu_g \times 10^6$ (ft^2/s)	$\lambda_g \times 10^3$ (Btu/ft h °F)	$(Pr)_g$
32	0.0	0.0886	1.006	1180.0	18.9	329	12.9	0.442	5.91	19500	10.0	0.94
40	4.4	0.1217	1.004	1027.0	16.5	333	11.1	0.443	6.02	14700	10.5	0.91
60	15.6	0.2562	1.000	753.0	12.1	345	7.86	0.447	6.24	7530	10.9	0.92
80	26.7	0.5069	0.998	576.0	9.26	354	5.85	0.447	6.47	4100	11.3	0.92
100	37.8	0.949	0.998	457.0	7.37	363	4.52	0.449	6.71	2350	11.7	0.93
120	49.9	1.693	0.999	372.0	6.03	371	3.61	0.452	6.95	1410	12.1	0.94
140	60.0	2.889	1.000	311.0	5.07	378	2.96	0.458	7.20	886	12.4	0.96
160	71.1	4.741	1.001	264.0	4.33	383	2.48	0.465	7.45	576	13.0	0.96
180	82.2	7.511	1.003	229.0	3.78	388	2.13	0.474	7.70	387	13.5	0.97
200	93.3	11.53	1.006	201.0	3.34	392	1.86	0.484	7.96	268	14.0	0.99
220	104.4	17.19	1.009	179.0	3.00	394	1.65	0.495	8.22	190	14.6	1.00
240	115.6	24.97	1.013	160.0	2.71	396	1.47	0.508	8.50	139	15.2	1.02
260	126.7	35.42	1.018	145.0	2.48	397	1.34	0.522	8.77	103	15.8	1.04
280	137.8	49.20	1.024	133.0	2.29	397	1.23	0.538	9.05	78.2	16.5	1.06
300	148.9	67.00	1.030	122.0	2.13	397	1.14	0.556	9.32	60.3	17.3	1.08
320	160.0	89.64	1.038	113.0	2.00	395	1.07	0.577	9.58	47.1	18.1	1.10
340	171.1	118.00	1.047	105.0	1.88	393	1.01	0.600	9.85	37.3	18.9	1.13
360	182.2	153.00	1.057	98.6	1.79	390	0.96	0.627	10.1	29.9	19.9	1.15
380	193.3	195.7	1.069	92.7	1.70	387	0.92	0.658	10.4	24.2	21.0	1.17
400	204.4	247.3	1.082	87.5	1.63	382	0.89	0.692	10.6	19.8	22.1	1.19

420	215.6	308.8	1.097	82.9	1.57	377	0.87	0.731	10.9	16.3	23.4	1.23
440	226.7	381.6	1.115	78.8	1.52	371	0.85	0.774	11.2	13.6	24.9	1.25
460	237.8	466.9	1.135	75.2	1.47	364	0.84	0.823	11.5	11.4	26.5	1.29
480	248.9	566.1	1.158	71.9	1.44	357	0.84	0.885	11.7	9.60	28.4	1.31
500	260.0	680.8	1.186	68.9	1.41	349	0.84	0.951	12.1	8.14	30.5	1.36
520	271.1	812.4	1.229	66.2	1.38	340	0.86	1.038	12.4	6.94	32.9	1.41
540	282.2	962.6	1.275	63.7	1.37	330	0.88	1.147	12.8	5.95	35.8	1.48
560	293.3	1133.2	1.338	61.5	1.36	319	0.92	1.286	13.2	5.11	39.2	1.56
580	304.4	1326.1	1.420	59.8	1.36	308	0.99	1.472	13.6	4.38	43.3	1.66
600	315.6	1543.3	1.520	58.0	1.37	296	1.07	1.735	14.4	3.85	48.4	1.86
620	326.7	1787.1	1.659	55.7	1.37	283	1.17	2.153	15.3	3.37	54.9	2.16
640	337.8	2060.3	1.880	52.9	1.37	269	1.33	2.832	16.4	2.95	63.6	2.63
660	348.9	2366.0	2.310	49.5	1.37	254	1.62	3.943	17.9	2.58	76.1	3.34
680	360.0	2708.3	3.466	45.2	1.37	231	2.44	5.676	20.2	2.25	97.0	4.26

TABLE A11 Surface Tension of Water

Temp (°F)	lb ft/ft × 10^3	Temp (°F)	lb ft/ft × 10^3
32	5.184	350	2.942
40	5.141	400	2.512
60	5.003	450	2.071
80	4.914	500	1.624
100	4.794	550	1.178
150	4.473	600	0.744
200	4.124	650	0.340
250	3.752	700	0.018
300	3.357		

TABLE A12a Specific Heat at Constant Pressure of Steam and Water (Btu/lbm °F)

Temp (°F)	Pressure (psia)											
	1	2	5	10	20	50	100	200	500	1000	2000	5000
1500	0.559	0.559	0.559	0.559	0.559	0.560	0.561	0.563	0.569	0.580	0.601	0.668
1400	0.551	0.551	0.551	0.551	0.551	0.552	0.553	0.555	0.563	0.575	0.600	0.681
1300	0.543	0.543	0.543	0.543	0.543	0.544	0.545	0.548	0.556	0.570	0.600	0.702
1200	0.533	0.533	0.533	0.533	0.534	0.535	0.536	0.540	0.550	0.567	0.603	0.740
1100	0.524	0.542	0.524	0.524	0.525	0.526	0.528	0.532	0.544	0.564	0.612	0.814
1000	0.515	0.515	0.515	0.515	0.516	0.518	0.519	0.524	0.539	0.566	0.633	0.970
900	0.506	0.506	0.506	0.506	0.507	0.509	0.512	0.518	0.537	0.576	0.683	1.382
800	0.497	0.497	0.497	0.497	0.498	0.501	0.505	0.513	0.544	0.605	0.800	2.420
700	0.488	0.488	0.488	0.489	0.490	0.494	0.500	0.513	0.563	0.681	1.181	1.897[b]
600	0.479	0.480	0.480	0.481	0.483	0.489	0.499	0.522	0.621	0.888	1.453	1.253
500	0.472	0.472	0.473	0.475	0.478	0.489	0.508	0.554	0.773	1.181	1.157	1.106
400	0.464	0.465	0.467	0.470	0.476	0.497	0.536	0.636	1.077	1.072	1.063	1.041
300	0.458	0.459	0.463	0.469	0.482	0.524	1.029	1.028	1.027	1.024	1.019	1.006
250	0.456	0.458	0.463	0.471	0.489	1.015	1.014	1.014	1.013	1.011	1.007	0.996
200	0.453	0.455	0.463	0.475	1.005	1.005	1.005	1.004	1.003	1.002	0.998	0.989
150	0.451	0.455	0.866	1.001	1.000	1.000	1.000	1.000	0.998	0.997	0.993	0.984
100	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.997	0.996	0.994	0.990	0.980
50	1.002	1.002	1.002	1.002	1.002	1.002	1.001	1.001	0.999	0.996	0.989	0.972
32	1.007	1.007	1.007	1.007	1.007	1.007	1.006	1.006	1.003	0.999	0.990	0.969

[a] Horizontal bars indicate phase change

[b] Critical point ($P = 3{,}206.2$ psia; $T = 705.4$°F).

TABLE A12b Viscosity of Steam and Water (lbm/h ft)

Temp (°F)	Pressure (psia) 1	2	5	10	20	50	100	200	500	1000	2000	5000
1500	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.0996	0.1008	0.1008	0.1019	0.1066
1400	0.0938	0.0938	0.0938	0.0938	0.0938	0.0938	0.0952	0.0952	0.0952	0.0961	0.0973	0.1019
1300	0.0892	0.0982	0.0892	0.0892	0.0892	0.0892	0.0892	0.0892	0.0892	0.0903	0.0915	0.0973
1200	0.0834	0.0834	0.0834	0.0834	0.0834	0.0834	0.0834	0.0834	0.0846	0.0846	0.0867	0.0926
1100	0.0776	0.0776	0.0776	0.0776	0.0776	0.0776	0.0776	0.0776	0.0788	0.0799	0.0811	0.0892
1000	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0730	0.0741	0.0764	0.0857
900	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0683	0.0683	0.0707	0.0846
800	0.0614	0.0614	0.0614	0.0614	0.0614	0.0614	0.0614	0.0614	0.0625	0.0637	0.0660	0.0973
700	0.0556	0.0556	0.0556	0.0556	0.0556	0.0556	0.0568	0.0568	0.0568	0.0579	0.0625	0.171[b]
600	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510	0.210	0.221
500	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0452	0.0440	0.0440	0.250	0.255	0.268
400	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0394	0.0382	0.317	0.320	0.323	0.335
300	0.0336	0.0336	0.0336	0.0336	0.0336	0.0336	0.441	0.442	0.444	0.445	0.448	0.460
250	0.0313	0.0313	0.0313	0.0313	0.0313	0.551	0.551	0.551	0.552	0.554	0.558	0.569
200	0.0290	0.0290	0.0290	0.0290	0.725	0.725	0.725	0.726	0.729	0.729	0.732	0.741
150	0.0255	0.0255	1.032	1.032	1.032	1.032	1.032	1.032	1.033	1.034	1.037	1.044
100	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.645	1.646	1.646	1.648
50	3.144	3.144	3.144	3.144	3.144	3.144	3.144	3.142	3.141	3.139	3.134	3.119
32	4.240	4.240	4.240	4.240	4.240	4.240	4.240	4.239	4.236	4.231	4.222	4.192

[a] Horizontal bars indicate phase change.
[b] Critical point ($P = 3{,}206.2$ psia; $T = 705.4°$F).

TABLE A12c Thermal Conductivity of Steam and Water [(Btu/h ft °F) × 10^3]

Temp (°F)	Pressure (psia) 1	2	5	10	20	50	100	200	500	1000	2000	5000
1500	63.7	63.7	63.7	63.7	63.7	63.8	64.0	64.3	65.4	67.1	70.7	82.0
1400	59.2	59.2	59.2	59.2	59.3	59.4	59.6	59.9	60.9	62.7	66.3	78.2
1300	54.8	54.8	54.8	54.8	54.8	54.9	55.1	55.5	56.5	58.3	62.0	74.6
1200	50.4	50.4	50.4	50.4	50.4	50.5	50.7	51.0	52.1	53.9	57.8	71.6
1100	46.0	46.0	46.0	46.0	46.1	46.2	46.3	46.7	47.8	49.6	53.7	69.8
1000	41.7	41.7	41.8	41.8	41.8	41.9	42.1	42.4	43.5	45.5	50.0	70.7
900	37.6	37.6	37.6	37.6	37.6	37.7	37.9	38.3	39.4	41.5	46.8	80.2
800	33.6	33.6	33.6	33.6	33.6	33.7	33.9	34.3	35.5	37.9	44.9	129.6
700	29.7	29.7	29.7	29.7	29.8	29.9	30.1	30.4	31.8	35.0	47.5	262.8[b]
600	26.0	26.0	26.1	26.1	26.1	26.2	26.4	26.9	28.7	34.1	301.9	333.7
500	22.6	22.6	22.6	22.6	22.7	22.8	23.0	23.6	26.9	350.8	357.4	373.8
400	19.4	19.4	19.4	19.4	19.5	19.6	20.0	21.3	383.0	384.9	388.5	398.6
300	16.5	16.5	16.5	16.5	16.6	16.9	396.9	397.2	398.0	399.2	402.0	409.9
250	15.1	15.1	15.1	15.2	15.3	396.9	397.0	397.3	398.1	399.4	402.1	409.7
200	13.8	13.8	13.9	14.0	391.6	391.6	391.8	392.1	393.0	394.4	397.2	404.9
150	12.7	12.7	380.5	380.5	380.6	380.7	380.8	381.1	382.1	383.7	386.7	394.7
100	363.3	363.3	363.3	363.3	363.3	363.4	363.6	363.9	365.0	366.6	369.8	378.3
50	339.1	339.1	339.1	339.1	339.2	339.3	339.4	339.8	340.8	342.5	345.7	354.6
32	328.6	328.6	328.6	328.6	328.6	328.7	328.9	329.2	330.3	331.9	335.1	344.1

[a] Horizontal bars indicate phase change.
[b] Critical point ($P = 3{,}206.2$ psia; $T = 705.4$°F).

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Glossary

acfh	Actual cubic feet per hour.
acfm	Actual cubic feet per minute, a term used to indicate the flow rate of gases, at any condition of temperature and pressure.
°API	A scale adopted by American Petroleum Institute to indicate the specific gravity of a liquid. Water has an API gravity of 10°API and No. 2 fuel oil, about 35°API.
ABMA	American Boiler Manufacturers Association.
ASME	American Society of Mechanical Engineers.
ASR	Actual steam rate, a term used to indicate the actual steam consumption of steam turbines in lb/kWh.
BHP	Brake horsepower, a term used for power consumption or rating of turbomachinery. This does not include the efficiency of the drive.
Btu	British thermal unit, a term for measuring heat.
CFD	Computational fluid dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
cP	Centipoise, a unit for measurement of absolute viscosity.
CR	Circulation ratio, a term used to indicate the ratio by weight of a mixture of steam and water to that of steam in the mixture. A CR

	of 4 means that 1 lb of steam–water mixture has $\frac{1}{4}$ lb of steam and the remainder water.
dB	Decibel, a unit for measuring noise or sound pressure levels.
dBA	Decibel, scale A; a unit for measuring sound pressure levels corrected for frequency characteristics of the human ear.
DNB	Departure from nucleate boiling.
FGR	Flue gas recirculation.
fps, fpm, fph	Feet per second, minute, and hour; units for measuring the velocity of fluids.
HAT	Humid air turbine.
gpm, gph	Volumetric flow rate in gallons per minute or hour.
HHV	Higher heating value or gross heating value of fuels.
HRSG	Heat recovery steam generator.
ICAD	Intercooled aeroderivative.
ID	Inner diameter of tube or pipe.
IGCC	Integrated gasification and combined cycle.
in. WC	A unit to measure pressure of gas streams; inches of water column.
kW	Kilowatt, a unit of measurement of power.
LHV	Lower heating value or net heating value of a fuel.
LMP	Larson–Miller parameter.
LMTD	Log-mean temperature difference.
ln	Logarithm to base e; natural logarithm.
log	Logarithm to base 10.
M lb/h	Thousands of pounds per hour
MM Btu	Millions of British thermal units.
MW	Molecular weight.
NOx	Oxides of nitrogen.
NPSH	Net positive suction head, a term used to indicate the effective head in feet of liquid column to avoid cavitation. Subscripts r and a stand for required and available.
NTU	Number of transfer units; a term used in heat exchanger design.
OD	Outer diameter of tube or pipe.
oz	Ounce.
ozi	Ounces per square inch, a term for measuring fluid pressure.
ppm	Parts per million by weight or volume.
psia	Pounds per square inch absolute, a term for indicating pressure.
psig	Pounds per square inch gauge, a term for measuring pressure.
PWL	Sound power level, a term for indicating the noise generated by a source such as a fan or turbine.
RH	Relative humidity.
SBV, SBW	Steam by volume and by weight in a steam–water mixture, terms

	used by boiler designers.
scfm, scfh	Standard cubic feet per minute or hour, units for flow of gases at standard conditions of temperature and pressure, namely at 70°F and 29.92 in.Hg, or 14.696 psia. Sometimes 60°F and 14.696 psia is also used. The ratio of scfm at 70°F to scfm at 60°F is 1.019.
SCR	Selective catalytic reduction.
SNCR	Selective noncatalytic reduction.
SPL	Sound pressure level, a unit of measurement of noise in decibels.
SSU	Seconds, Saybolt Universal; a unit of kinematic viscosity of fluids.
SVP	Saturated vapor pressure, pressure of water vapor in a mixture of gases.
TSR	Theoretical steam rate, a term indicating the theoretical consumption of steam to generate a kilowatt of electricity in a turbine in lb/h.
UHC	Unburned hydrocarbon.
VOC	Volatile organic compound.