MMME2104

Design & Selection of Mining Equipment

Electrical Component

DC Machines

Lecture 8

24 September 2003

Lecture Outline

- DC Generators
  - Operating principle
  - Separately excited generator
  - Shunt generator
  - Compound generator
- DC Motors
  - Shunt motor
  - Series motor
  - Compound motor
  - Starting and braking
  - Basics of speed control

DC Generators: Operating Principle

Generating an AC voltage:

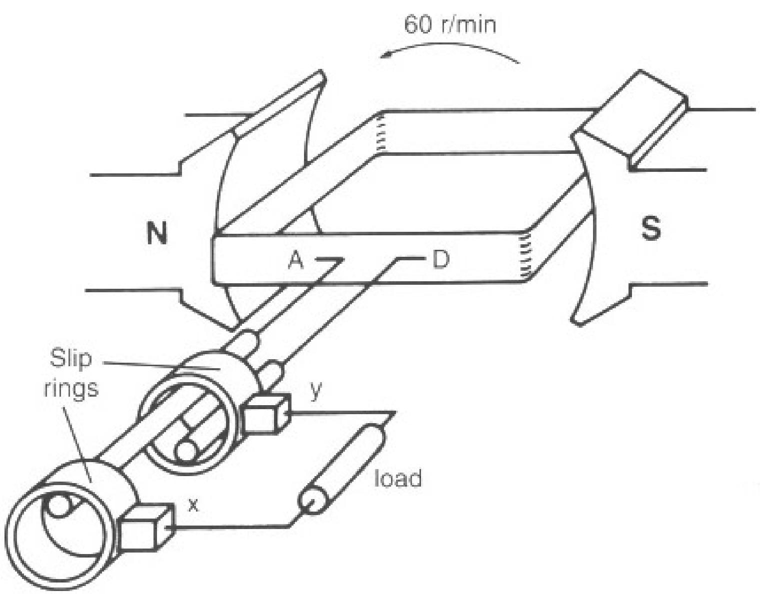


Figure 4.1
Schematic diagram of an elementary ac generator turning at 1 revolution per second.

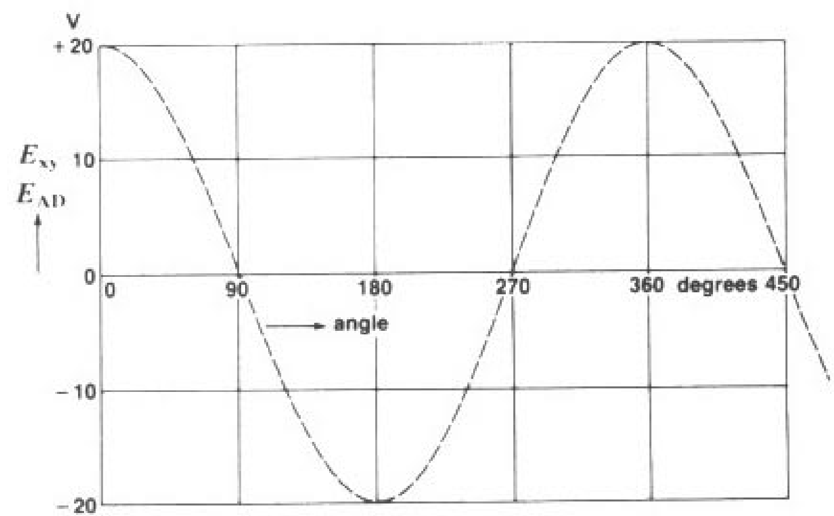


Figure 4.2
Voltage induced in the ac generator as a function of the angle of rotation.

DC Generators: Operating Principle

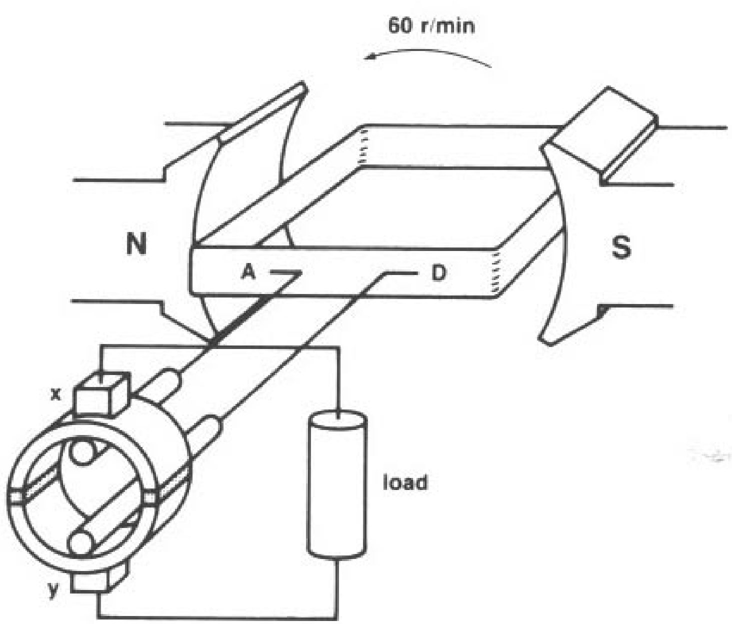


Figure 4.4
Elementary dc generator is simply an ac generator equipped with a mechanical rectifier called a *commutator.*

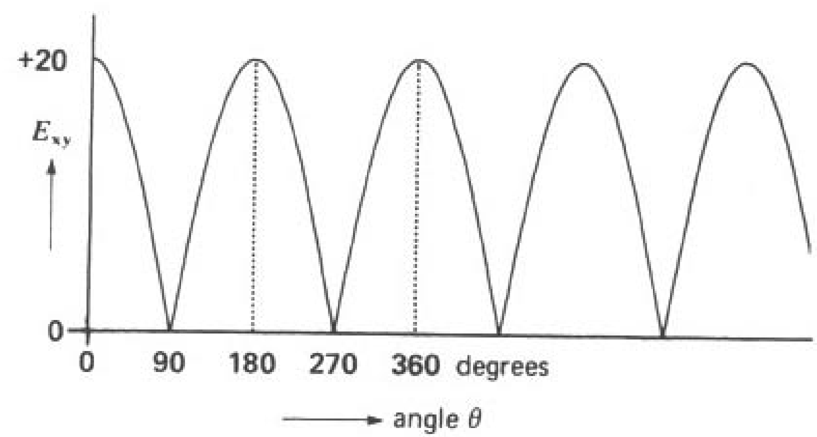


Figure 4.5
The elementary dc generator produces a pulsating dc voltage.

DC Generators: Operating Principle

The difference between AC and DC generators:

- AC generators use *slip rings*
- DC generators use *commutators*

Otherwise, the machine constructions are essentially the same.

DC Generators: Operating Principle

Improving the DC output waveform:

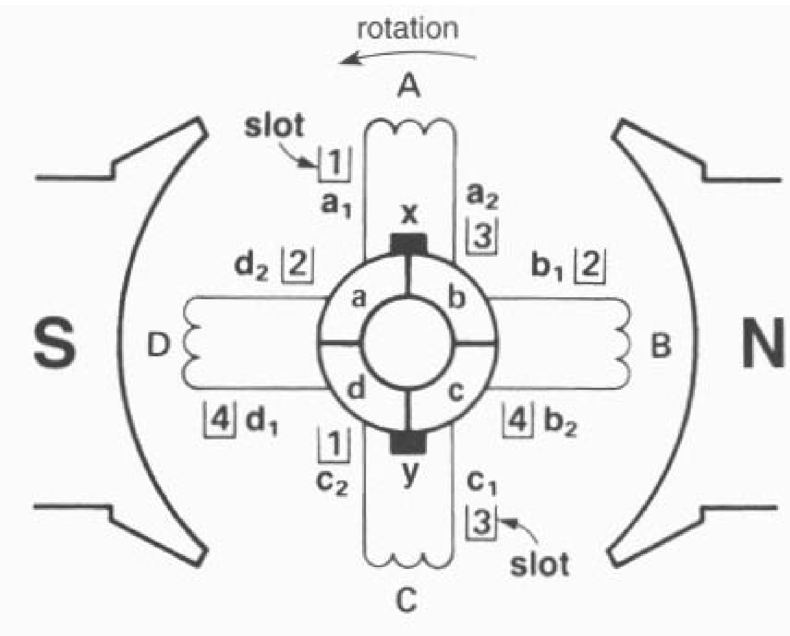


Figure 4.7
Schematic diagram of a dc generator having 4 coils and 4 commutator bars. See Fig. 4.9.

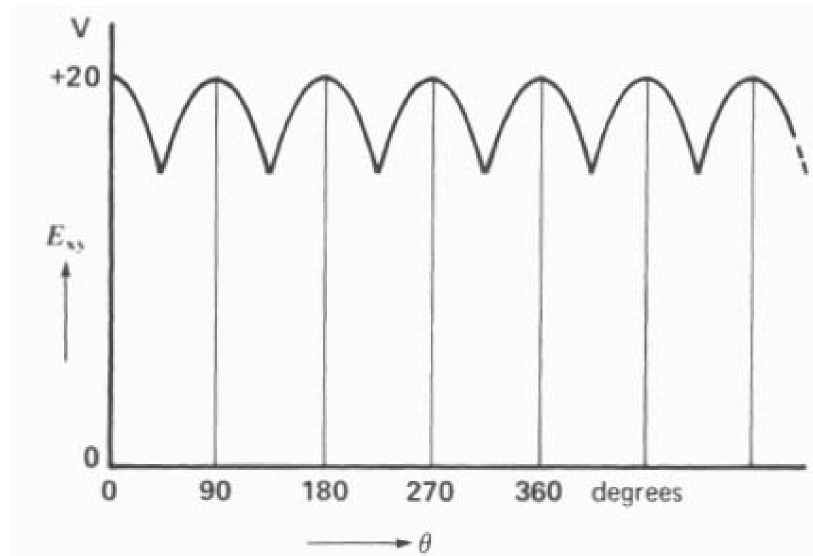


Figure 4.8
The voltage between the brushes is more uniform than in Fig. 4.5.

DC Generators: Operating Principle

Induced voltage in a DC generator: $E = B\,L\,v$ (Faraday's Law)

For a DC generator, this equation can be manipulated to give:

$$E_o = C\,n\,\Phi / 60$$

E_o = voltage between the brushes (V)
N = speed of rotation (rpm)
Φ = flux per pole (Wb)
C = total number of conductors on the armature*

*The number of conductors equals the number of slots (coils) times the number of turns per coil times two

DC Generators: Operating Principle

Neutral zones:

Neutral zones are those places on the surface of the armature where the flux density is zero.

When a generator operates at no-load, the neutral zones are located exactly between the poles.

No voltage is induced in a coil that cuts through the neutral zone.

We always try to set the brushes so they are in contact with coils that are momentarily in a neutral zone.

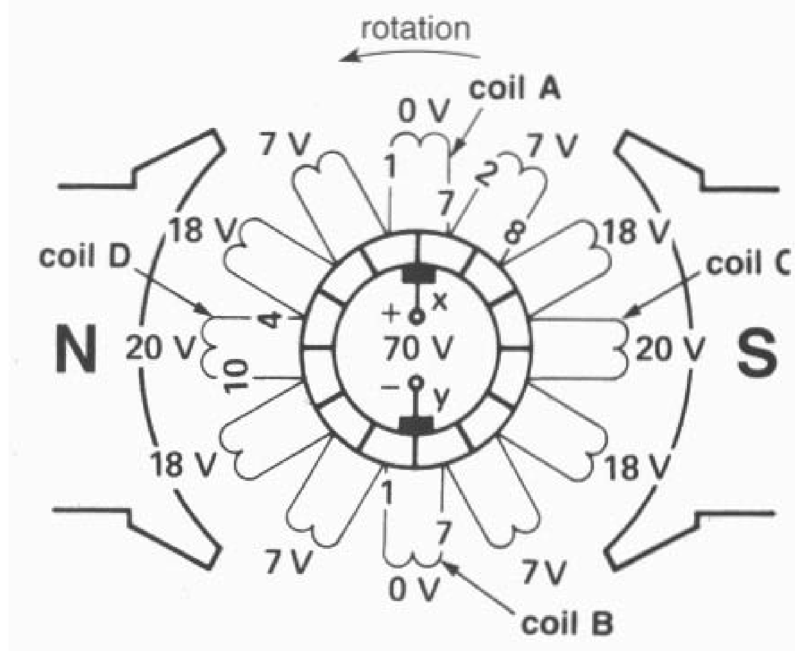


Figure 4.11b
Schematic diagram of the armature and the voltages induced in the 12 coils.

DC Generators: Operating Principle

Armature reaction:

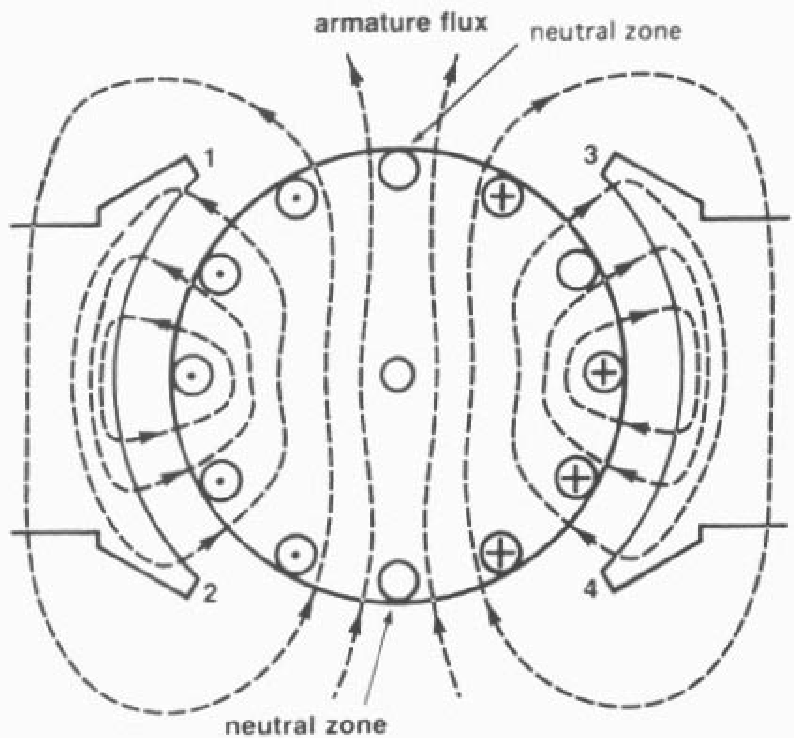


Figure 4.14
Magnetic field produced by the current flowing in the armature conductors.

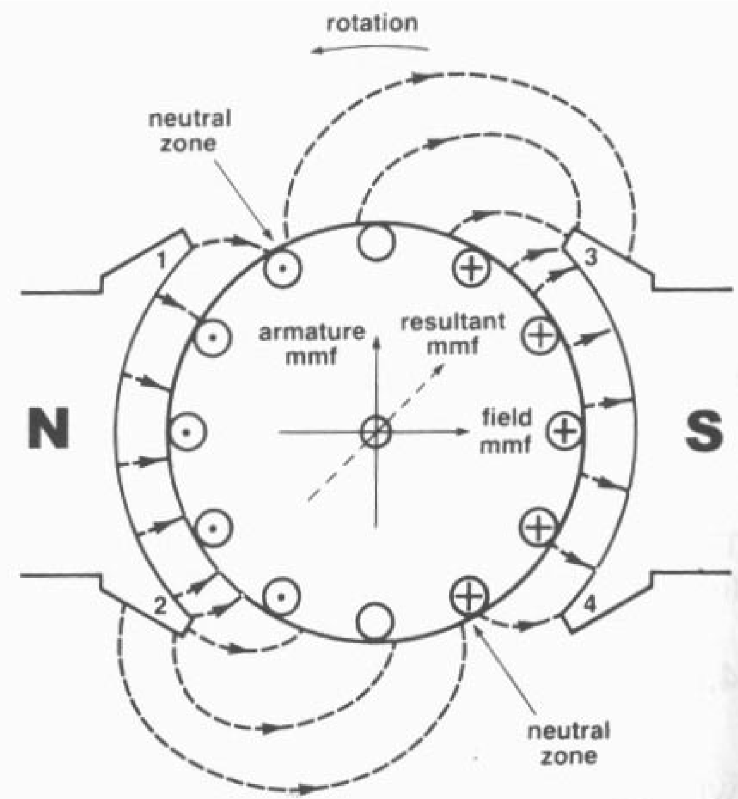


Figure 4.15
Armature reaction distorts the field produced by the N, S poles.

DC Generators: Operating Principle

Shifting the brushes to improve commutation and using commutating poles:

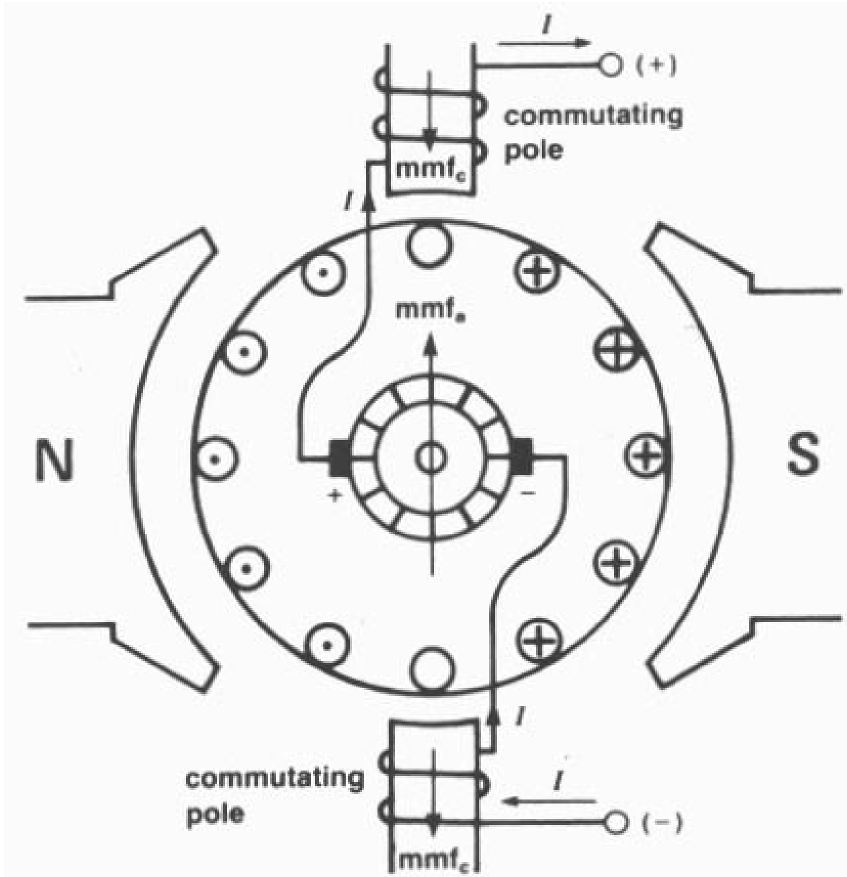
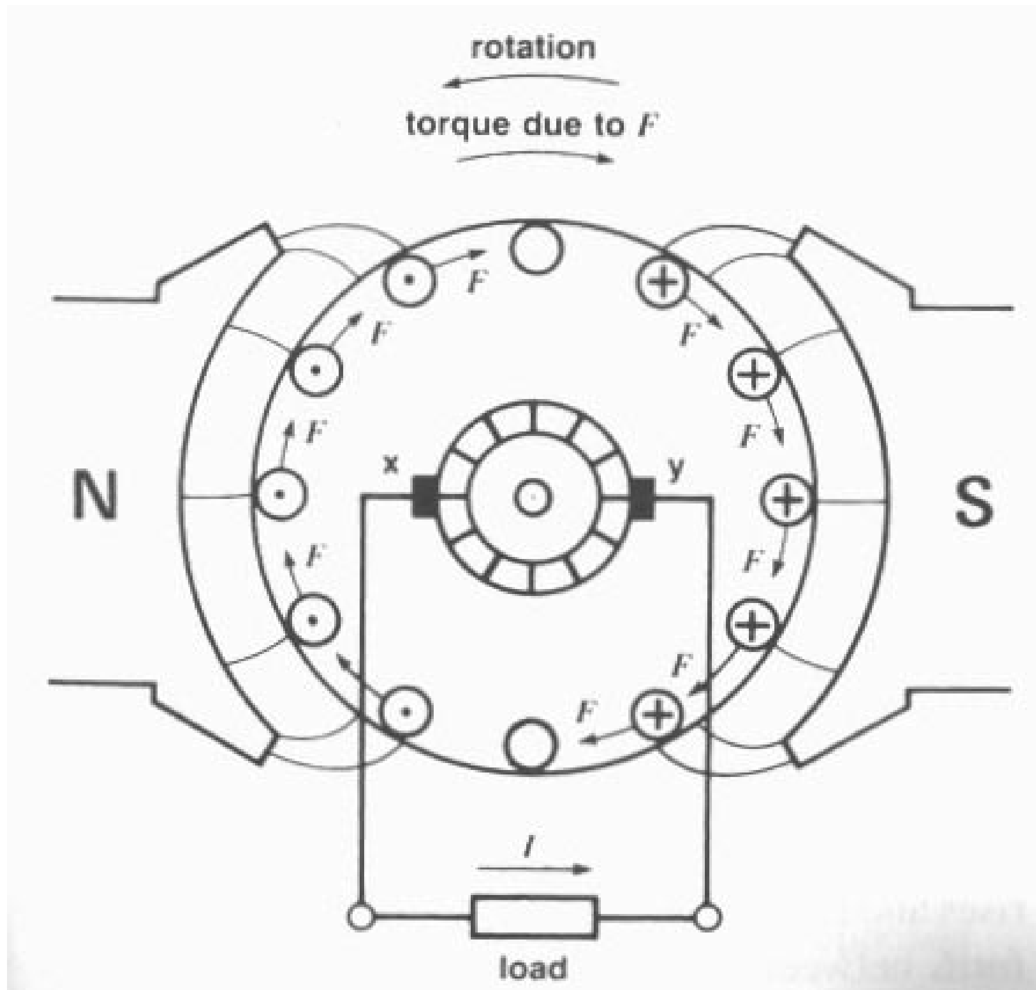


Figure 4.16
Commutating poles produce an mmf$_c$ that opposes the mmf$_a$ of the armature.

DC Generators: Operating Principle

The electromechanical energy conversion process



Separately Excited DC Generator

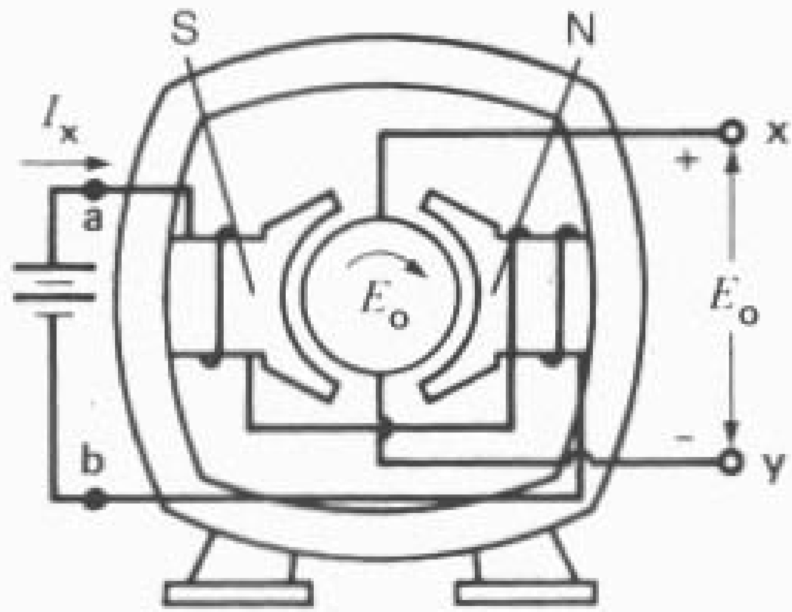


Figure 4.17
Separately excited 2-pole generator. The N, S field poles are created by the current flowing in the field windings.

No Load Saturation Curves

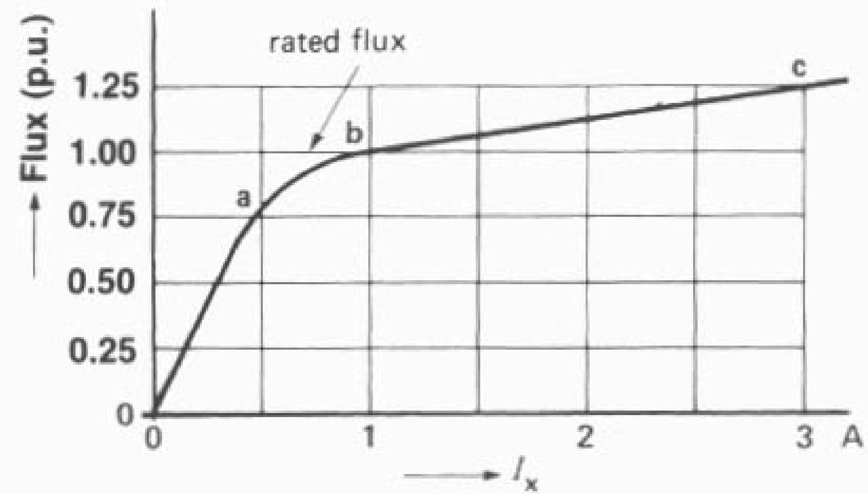


Figure 4.18a
Flux per pole versus exciting current.

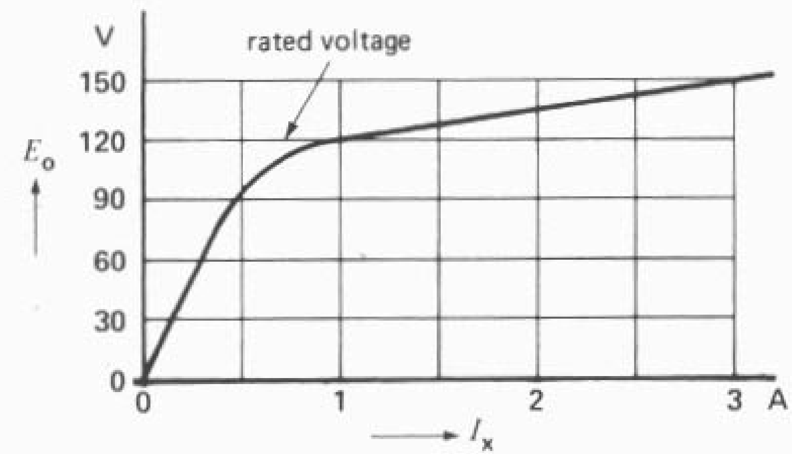
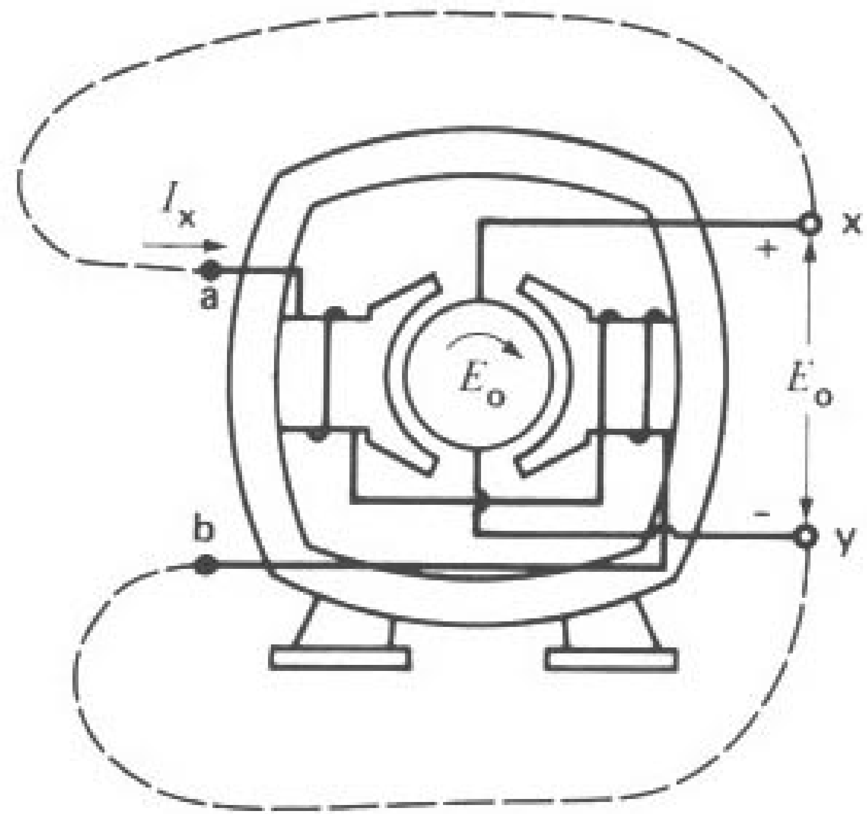


Figure 4.18b
Saturation curve of a dc generator.

Shunt DC Generator

Field winding in parallel with armature



Shunt DC Generator

Controlling the voltage of a shunt generator:

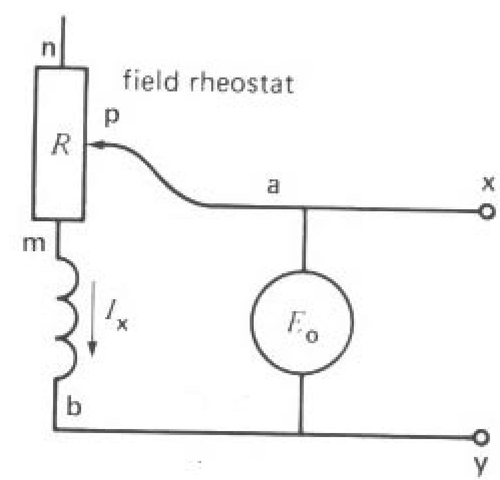


Figure 4.20
Controlling the generator voltage with a field rheostat. A rheostat is a resistor with an adjustable sliding contact.

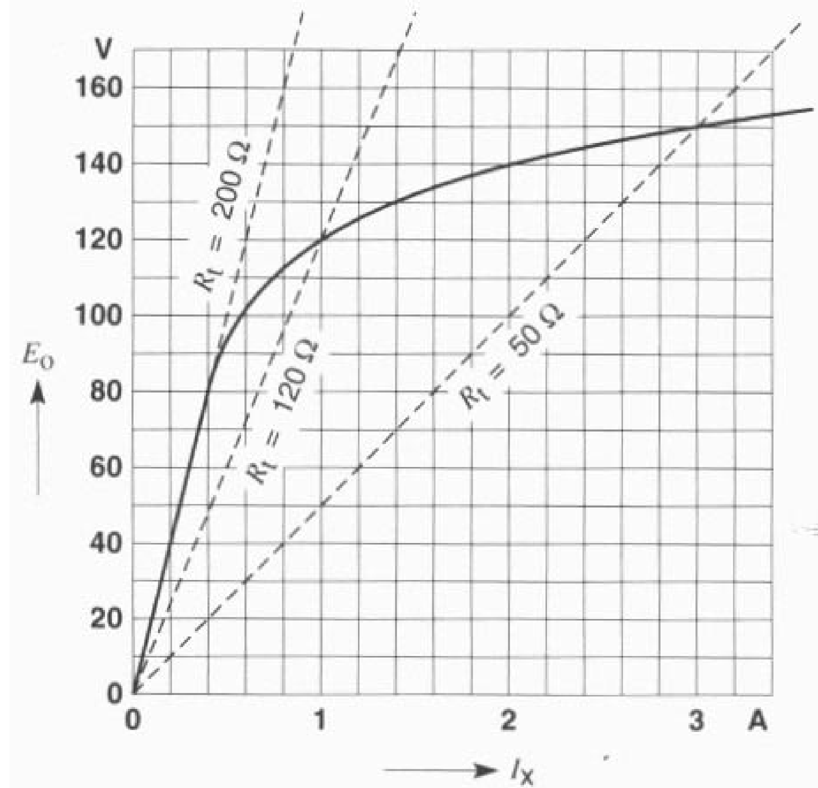


Figure 4.21
The no-load voltage depends upon the resistance of the shunt-field circuit.

Equivalent circuit of a DC Generator

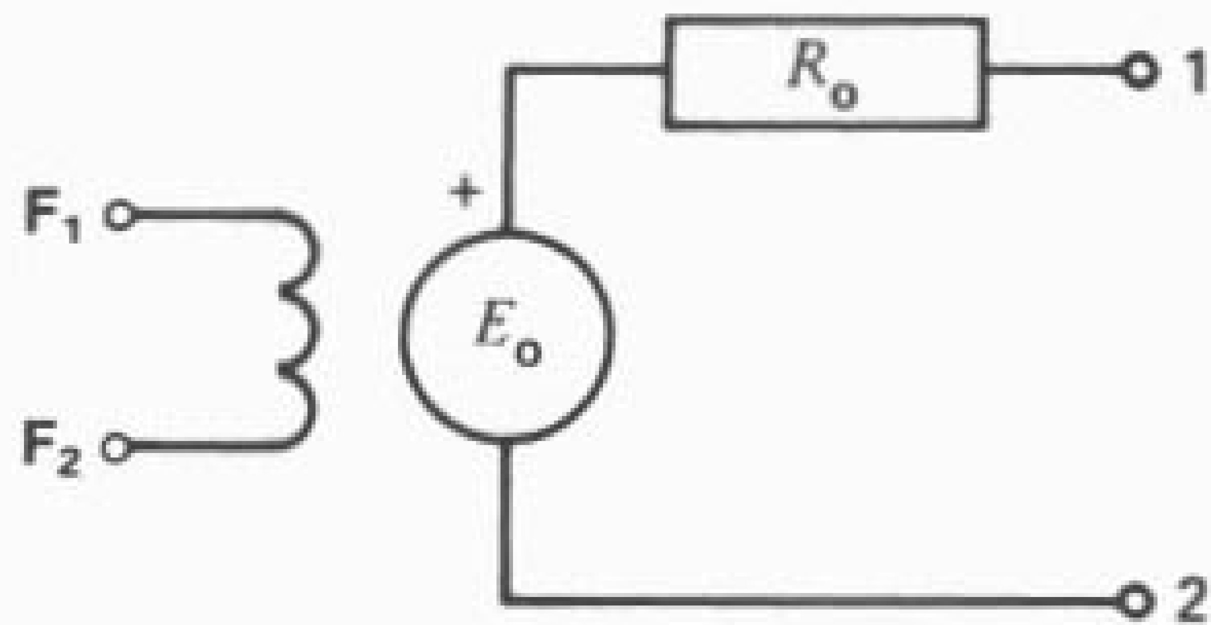


Figure 4.22
Equivalent circuit of a dc generator.

Separately Excited DC generator under load

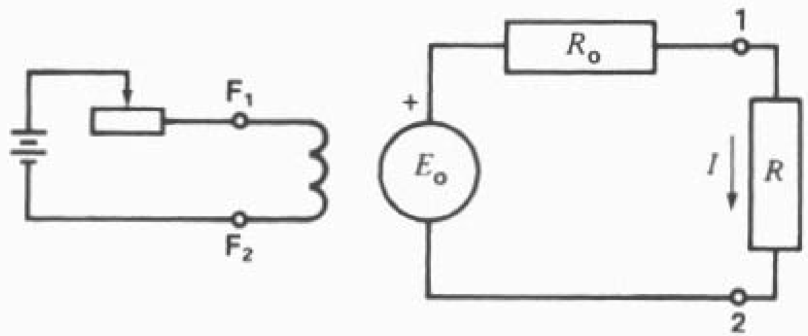


Figure 4.23
Separately excited generator under load.

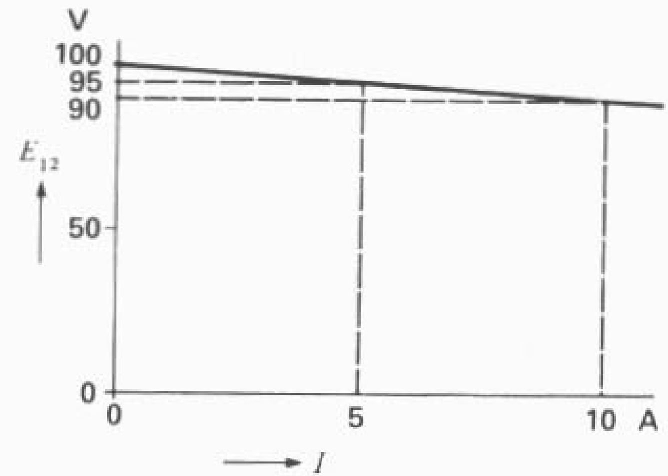
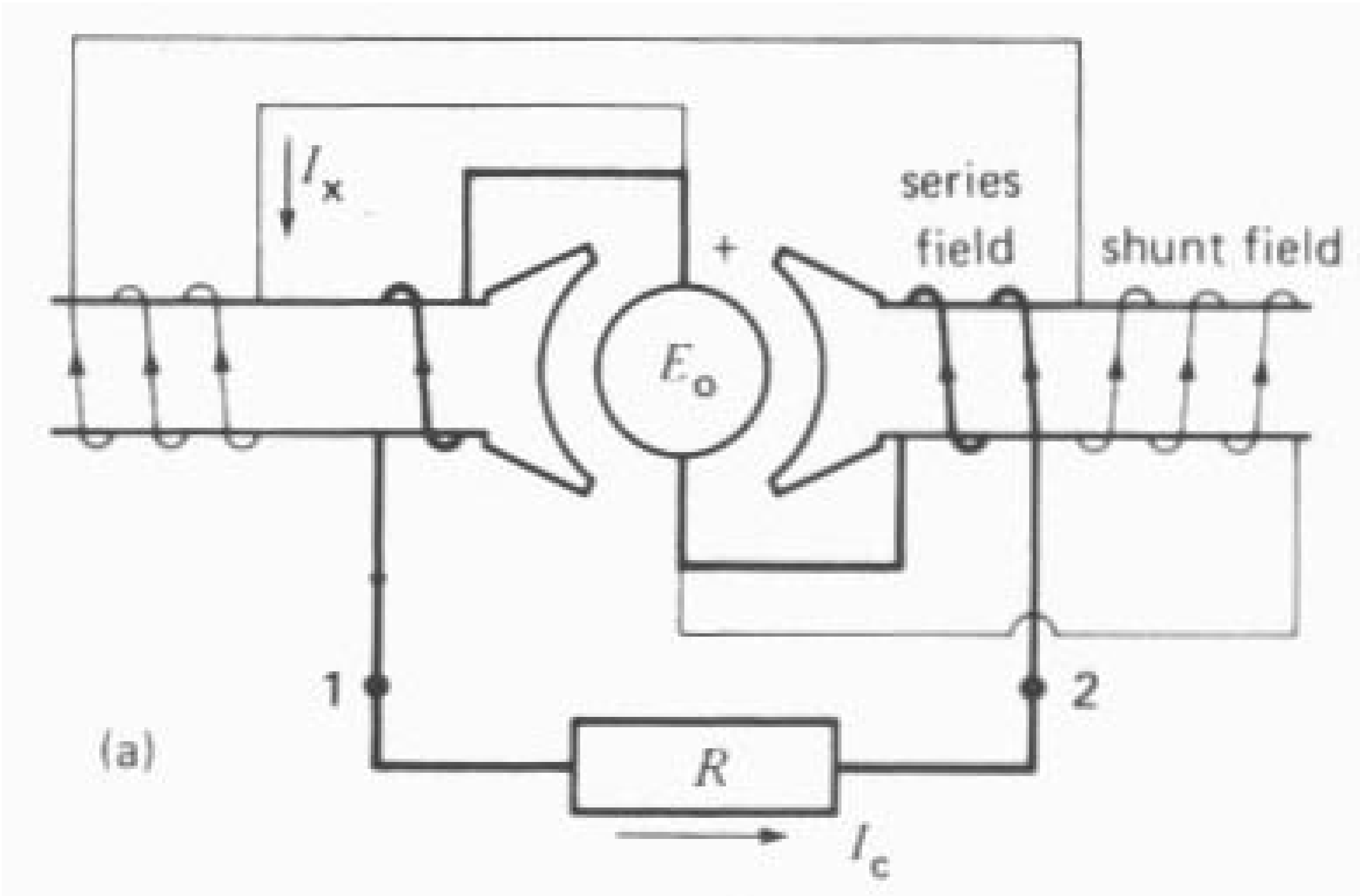


Figure 4.24
Load characteristic of a separately excited generator.

Compound DC Generator



DC Generator Load Characteristics

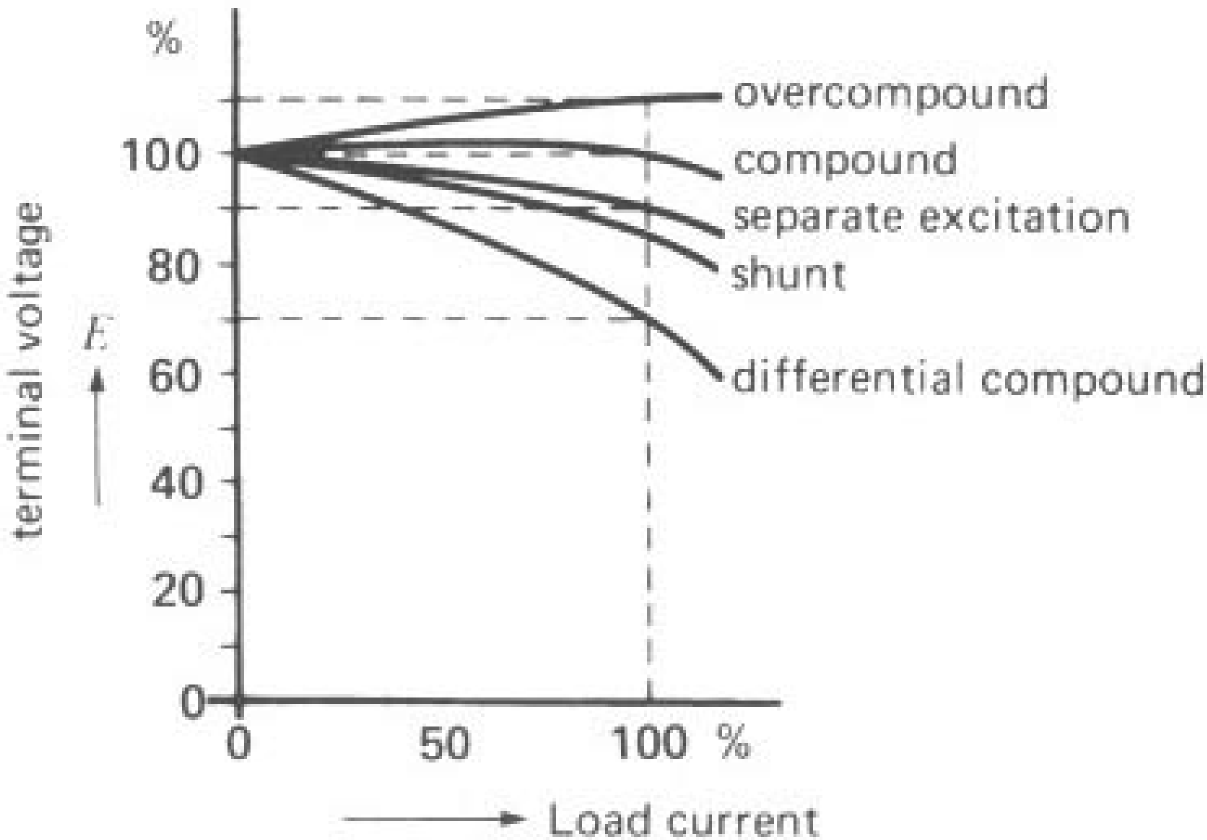


Figure 4.26
Typical load characteristics of dc generators.

DC Motors

Important DC motor types:

- Shunt Motors
- Series Motors
- Compound Motors

Direct current motors are seldom used in ordinary industrial applications because all electric utilities supply AC. However, for special applications such as in steel mills, mines, and electric trains, it is sometimes advantageous to transform the AC into DC in order to use DC motors. The reason is that the torque-speed characteristics of DC motors can be varied over a wide range while retaining high efficiency.

DC Motors: Back EMF

Direct current motors are built the same way as generators are; consequently, a DC machine can operate either as a motor or as a generator.

When a motor spins, a voltage is induced in the same manner as a generator. This voltage opposes the motor supply voltage, and is known as *back EMF*:

$$E_o = Cn\Phi/60$$

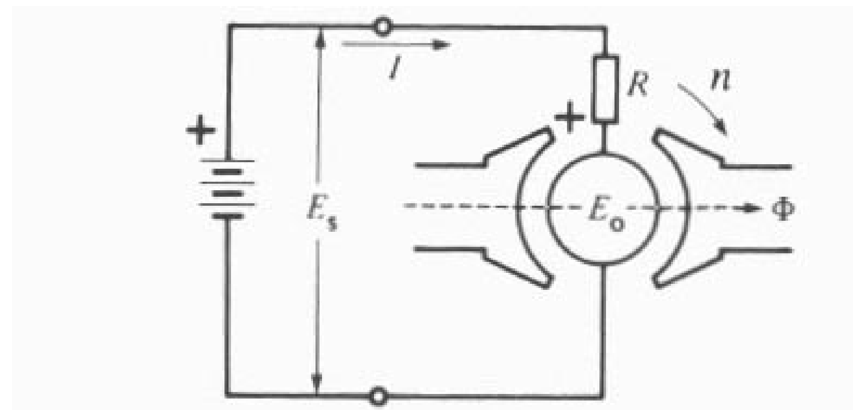


Figure 5.2
Counter-electromotive force (cemf) in a dc motor.

Acceleration of DC Motors

The net voltage acting on the armature circuit of a DC motor is $(E_s - E_o)$ volts. The resulting current is limited only by the armature resistance R, and so

$$I = (E_s - E_o)/R$$

When the motor is at rest, the induced voltage $E_o = 0$, and so the starting current is

$$Is = E_s/R$$

The starting current produces a powerful starting torque that rapidly accelerates the rotor. As the speed increases, the back EMF increases, with the result that the armature current falls.

The motor continues to accelerate until it reaches the no-load speed. At this speed a back EMF is produced that is slightly less than the supply voltage. The slight voltage difference results in a small *no-load current* that produces sufficient torque to overcome friction.

Mechanical power and torque

Power:

We know that $E_o = C\ n\ \Phi / 60$.

We also know that the electrical power supplied to the armature is given by:

$$P_a = E_s\ I$$

Furthermore, the supply voltage is the sum of the back EMF and the resistive drop in the armature: $E_s = E_o + IR$

It follows that $P_a = E_o\ I + I^2R$

The I^2R term represents heat losses in the armature.

The E_oI term is the electrical power that is converted to mechanical power:

$$P_m = E_oI$$

In reality, the actual mechanical output power is slightly less than Pm due to bearing friction losses, windage losses and armature iron losses.

Mechanical power and torque

Torque:

We also know that the mechanical power is given by $P_m = \pi nT/30$. Therefore we may write $\pi nT/30 = Cn\Phi I/60$

$$T = C\Phi I/2\pi = K_T I \qquad \text{where} \quad K_T = C\Phi/2\pi$$

K_T is known as the *torque constant (Nm/A)* of the motor.

This shows that we can increase the torque of the motor either by raising the armature current or by raising the pole flux.

DC Motors: Speed of Rotation

When a DC motor drives a a load between no-load and full-load, the voltage drop due to armature resistance is always small compared to the supply voltage ($IR << E_s$). Therefore, $E_o \approx E_s$

So we may write:

$$E_s \approx C\, n\, \Phi / 60 \qquad \text{or} \qquad n \approx 60\, E_s / C\, \Phi$$

If the motor speed is expressed in radians per second, we may write:

$\omega = 2\pi\, E_s / C\, \Phi = E_s / K_e$ where $K_e = C\Phi/2\pi$

Ke is known as the *speed constant (Vs/rad)* of the motor

Torque and Speed Constants

When expressed in SI units, the torque and speed constants are exactly the same!

$$K_e = K_T = C\Phi/2\pi$$

DC Motors: Speed of Rotation

The expressions for motor speed show that the speed of the motor is directly proportional to the armature supply voltage and inversely proportional to the flux per pole. This gives rise to two methods of controlling the speed of DC motors:

1. Armature speed control
2. Field speed control

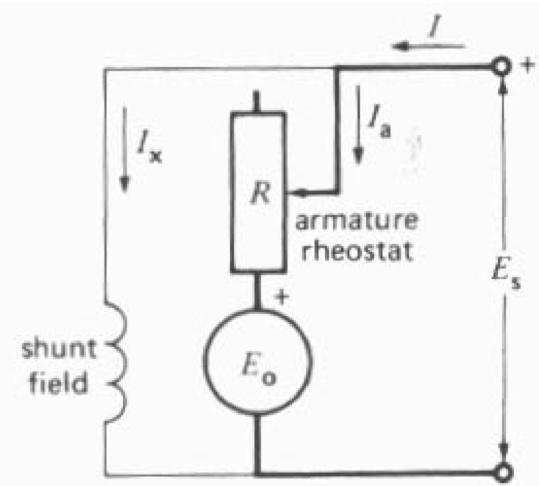
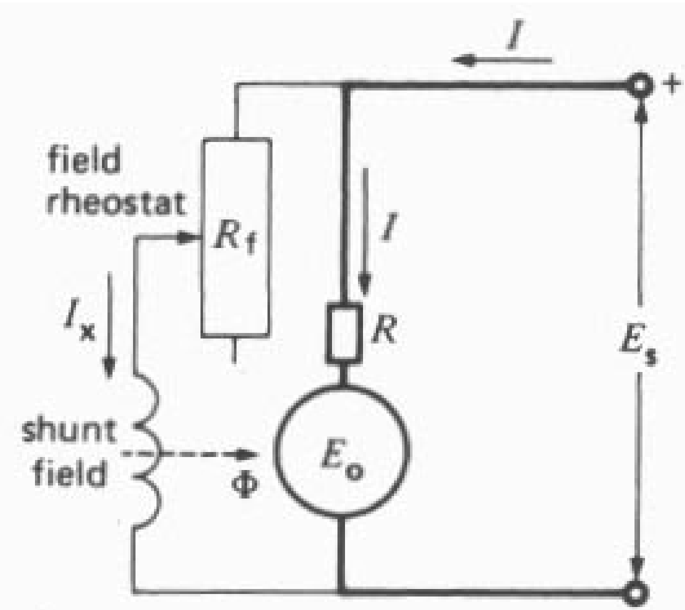


Figure 5.7
Armature speed control using a rheostat.

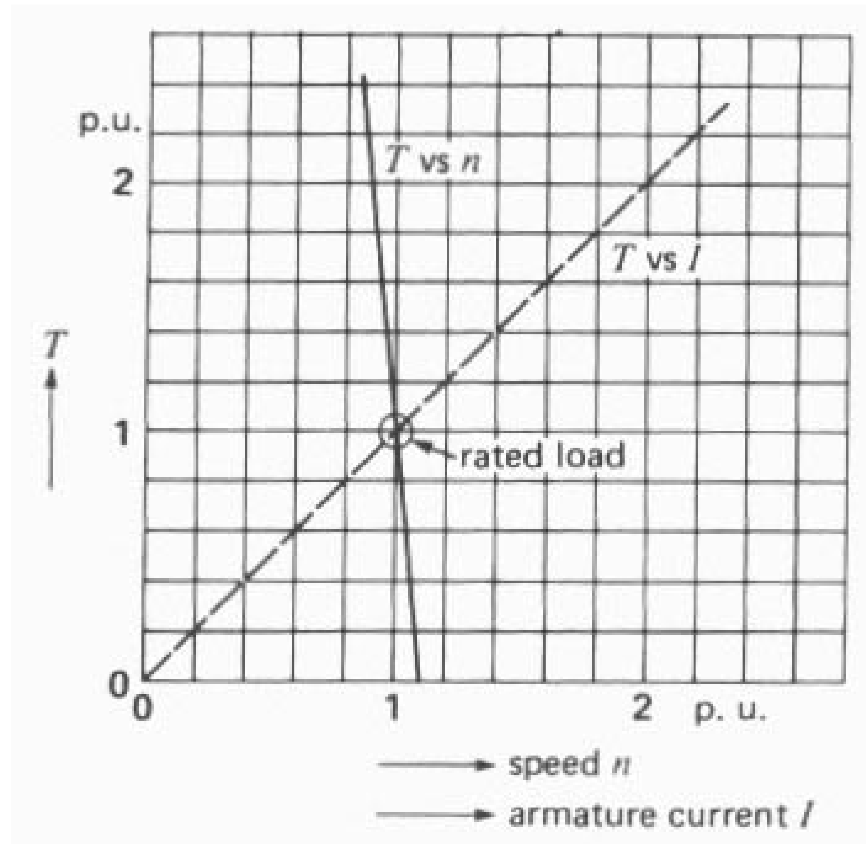


Shunt Motor Under Load

For shunt motors, as the load increases, the speed drops and the armature current (and torque) rises.

The speed of a shunt motor stays relatively constant from no-load to full load – 10-15% drop in small motors, and much less in large motors.

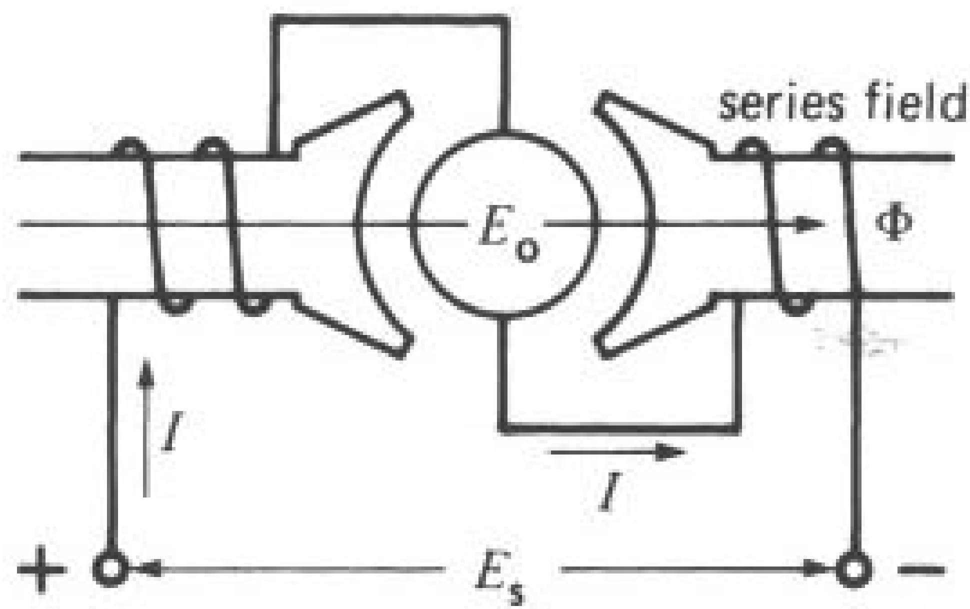
Of course, via field control the speed can be kept constant regardless of load.



Series DC Motors

A series DC motor is identical in construction to a shunt motor except for the field winding. The field is connected in series with the armature and must therefore carry the full armature current.

Therefore the series field winding is normally composed of a few turns of wire with cross section large enough to carry he current.



Series DC Motors

The properties of a series motor are completely different from those of a shunt motor.

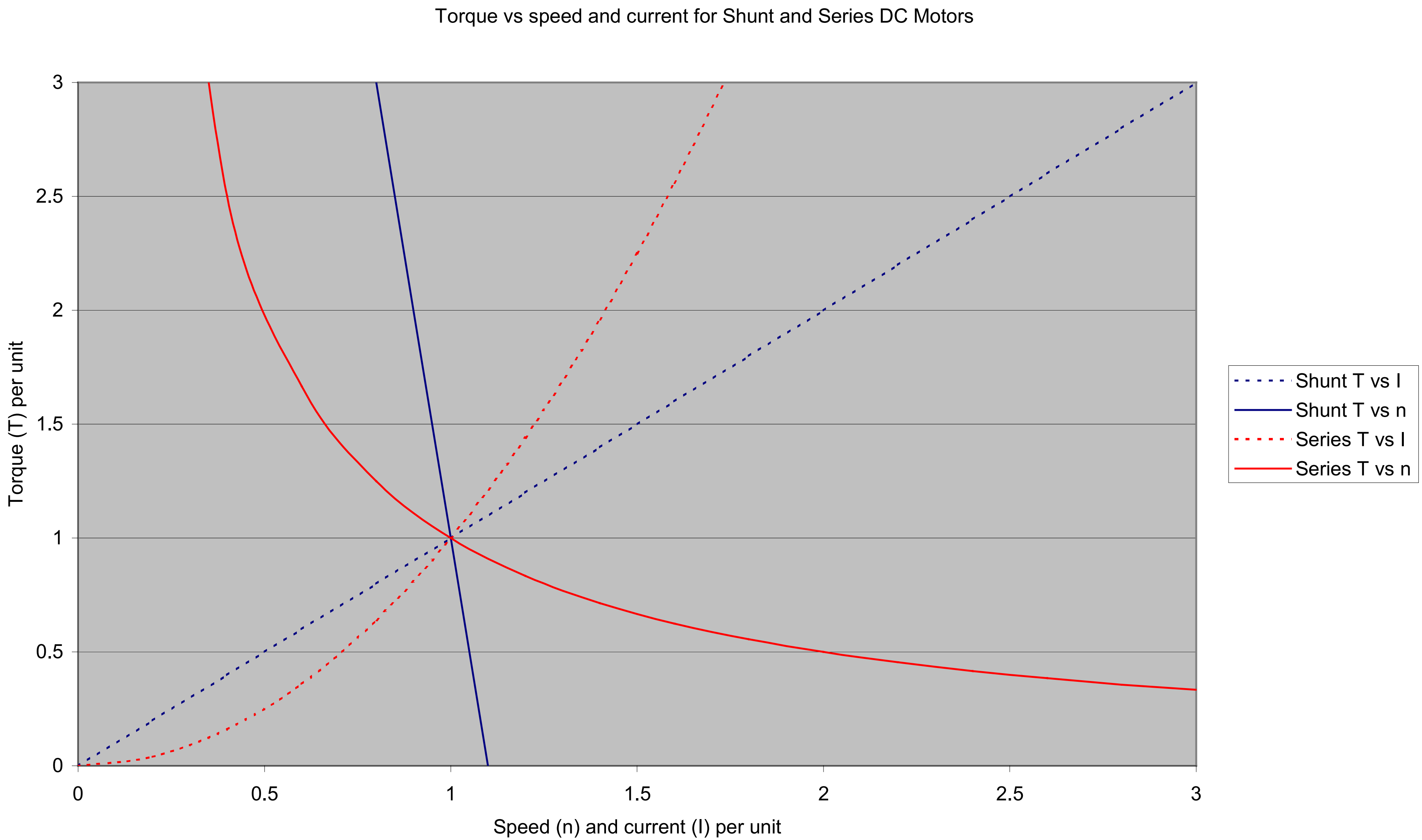
In a shunt motor, the flux per pole is constant at all loads because the shunt field is connected directly to the supply. In a series motor, the flux per pole depends upon the armature current and hence the load.

When a series motor operates at full load, the flux per pole is the same as that of a shunt motor of identical power and speed.

When the series motor starts, the armature current is higher than normal AND the flux per pole is higher than normal. Therefore series motors have extremely high starting torque.

Conversely, when the motor operates below full load, the armature current and pole flux are both smaller. The weaker field causes the speed to rise much higher than normal.

Series vs Shunt DC Motors

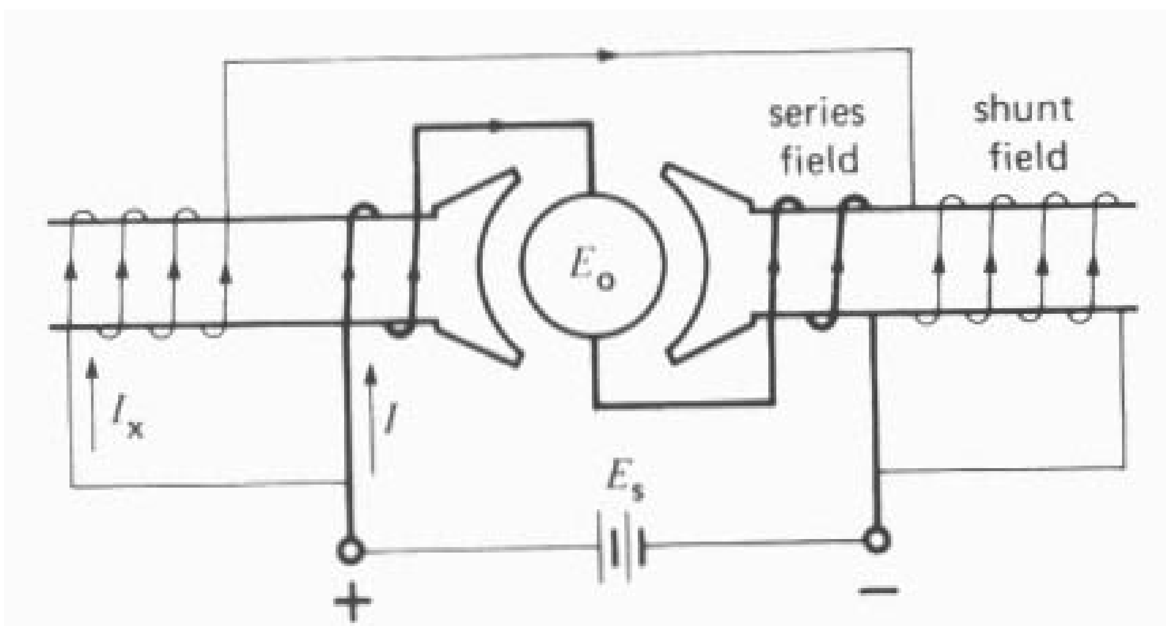


Compound DC Motors

A compound DC motor carries both a series field winding and a shunt field winding.

The two fields are oriented so they add.

Therefore as the load increases, the speed decreases – much more than it would for a plain shunt motor – typically 10-30%.



Compound vs Series vs Shunt DC Motors

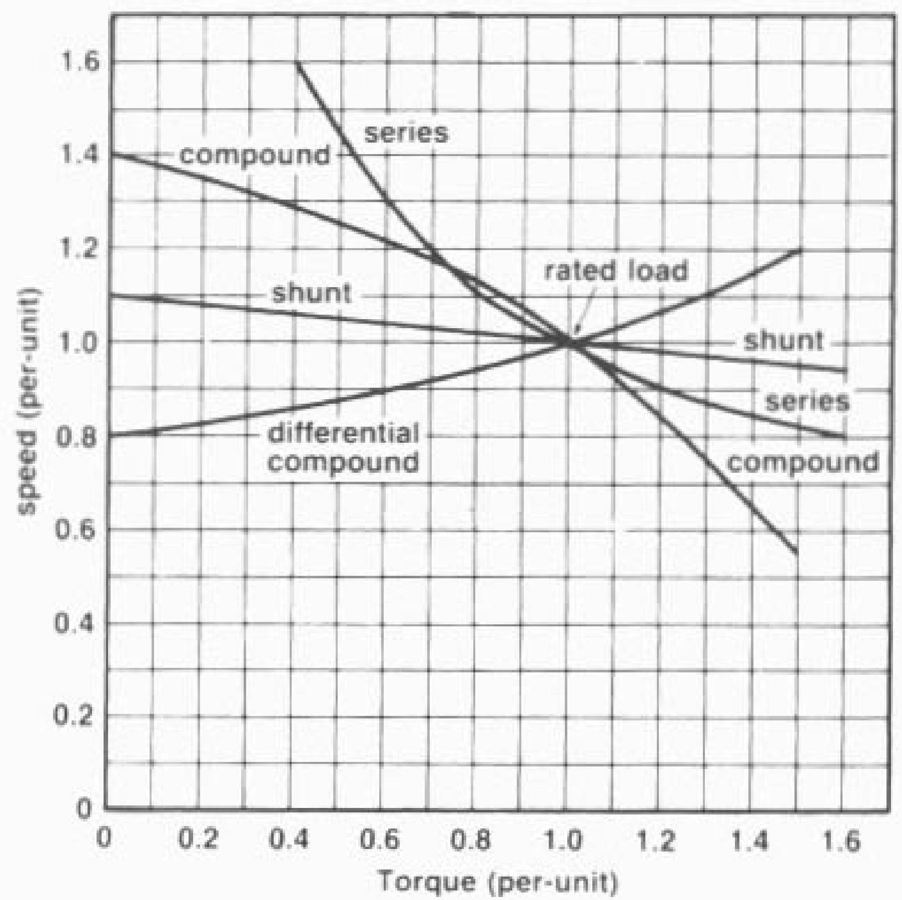


Figure 5.13
Typical speed versus torque characteristics of various dc motors.

Reversing the Direction of Rotation of a DC Motor

To reverse the direction of rotation of a DC motor, we must either:

- Reverse the armature connections
- Reverse both the shunt and series field connections

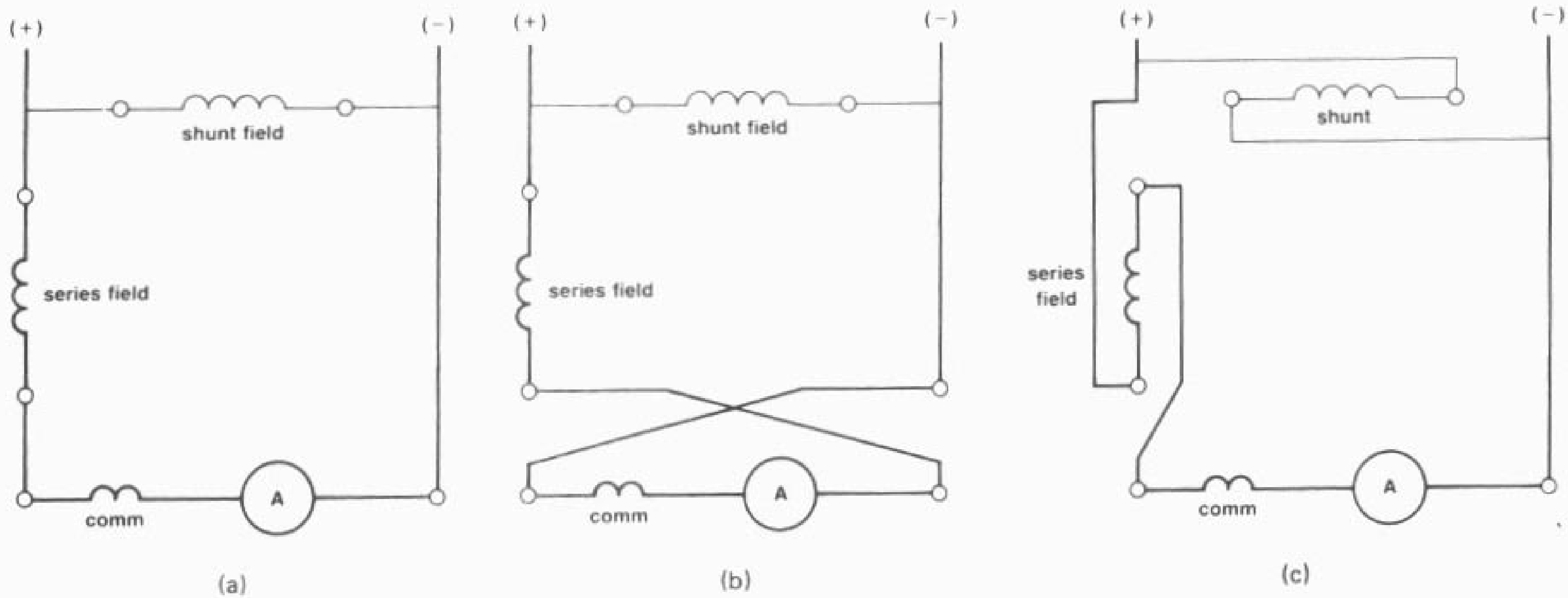


Figure 5.15
a. Original connections of a compound motor.
b. Reversing the armature connections to reverse the direction of rotation.
c. Reversing the field connections to reverse the direction of rotation.

Starting a DC Motor

If we apply full voltage to a stationary motor, the starting current in the armature will be very high (20-30 times the nominal load current) and we run the risk of:

- Burning out the armature
- Damaging the commutator and brushes, due to heavy sparking
- Overloading the supply
- Breaking the shaft due to mechanical shock
- Damaging the driven equipment due to the sudden torque surge

All DC motors must therefore be provided with a means to limit the starting current to reasonable values.

Stopping a DC Motor

There are three ways to brake a DC motor:

- Mechanical (friction) braking
- Dynamic braking
- Plugging

Dynamic Braking

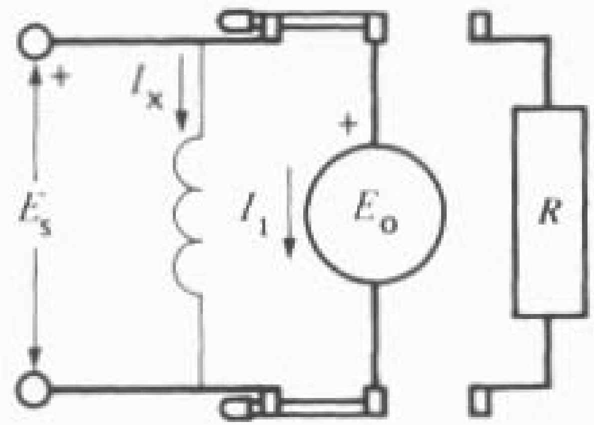


Figure 5.17a
Armature connected to a dc source E_s.

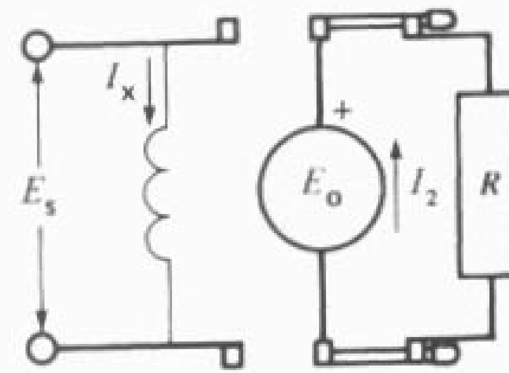


Figure 5.17c
Dynamic braking.

Plugging

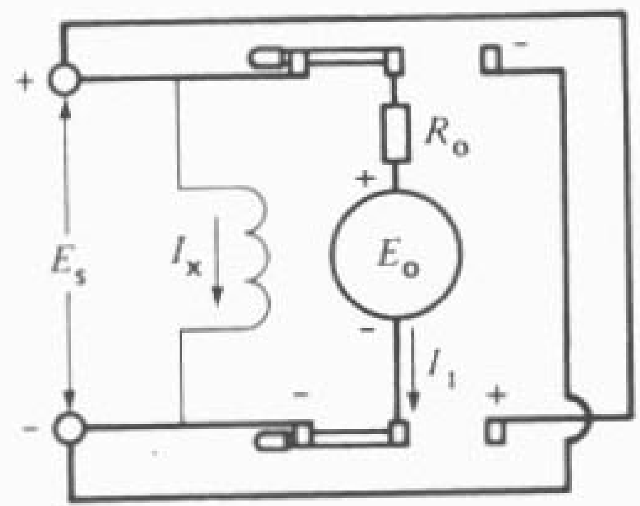


Figure 5.19a
Armature connected to dc source E_s.

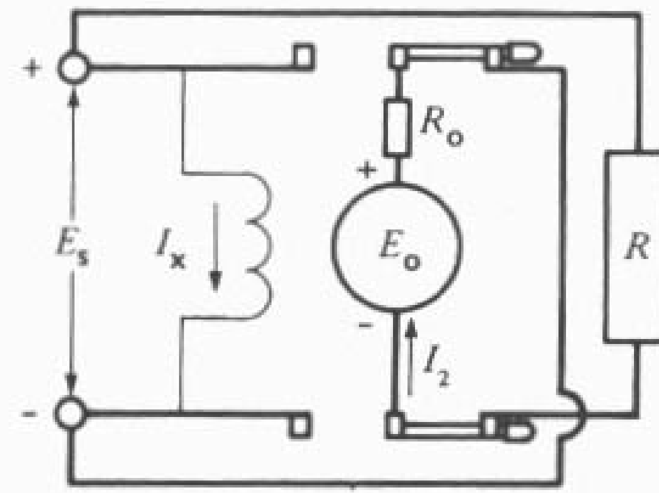


Figure 5.19b
Plugging.

Comparison of Braking Methods

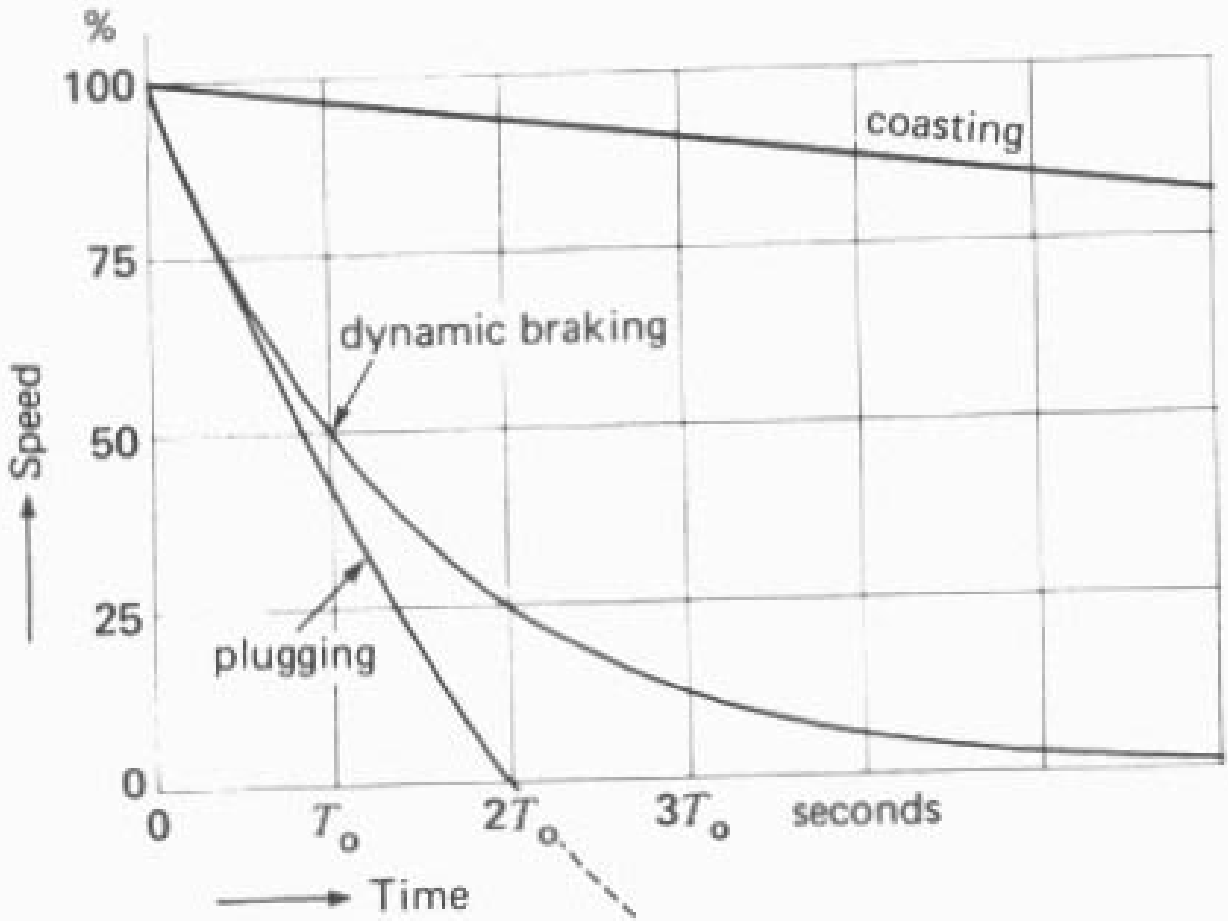


Figure 5.18
Speed versus time curves for various braking methods.

Armature Reaction in DC Motors

The current flowing in the armature creates a magnetic field that distorts and weakens the flux coming from the poles.

Armature reaction can cause poor commutation (sparking) and also pole tip saturation.

Commutating poles are used to cancel the armature reaction at the neutral point.

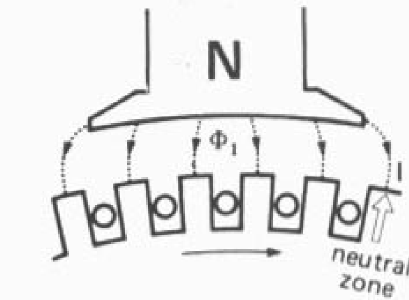


Figure 5.20
Flux distribution in a motor running at no-load.

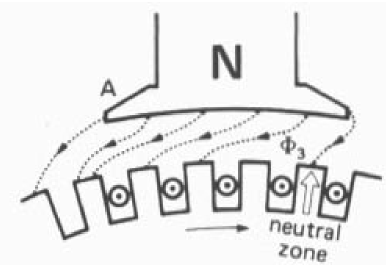


Figure 5.22
Resulting flux distribution in a motor running at full-load.

Basics of Variable Speed Control

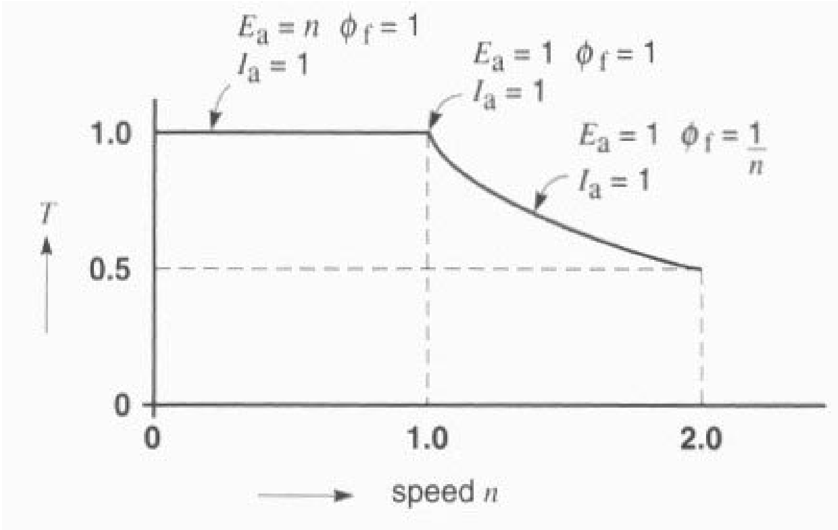


Figure 5.26

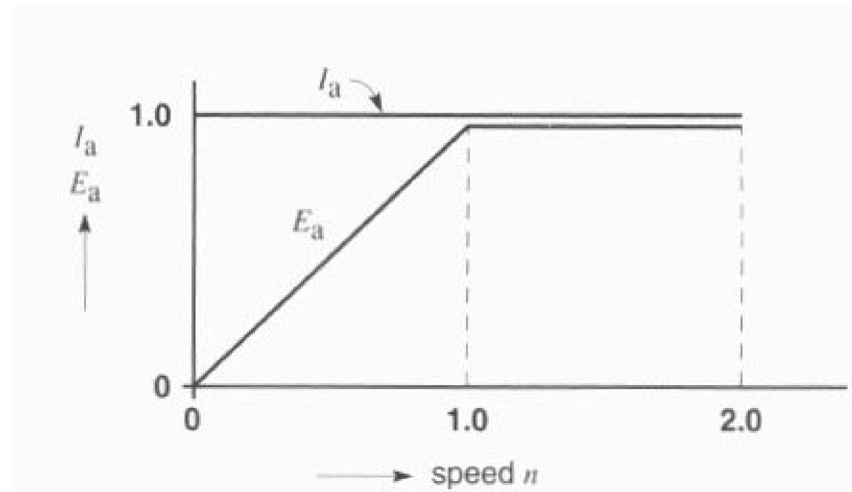


Figure 5.27

Realistic Torque-Speed Curve

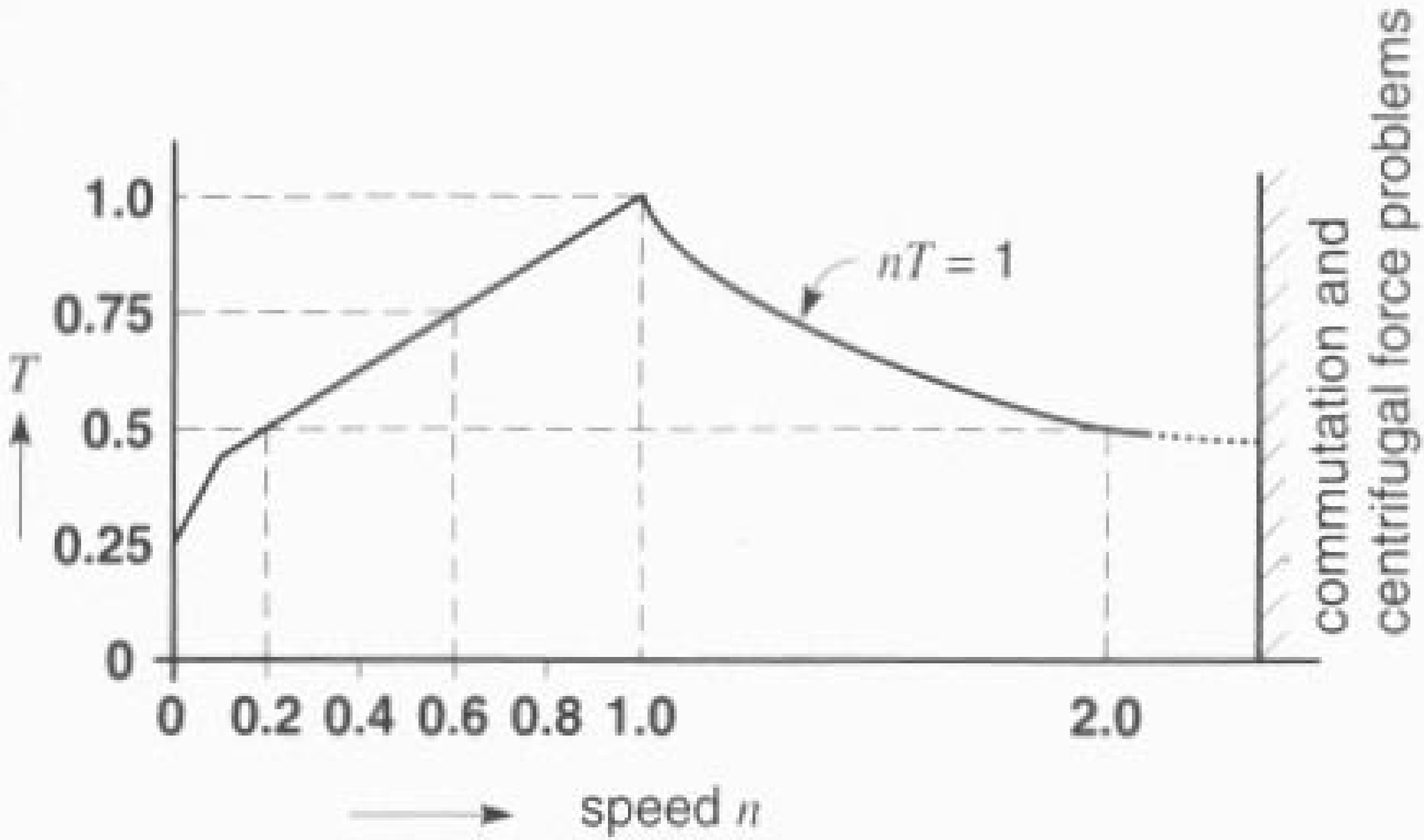


Figure 5.29
Torque-speed curve of a typical dc motor.

Permanent magnet motors

Instead of using a field winding, permanent magnets can be used to establish the field.

By using magnets, the energy consumed, the heat produced, and the volume of the motor is reduced.

Furthermore, magnets increase the effective air gap (since magnets have permeability similar to air). This has two benefits:

1. The armature reaction effects are minimised
2. The inductance of the armature reduces, giving the motor better transient response.

The drawback of permanent magnet motors is the high cost of the magnets and the inability to weaken the field.

Construction of DC machines

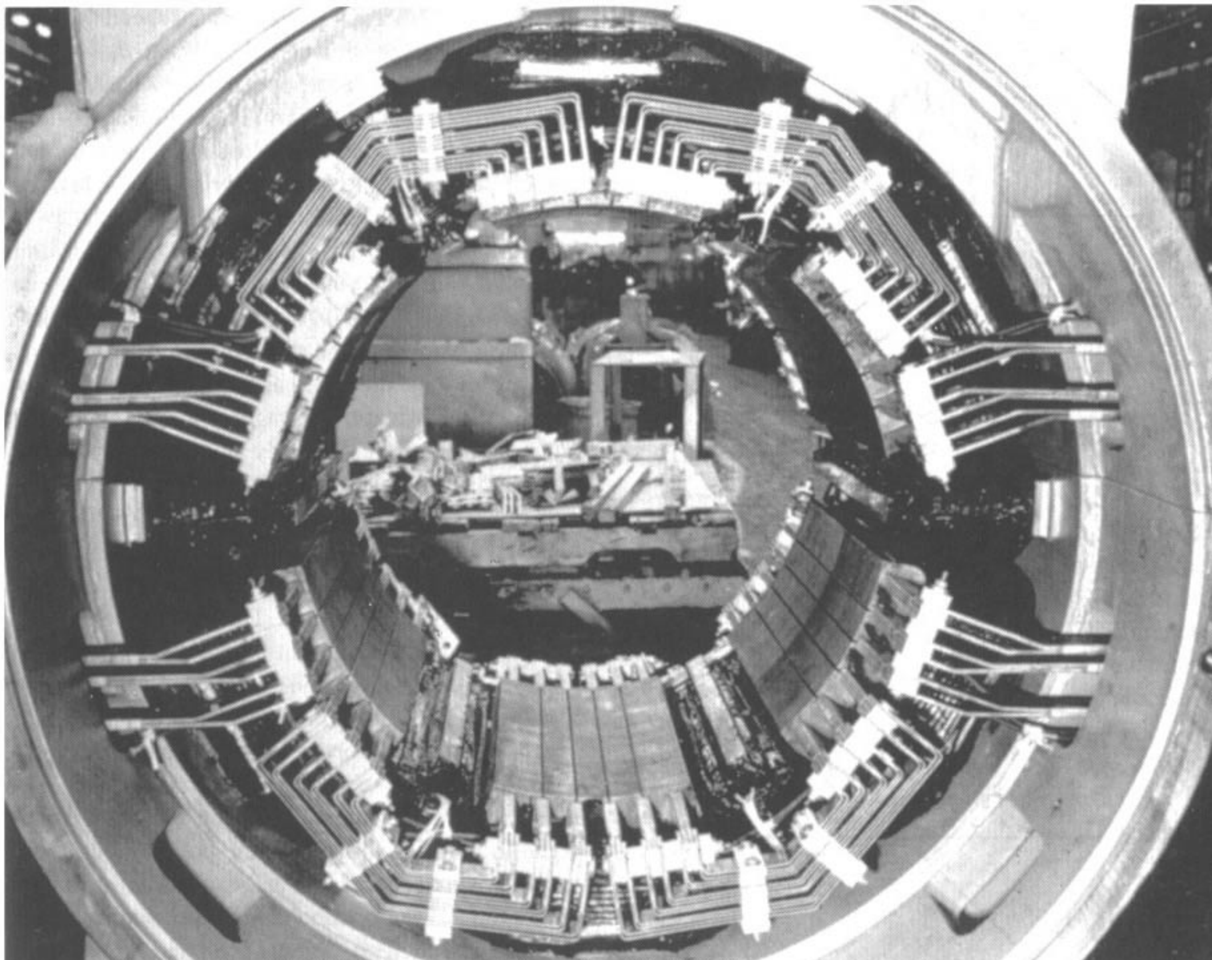


Figure 5.24
Six-pole dc motor having a compensating winding distributed in slots in the main poles. The machine also has 6 commutating poles.
(*Courtesy of General Electric Company*)

Construction of DC machines

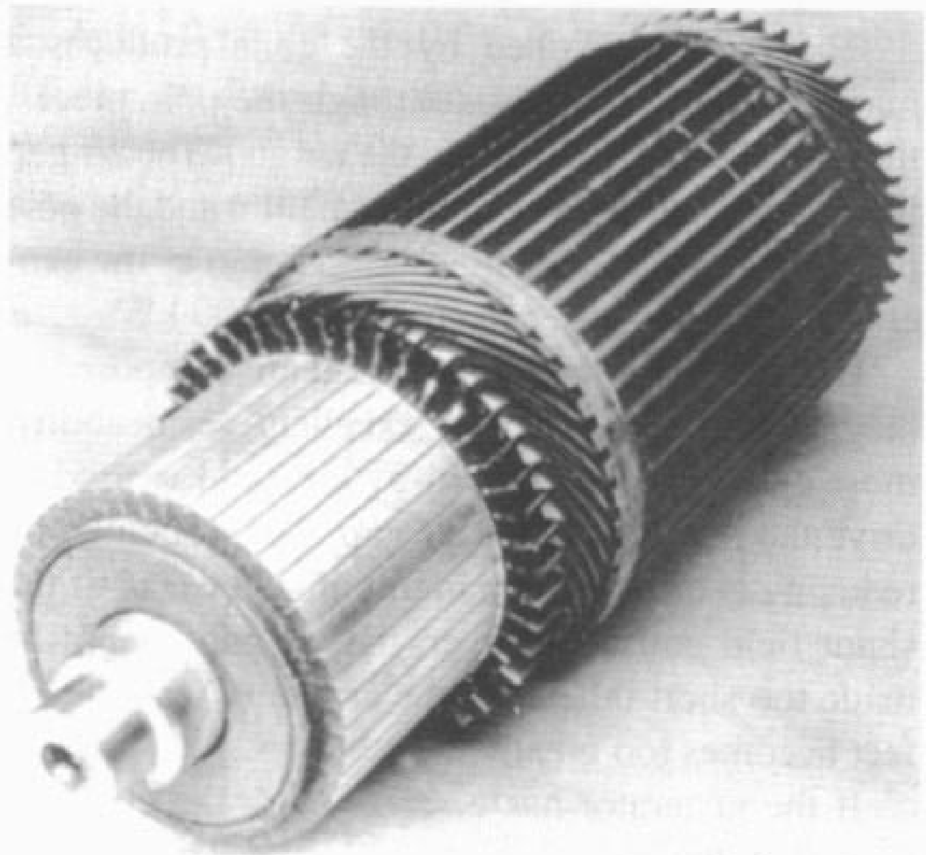


Figure 4.30
Armature of a dc generator showing the commutator, stacked laminations, slots, and shaft.
(Courtesy of General Electric Company, USA)

Construction of DC machines

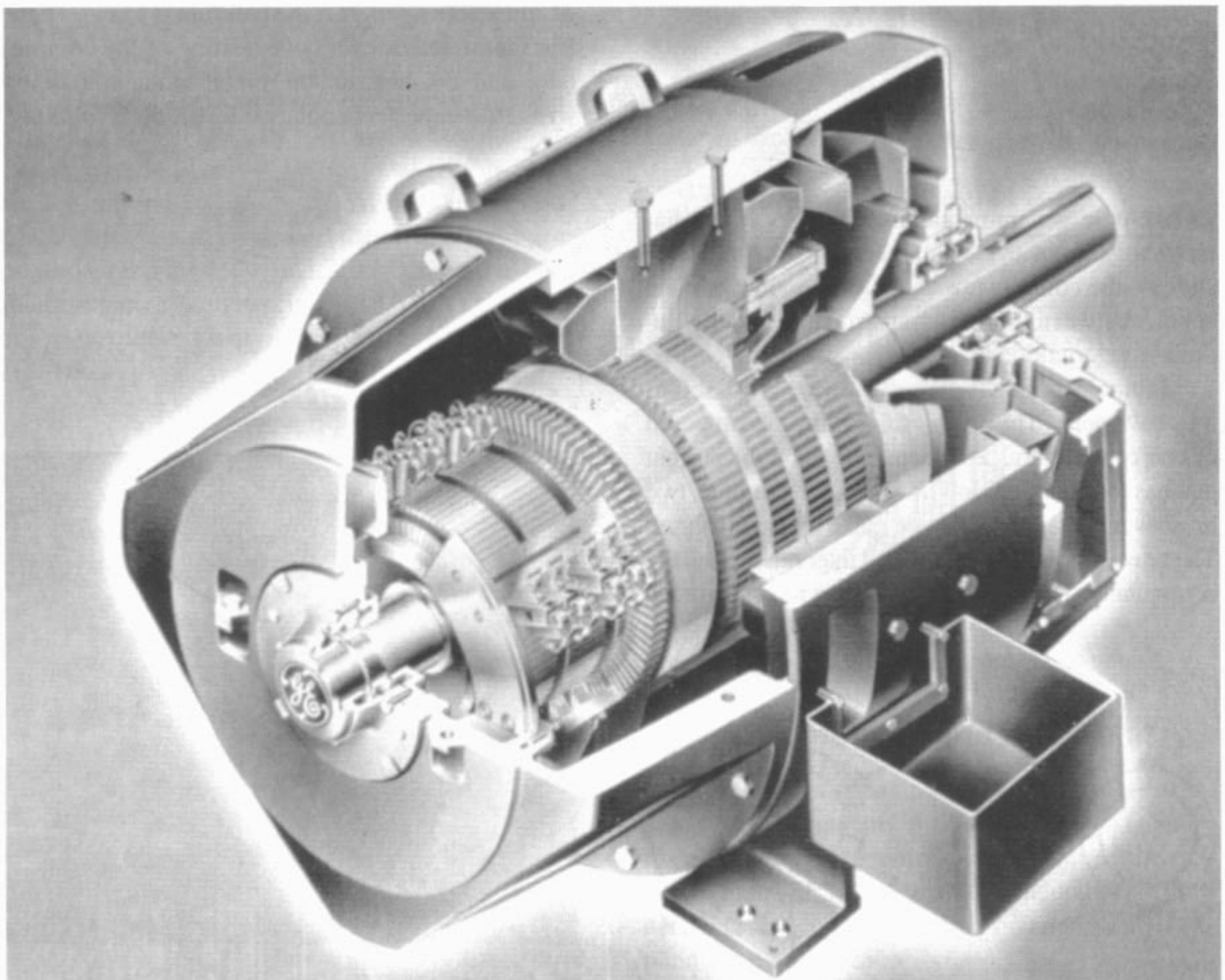


Figure 4.36
Sectional view of a 100 kW, 250 V, 1750 r/min 4-pole dc generator.
(Courtesy of General Electric Company, USA)

Construction of DC machines

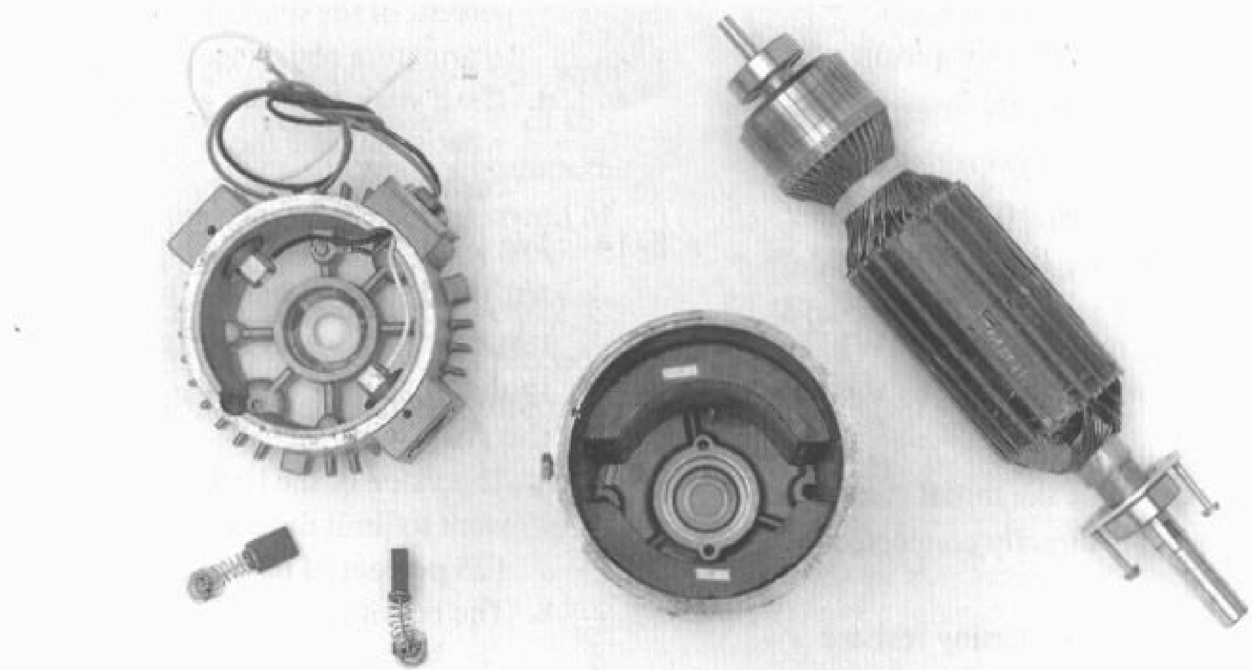


Figure 5.30
Permanent magnet motor rated 1.5 hp, 90 V, 2900 r/min, 14.5 A. Armature diameter: 73 mm; armature length: 115 mm; slots 20; commutator bars: 40; turns per coil: 5; conductor size: No. 17 AWG, lap winding. Armature resistance at 20°C: 0.34 Ω.
(*Courtesy of Baldor Electric Company*)