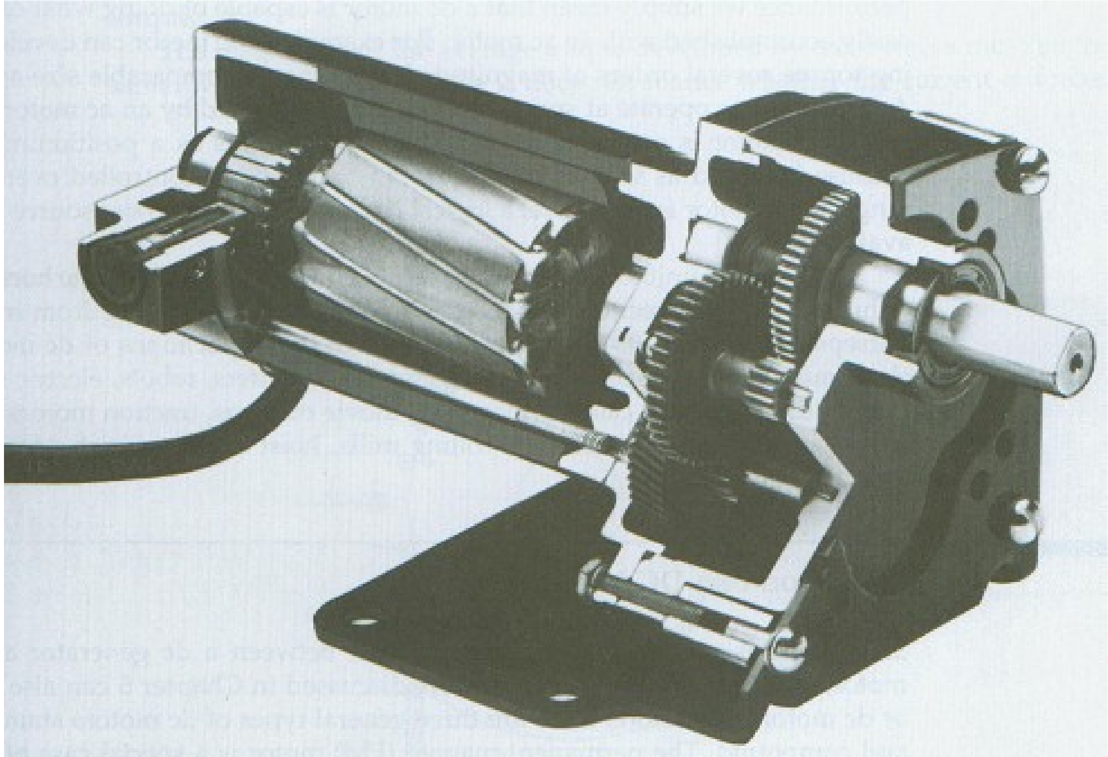
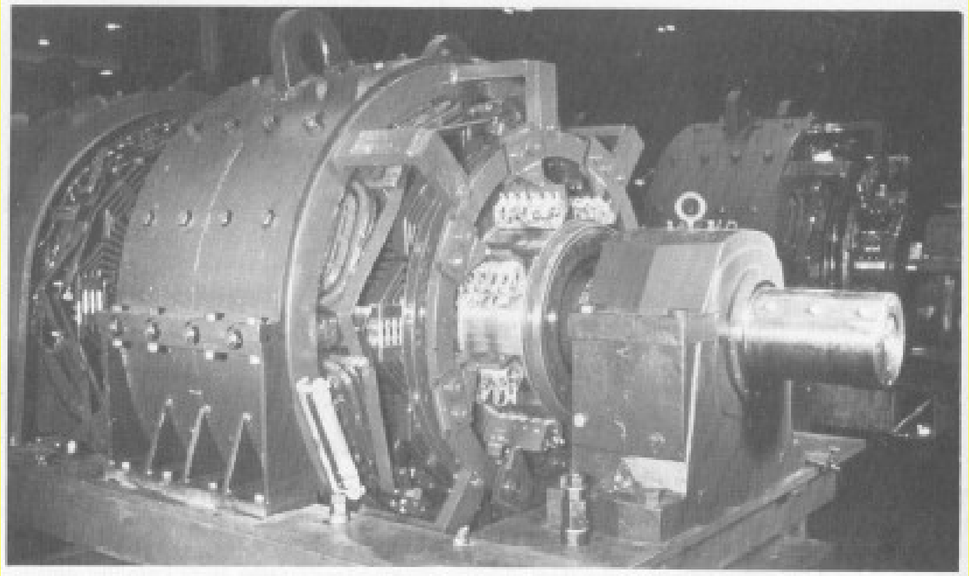
Chapter 6

Direct Current Motors

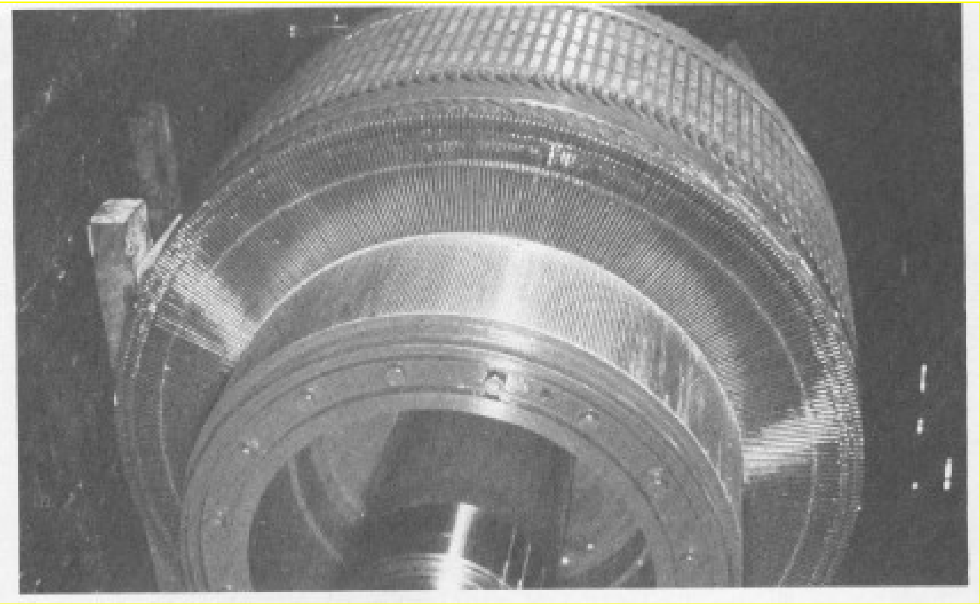


DC Motors

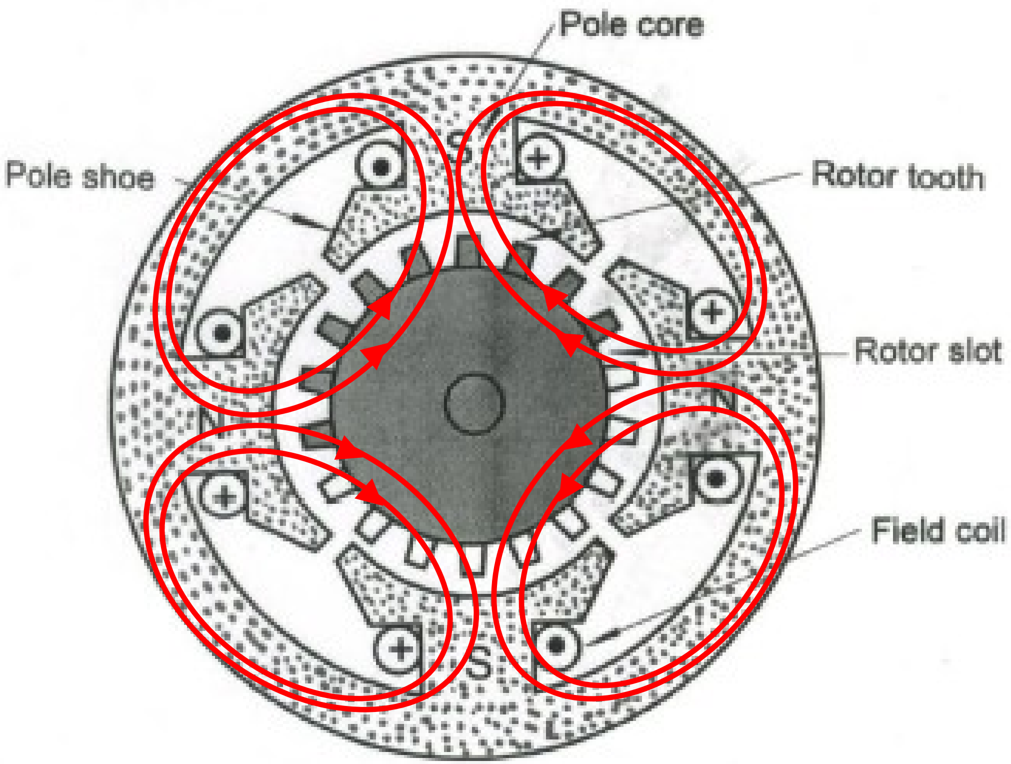
A DC Motor



Armature (rotor) along with the commutator



Constructional Features of DC Motors



A 4-Pole DC Motor

- Commutator along with the armature on the rotor
- Salient-poles on the stator
- Field windings – Two exciting field windings, the shunt and series windings

Significant Features of DC Motors

- DC motors convert electrical energy into mechanical energy
- Constant mechanical power output or constant torque
- Types – Shunt motors, series motors and compound motors
- Rapid acceleration or deceleration
- Extensively used as a positioning device because its speed as well as torque can be controlled precisely over a wide range
- 1W to 10,000 hp
- Applications – in automobiles, robots, VCRs, movie camera, electric vehicles, in steel and aluminum rolling mills, electric trains, overhead cranes, control devices, etc.
- Biggest advantage over other motors – Torque-speed characteristics of dc motors can be varied over a wide range while retaining high efficiency

Faraday's Law

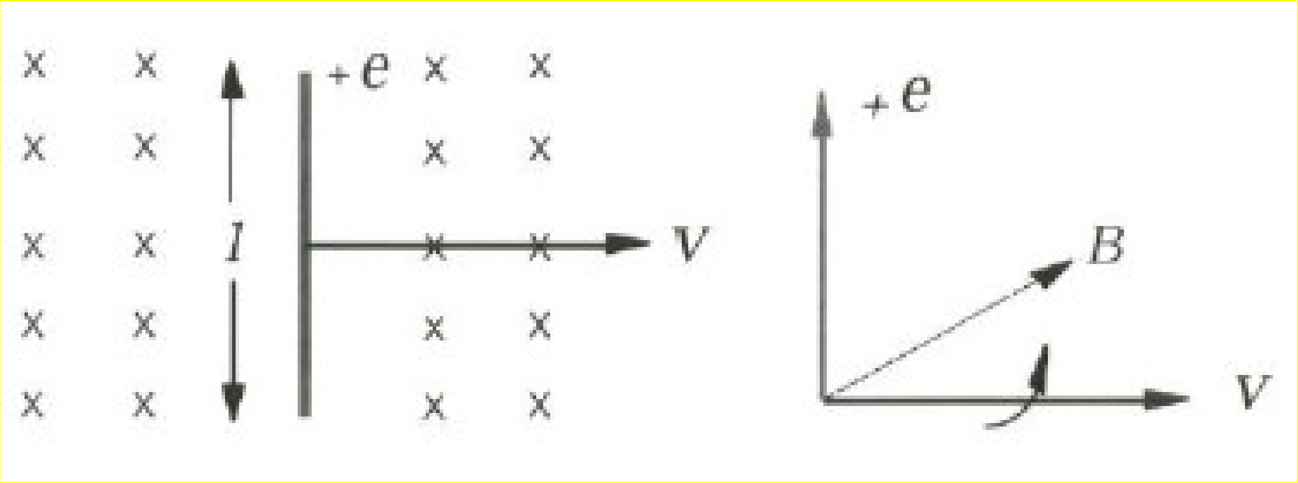
If a flux passes through a turn of coil of wire, a voltage will be induced in the turn of wire that is directly proportional to the rate of change in the flux with respect to time.

$$e = \frac{d\phi}{dt}$$

If a coil has N turns and if the same flux passes through all of them, then the induced voltage across the whole coil is given by

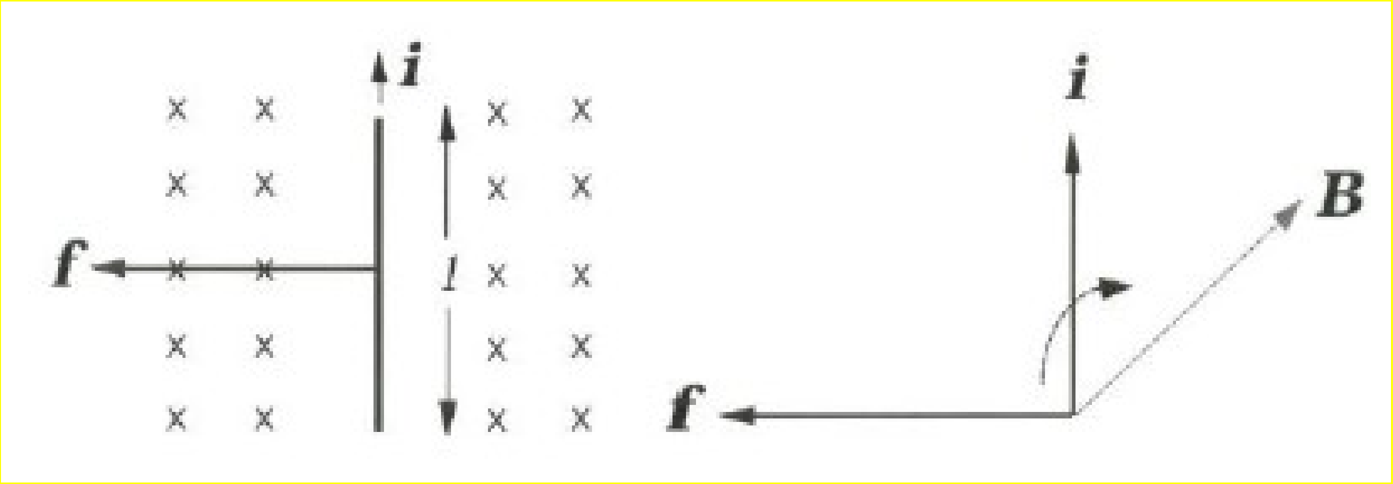
$$e = N\frac{d\phi}{dt}$$

Polarity of the Induced Voltage, *e*



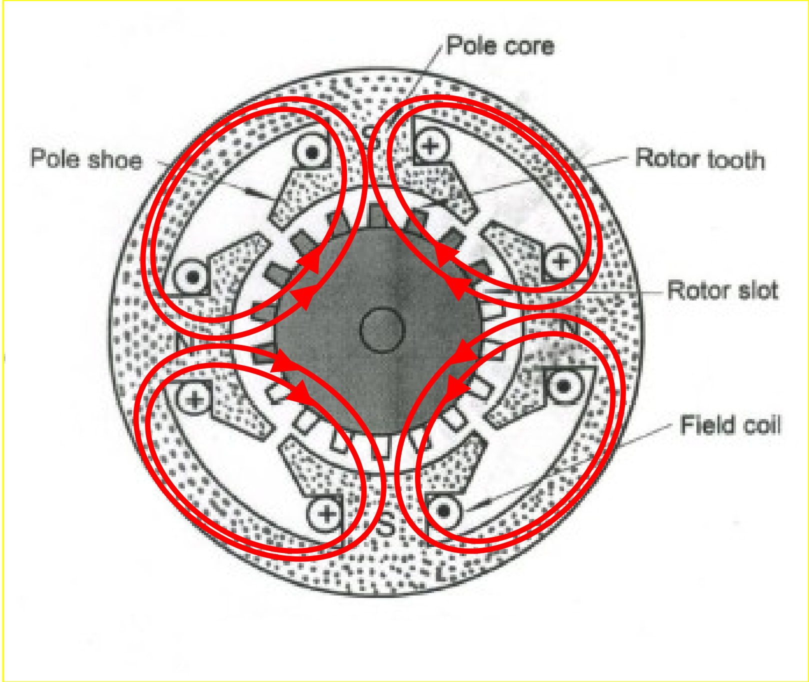
$e=Blv$, where B, v and e are mutually perpendicular. The polarity of the induced voltage can be determined from the right hand screw rule. Turn the vector v towards the vector B. If a right hand screw is turned in the same way the motion of the screw will indicate the direction of positive polarity of the induced voltage e.

Electromagnetic Force, *f*



$f=Bli$, where B, f and i are mutually perpendicular. Turn the current vector i towards the flux vector B. If a right hand screw is turned in the same way, the direction in which the screw will move represents the direction of the force f.

Operation Principle



- As soon as the switch is closed, a large amount of current will flow through the armature conductors.
- The current carrying armature conductors are in a magnetic field produced by the current in stator field winding.
- The armature conductors will experience a mechanical force or torque which will cause the rotor of the dc motor to spin.

Operation Principle

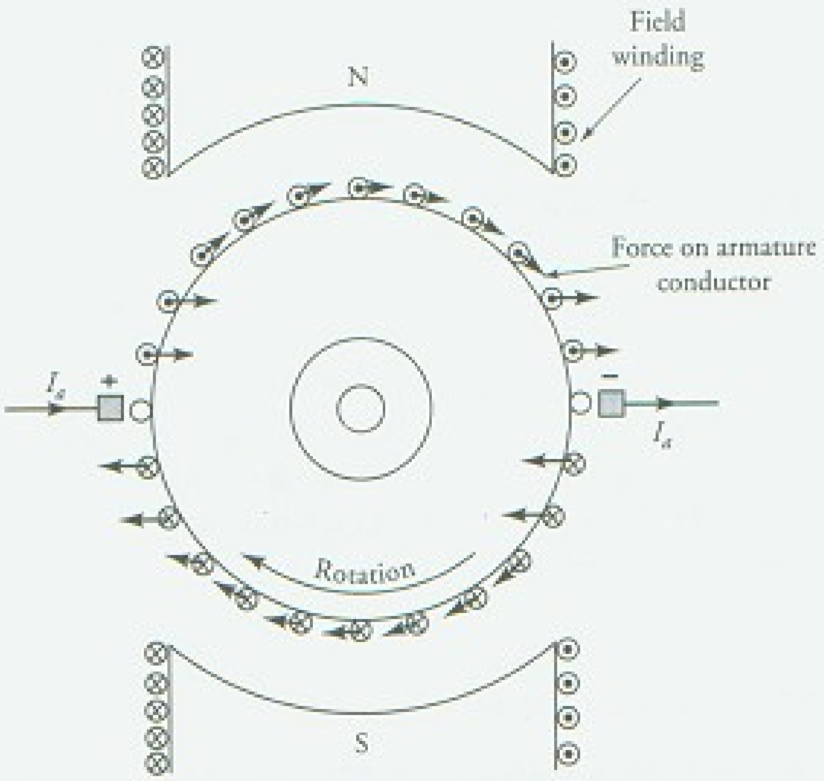


Figure 6.1 Force experienced by armature conductors in a 2-pole dc motor.

Back emf or Counter emf

As the armature rotates, each coil on the armature experiences a change in the flux passing through its plane.

Therefore, an electromotive force (emf) is induced in each coil.

In accordance with Faraday's law of induction, the induced emf must oppose the current entering the armature.

In other words, the induced emf opposes the applied voltage.

For this reason, we commonly refer to the induced emf in a motor as the back emf or counter emf of the motor.

The value of the armature voltage, $E_a = K_a \phi_p \omega_m$

ω_m = angular velocity of the armature (rotor)
ϕ_p =flux produced by each pole
K_a =constant

Back emf or Counter emf

If R is the effective (total) resistance in the armature circuit and V_s is the applied voltage across the armature terminals, then the armature current is

$$I_a=[V_s-E_a]/R$$

This equation can also be written as

$$V_s = E_a + I_aR$$

Since the resistance of the armature circuit R is usually very small, the voltage drop across it is also small in comparison with the back emf E_a.

Starting of a DC Motor

At the time of starting, the back emf in the motor is zero because the armature is not rotating.

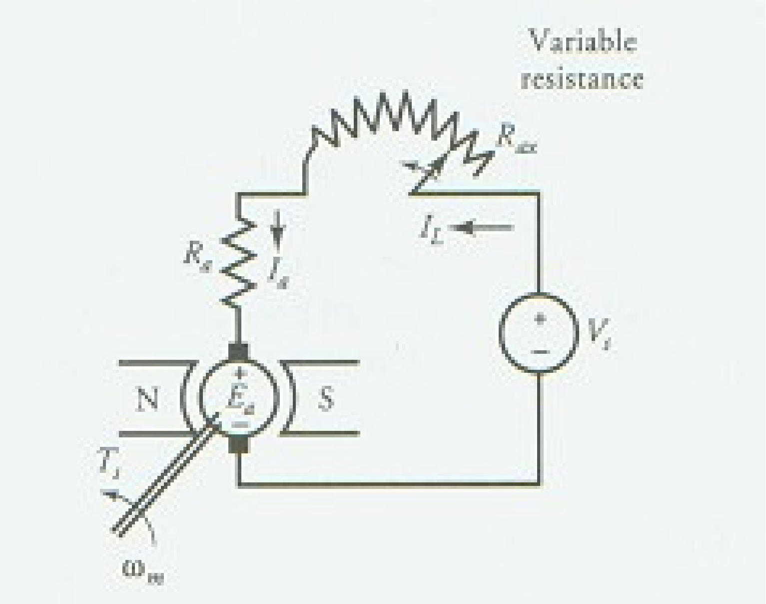
For a small value of the armature-circuit resistance R, the starting current in the armature will be extremely high if the rated value of Vs is impressed across the armature terminals.

The excessive current can cause permanent damage to the armature windings.

Thus, a dc motor should never be started at its rated voltage.

In order to start a dc motor, an external resistance must be added in series with the armature circuit.

Starting of a DC Motor



In order to start a dc motor, an external resistance must be added in series with the armature circuit.

The external resistance is gradually decreased as the armature comes up to speed.

Finally, when the armature has attained its normal speed, the external resistance is "cut out" of the armature circuit.

Speed Regulation in DC Motors

- The armature current of a motor increases with load.
- For a constant applied voltage, the increase in the armature current results in a decrease in the back emf.
- The reduction in the back emf causes a drop in the speed of the motor.
- The speed regulation is a measure of the change in speed from no load to full load.
- When the change in speed at full load is expressed as a percent of its full-load speed, it is called the percent speed regulation (SR%).
- In equation form, the percent speed regulation is

$$SR\% = \frac{N_{motor\_No\,load} - N_{motor\_Full\,load}}{N_{motor\_Full\,load}} \times 100$$

Losses in a DC Motor

- The power input to a dc motor is electrical and the power output is mechanical.
- The difference between the power input and the power output is the power loss.
- When the power is supplied to a motor, a significant portion of that power is dissipated by the resistances of the armature and the field windings as copper loss.
- The remainder power (the developed power) is converted by the motor into mechanical power.
- A part of the developed power is consumed by the rotational loss.
- The difference is the net mechanical power available at the shaft of the motor.
- A typical power-flow diagram of a dc motor is shown in Figure 6.3.

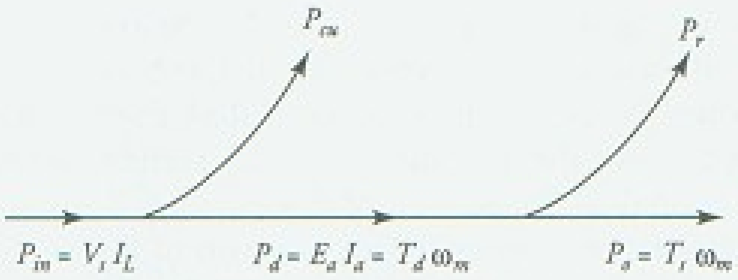


Figure 6.3 A typical power-flow diagram of a dc motor.

A Series DC Motor

- In a series motor the field winding is connected in series with the armature circuit as shown in Figure 6.4.
- We have also included an external resistance Rax in series with the armature that can be used either to start the motor and then be shorted or to control the speed of the motor.
- Since the series field winding carries the rated armature current of the motor, it has few turns of heavy wire.
- As the armature current changes with the load, so does the flux produced by the field winding. In other words, the flux set up by a series motor is a function of the armature current.

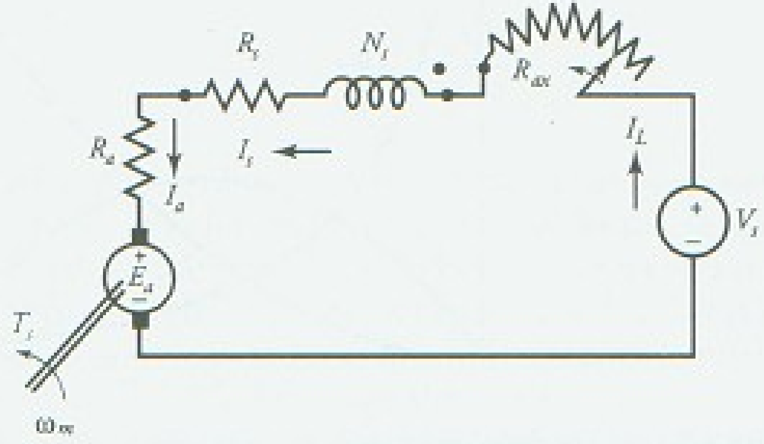


Figure 6.4 An equivalent circuit of a series motor with a variable starting resistance.

A Series DC Motor

- Flux per pole:

$$\phi_p = K_f I_a$$

- Then the back emf is.

$$E_a = K_a K_f I_a \omega_m$$

- The torque developed by the series motor:

$$T_d = K_a K_f I_a^2$$

- From the above equations, it is evident that the back emf in the motor is proportional to the armature current, and the torque developed by a series motor is proportional to the square of the armature current

A Series DC Motor

- As the armature current increases, so does the flux produced by it.
- An increase in the flux enhances the level of saturation in the motor.
- When the motor is saturated, the flux increases only gradually with further increase in the armature current.
- Hence, the torque developed is no longer proportional to the square of the current.
- The torque versus armature current characteristic of a series motor is given in Figure 6.5.

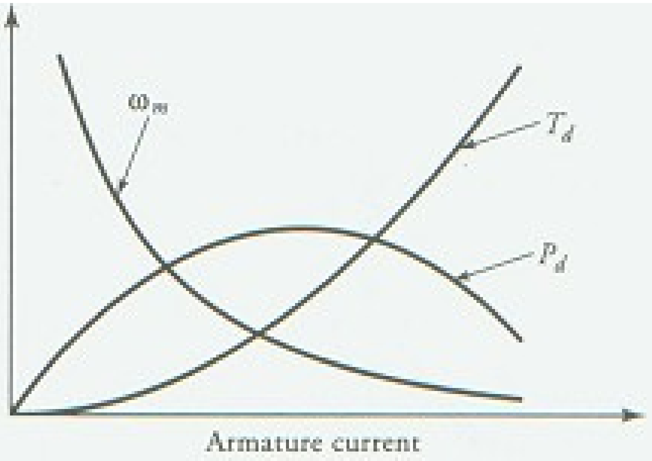


Figure 6.5 Torque developed, power developed, and speed characteristics of a series motor as a function of armature current.

A Series DC Motor

- As we load the motor, the torque developed by it must increase.
- The increase in the torque necessitates an increase in the armature current.
- The increase in the armature current causes an increase in the voltage drop across the armature-circuit resistance, the field-winding resistance, and the external resistance.
- For a fixed applied voltage, the back emf must decrease with load.
- Since the back emf is also proportional to the armature current, the speed of the motor must drop.

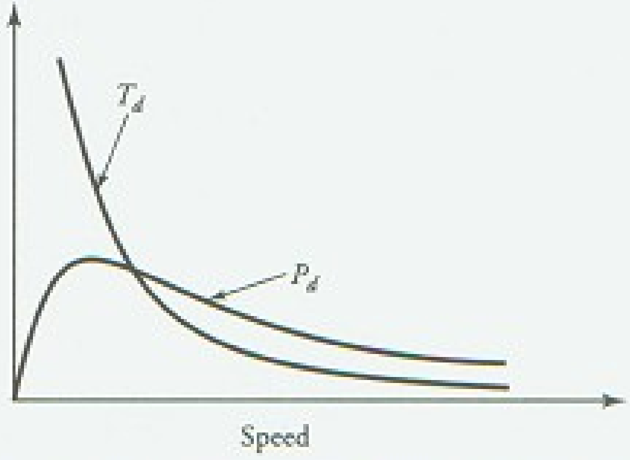
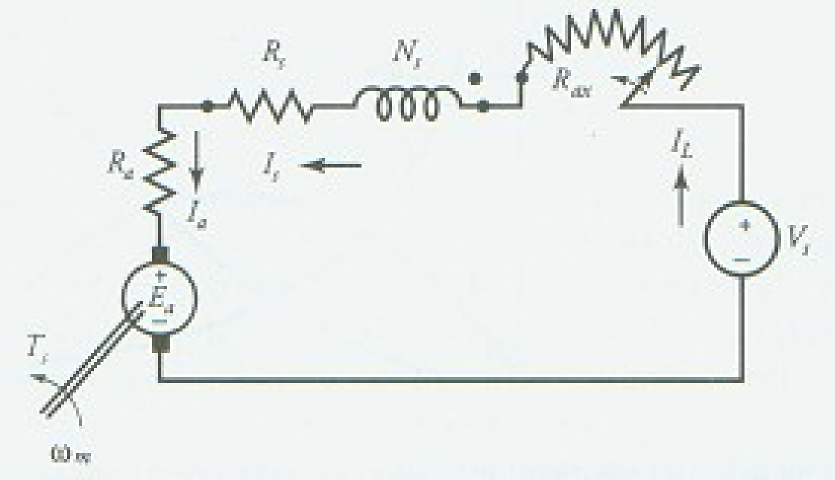


Figure 6.6 Torque and power developed characteristics of a series motor as a function of speed.

A Series DC Motor

$$E_a = K_a k_f I_a \omega_m = V_s - I_a \left(R_a + R_s + R_{ax} \right) = V_s - I_a R$$

$$\therefore \quad \omega_m = \frac{V_s - I_a R}{K_a k_f I_a}$$



$$I_a = \frac{V_s}{K_a k_f \omega_m + R}$$

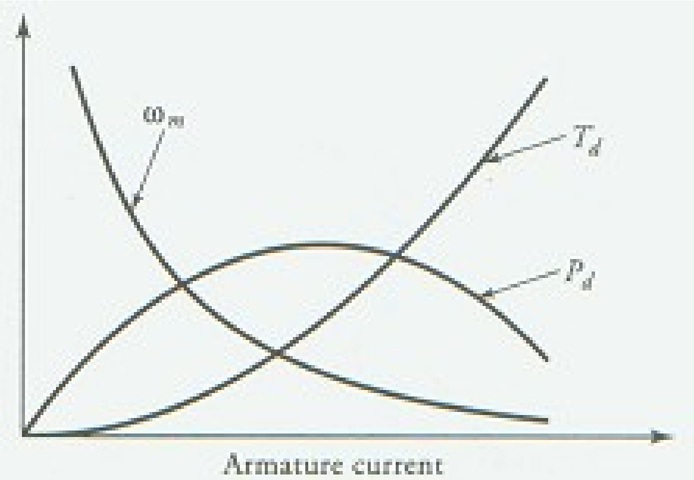
$$\therefore \quad T_d = \frac{K_a k_f V_s^2}{\left[K_a k_f \omega_m + R \right]^2}$$

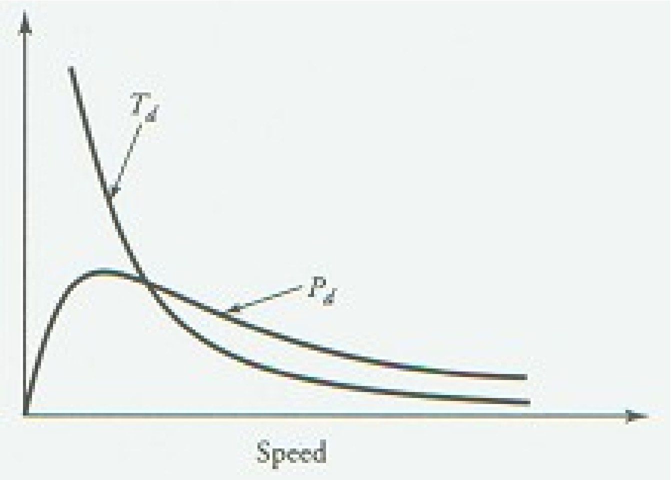
A Series DC Motor

- The speed of a series motor is practically inversely proportional to the armature current.
- The torque developed by a series motor is inversely proportional to the square of its speed.
- It provides high torque at low speed and low torque at high speed.
- For this reason, a series motor is suitable for hoists, cranes, electric trains, and a host of other applications that require large starting torques.
- Since the torque developed by a series motor is also proportional to the square of the applied voltage, the torque developed by it can be controlled by controlling the applied voltage.

$$\omega_m = \frac{V_s - I_a R}{K_a k_f I_a}$$

$$T_d = \frac{K_a k_f V_s^2}{\left[K_a k_f \omega_m + R\right]^2}$$





Example 6.1 (page 360)

- The magnetization curve of a 10-hp, 220-V series motor is given in Figure 6.7 at 1200 rpm. The other parameters of the series motor are $R_a = 0.75\ \Omega$, $R_s = 0.25\ \Omega$, and $P_r = 1.04$ kW. What is the armature current when the motor delivers its rated load at 1200 rpm? What is the efficiency of the motor at full load? What is the number of turns per pole? When the load is gradually reduced, the armature current decreases to 16.67 A. Determine (a) the new speed of the motor and (b) the driving torque.

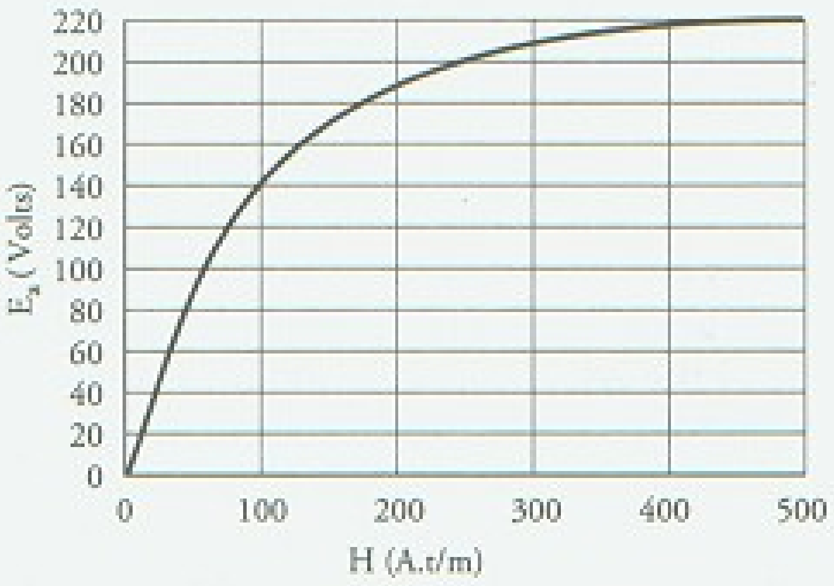


Figure 6.7 The magnetization curve of a dc motor at 1200 rpm.

A Shunt DC Motor

- The equivalent circuit of a shunt motor is shown in Figure 6.8 with a starting resistor in the armature circuit.
- The field winding is connected directly across the source.

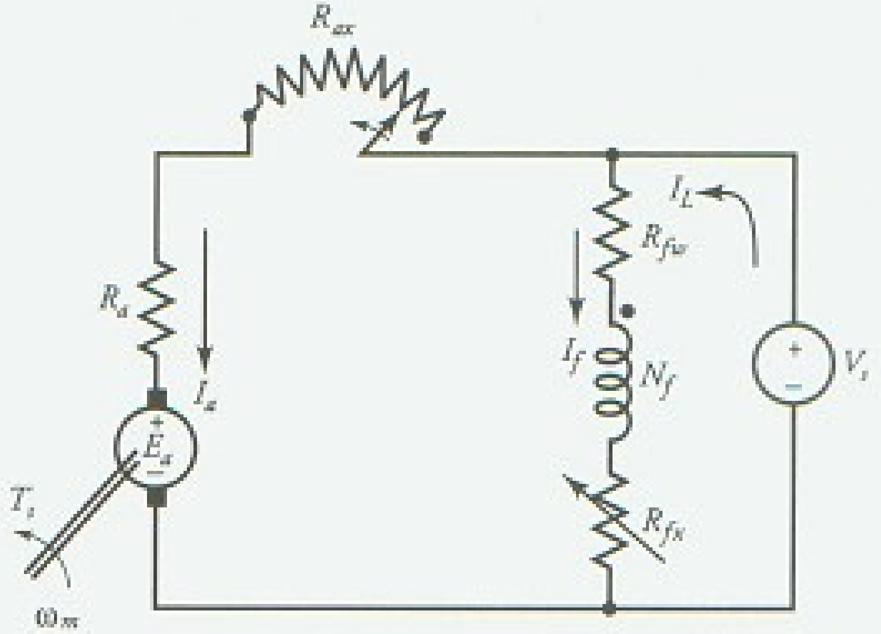


Figure 6.8 An equivalent circuit of a shunt motor with a starting resistor in the armature circuit.

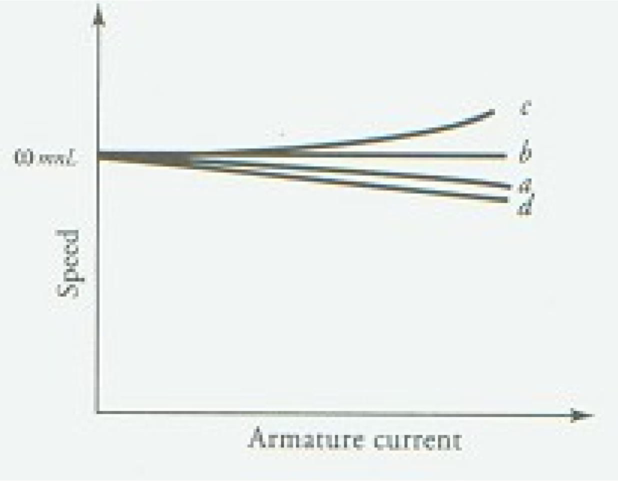
A Shunt DC Motor

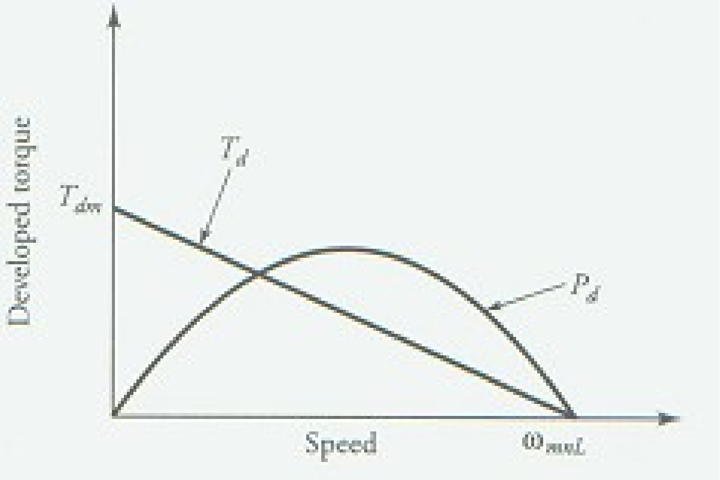
$$E_a = K_a \phi_p \omega_m = V_s - I_a R_a$$

$$\omega_m = \frac{V_s - I_a R_a}{K_a \phi_p}$$

$$I_a = \frac{V_s - K_a \phi_p \omega_m}{R_a}$$

$$T_d = K_a \phi_p I_a = K_a \phi_p \left[\frac{V_s - K_a \phi_p \omega_m}{R_a} \right] = \frac{K_a k_f V_s^2}{\left[K_a k_f \omega_m + R_a \right]^2}$$



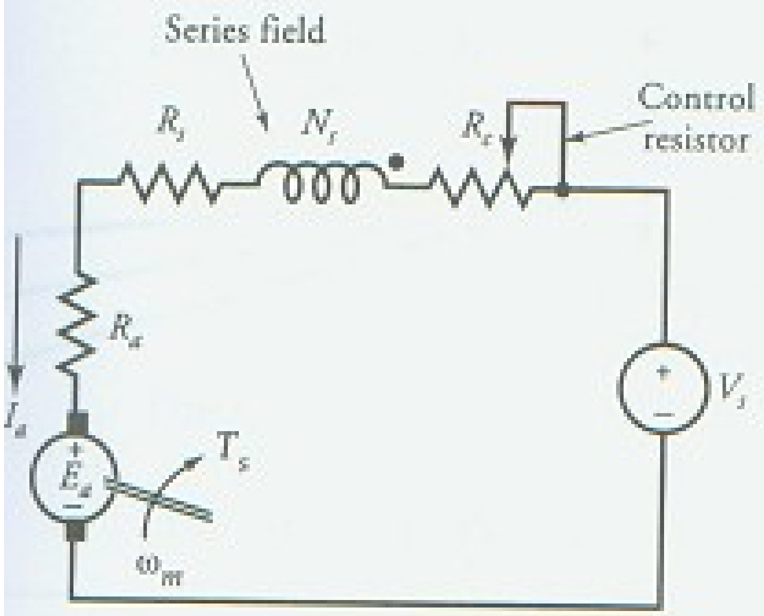


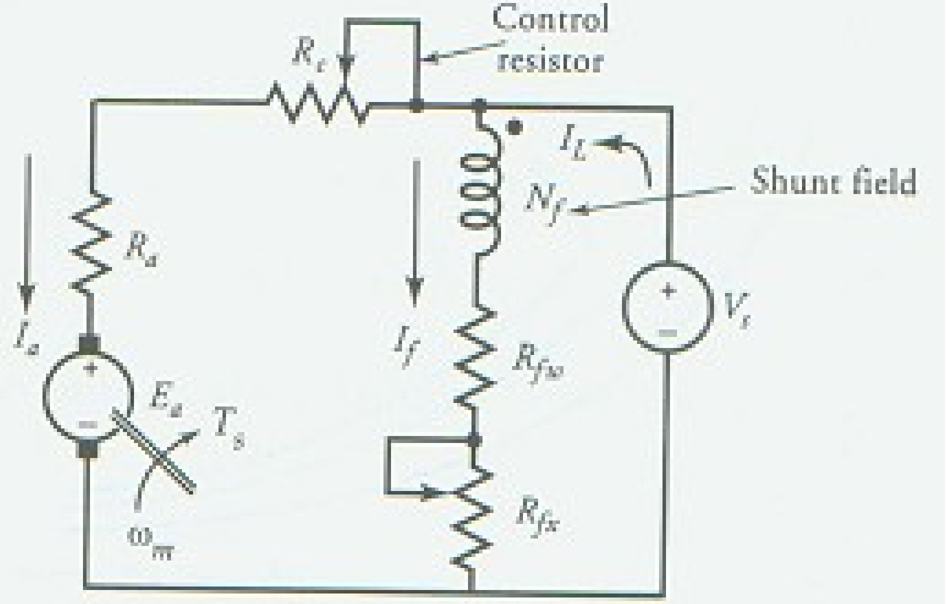
Methods of Speed Control

- The two methods that are commonly used to secure speed control are
  - armature resistance control and
  - field control.

Speed Control: Armature Resistance Control

- In this method, the speed control is achieved by inserting a resistance R_c in the armature circuit of a shunt or series motor as illustrated in the figure below.
- In a shunt, the field winding is connected directly across the full-line voltage. The additional resistance in the armature circuit decreases the back emf in the motor for any desired armature current.
- Since the flux in the motor is constant and the torque depends upon the armature current, the decrease in the back emf forces a drop in the motor speed.



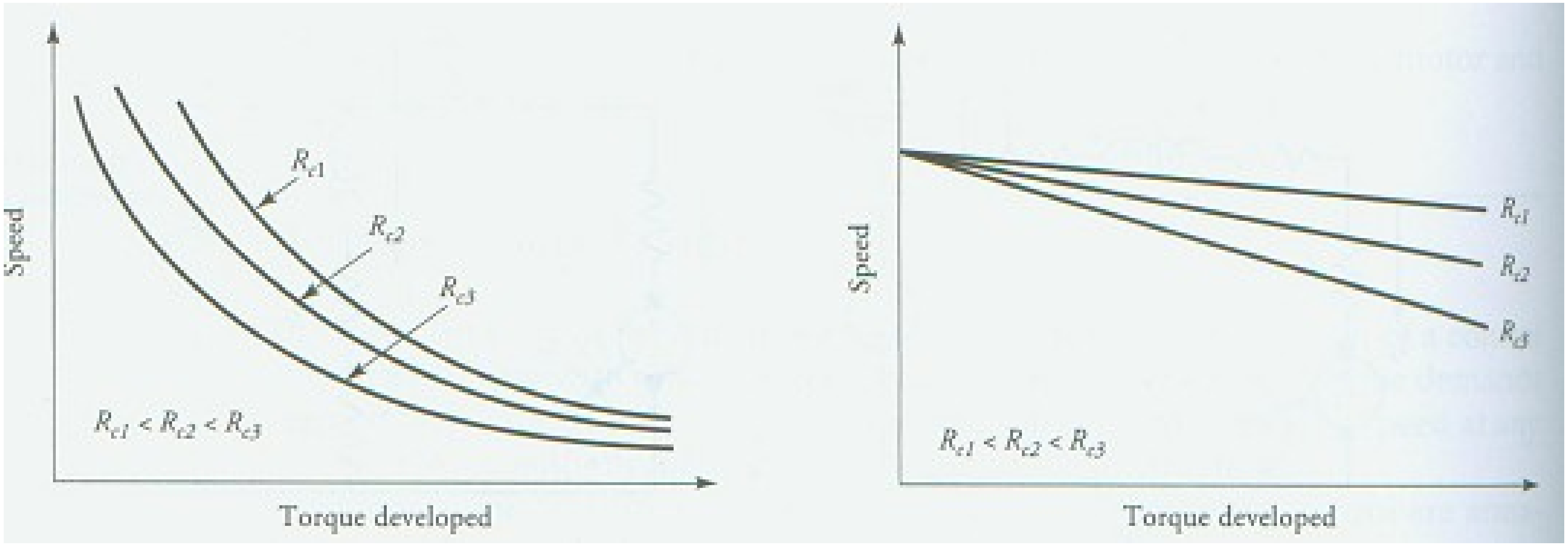


Speed Control: Armature Resistance Control

- Speed in terms of armature current:

$$\omega_m = \frac{V_s - I_a\left(R_a + R_s + R_c\right)}{K_a \phi_p}$$

- Any increase in the value of the control resistance R_c decreases the speed of the motor.
- The control method, therefore, is suitable to operate the motor at a speed lower than its rated speed while delivering the same torque.
- The speed-torque characteristics of series and shunt motors for various values of the control resistor are depicted in the figure below.



Disadvantages of Armature Resistance Control Method

- The disadvantages of this method of speed control are the following:
  - A considerable power loss in the control resistance R
  - A loss in the efficiency of the motor
  - Poor speed regulation for the shunt and the compound motors
- The armature resistance control method is essentially based upon the reduction in the applied voltage across the armature terminals of a dc motor.
- Therefore, it should be possible to control the speed of a dc motor by simply connecting its armature to a variable voltage source. This method of speed control is known as the Ward-Leonard method

Speed Control: Field-Control Method

- This approach involves the control of the field current, which in turns controls the flux in the motor.

- The field current in a shunt motor can be controlled by inserting an external resistor in series with the field winding.

- Because the field current is a very small fraction of the total current intake of a shunt motor, the power dissipated by the external resistor is relatively small.

- Therefore, the flux-control method is economically better than the armature-resistance control method.

- To control the flux in a series motor, a field diverter resistor can be connected in parallel with the series field winding.

Speed Control: Field-Control Method

- The addition of a resistance in series with the shunt field winding or in parallel with the series field winding causes the field current and thereby the flux in the motor to decrease.
- Since the speed of a motor is inversely proportional to its flux, a decrease in its flux results in an increase in its speed.
- Thus, the flux-control method makes a motor operate at a speed higher than its rated speed.
- As the torque developed by a shunt motor is proportional to the product of the armature current and the flux per pole, a decrease in the flux must be accompanied by a corresponding increase in the armature current for the motor to deliver the same torque.

Braking or Reversing DC Motors

- In some applications, it may be necessary to either stop the motor quickly or reverse its direction of rotation.
- The commonly employed methods are:
  - Plugging
  - Dynamic braking
  - Regenerative braking

Braking or Reversing DC Motors: Plugging

- Stopping and/or reversing the direction of a dc motor merely by reversing the supply connections to the armature terminals is known as plugging or counter current braking.
- The field-winding connections for shunt motors are left undisturbed.
- This method is employed to control the dc motors used in elevators, rolling mills, printing presses, and machine tools, to name just a few.
- Just prior to plugging, the back emf in the motor is opposing the applied source voltage.
- Because the armature resistance is usually very small, the back emf is almost equal and opposite to the applied voltage.
- At the instant the motor is plugged, the back emf and the applied voltage are in the same direction.
- Thus, the total voltage in the armature circuit is almost twice as much as the applied voltage.

Braking or Reversing DC Motors: Plugging

- To protect the motor from a sudden increase in the armature current, an external resistance must be added in series with the armature circuit.

- The circuit connections, in their simplest forms, for shunt and series motors are given in the figure below.

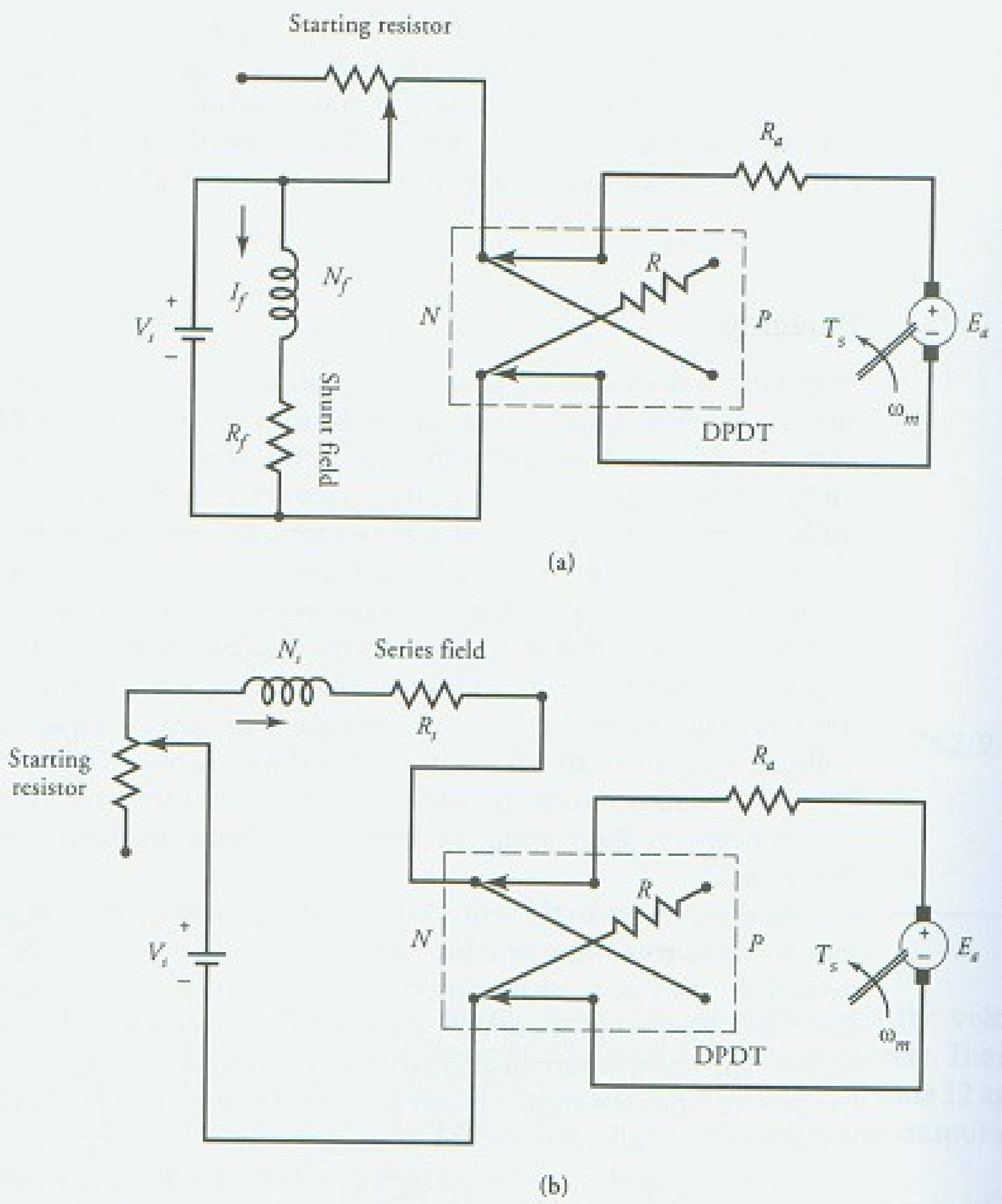


Figure 6.22 Plugging of (a) a shunt motor and (b) a series motor.

Braking or Reversing DC Motors: Plugging

- As the current in the armature winding reverses direction, it produces a force that tends to rotate the armature in a direction opposite to its initial rotation.
- This causes the motor to slow down, stop, and then pick up speed in the opposite direction. Plugging, therefore, allows us to reverse the direction of rotation of a motor.
- This technique can also be used to brake the motor by simply disconnecting the power from the motor when it comes to rest.
- At any time during the plugging action, the armature current is

$$I_a = \frac{V_s + E_a}{R_a + R} = \frac{V_s}{R_a + R} + \frac{E_a}{R_a + R} = \frac{V_s}{R_a + R} + \frac{K_a \phi_p \omega_m}{R_a + R}$$

$$Braking\ \ Torque$$

$$T_b = K_a \phi_p I_a = K_a \phi_p \left[\frac{V_s}{R_a + R} + \frac{K_a \phi_p \omega_m}{R_a + R} \right] = K_1 \phi_p + K_2 \phi_p^2 \omega_m$$

Braking or Reversing DC Motors: Dynamic Braking

- If the armature winding of a dc motor is suddenly disconnected from the source, the motor will coast to a stop.
- The time taken by the motor to come to rest depends upon the kinetic energy stored in the rotating system.
- Dynamic braking, on the other hand, makes use of the back emf in the motor in order to stop it quickly.
- If the armature winding, after being disconnected from the source, is connected across a variable resistance R, the back emf will produce a current in the reverse direction.
- A current in the reverse direction in the armature winding results in a torque that opposes the rotation and forces the motor to come to a halt.

Braking or Reversing DC Motors: Dynamic Braking

- The dynamic braking effect is controlled by varying R.
- At the time of dynamic braking, R is selected to limit the inrush of armature current to about 150% of its rated value.
- As the motor speed falls, so doe the induced emf and the current through R.
- Thus, the dynamic braking action is maximum at first and diminishes to zero as the motor comes to a stop.

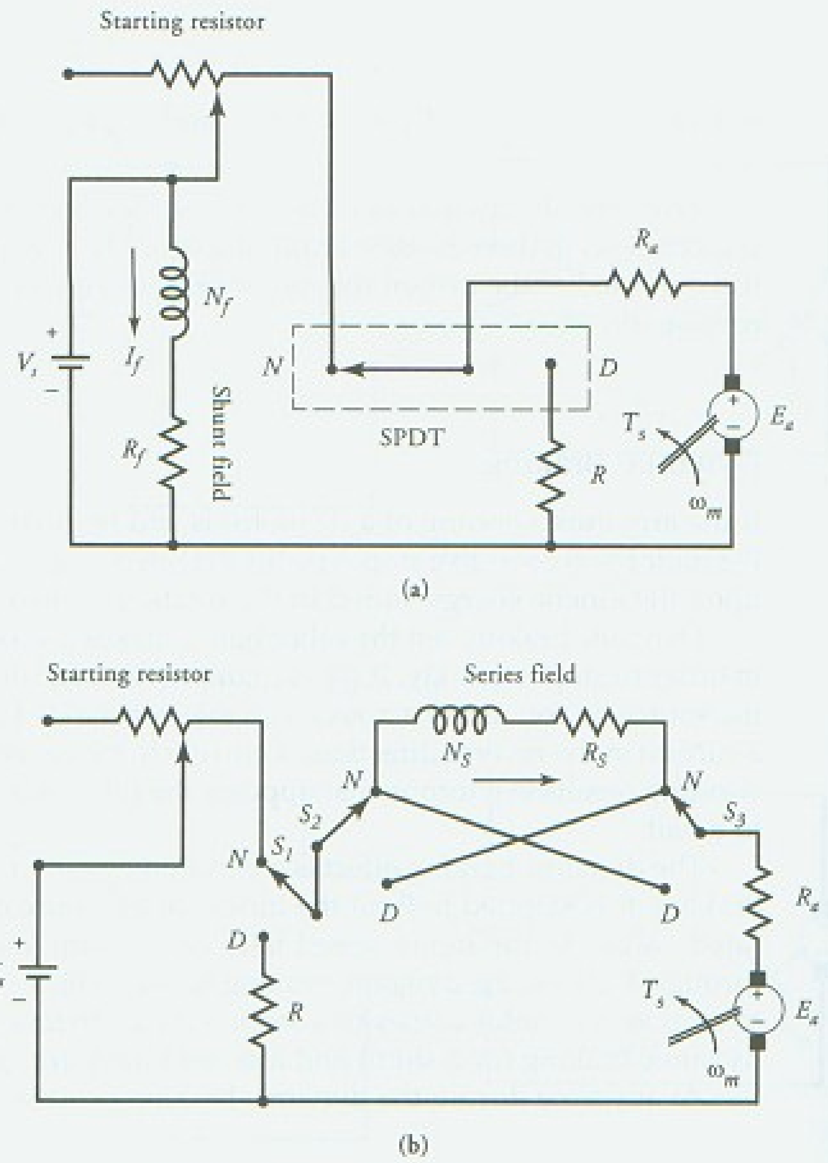


Figure 6.23 Dynamic braking of **(a)** a shunt motor and **(b)** a series motor.

Braking or Reversing DC Motors: Dynamic Braking

- At any time during the dynamic braking, the armature current is

$$I_a = \frac{E_a}{R_a + R} = \frac{K_a \phi_p \omega_m}{R_a + R}$$

$$Braking\ \ Torque$$

$$T_b = K_a \phi_p I_a = K_a \phi_p \left[\frac{K_a \phi_p \omega_m}{R_a + R} \right] = \frac{K_a^2 \phi_p^2 \omega_m}{R_a + R} = K_2 \phi_p^2 \omega_m$$

$$T_{b\_series\,motor} = K_2 K_f^2 I_a^2 \omega_m \qquad \phi_p = K_f I_a$$

$$T_{b\_shunt\,motor} = K_4 \omega_m$$

- It is evident that the braking torque vanishes as the motor speed approaches zero.

Braking or Reversing DC Motors: Regenerative Braking

- Regenerative braking is used in applications in which motor speed is likely to increase from its rated value.
- Applications: electric trains, elevators, cranes, and hoists.
- Under normal operation of a dc motor, say a permanent-magnet motor in an electric train, the back emf is slightly less than the applied voltage.
- Note that the back emf in a PM motor is directly proportional to the motor speed.
- Now assume that the train is going downhill. As the motor speed increases, so does the back emf in the motor.

Braking or Reversing DC Motors: Regenerative Braking

- Now assume that the train is going downhill. As the motor speed increases, so does the back emf in the motor.
- If the back emf becomes higher than the applied voltage, the current in the armature winding reverses its direction and the motor becomes a generator.
- It sends power back to the source and/or other devices operating from the same source.
- The reversal of armature current produces a torque in a direction opposite to the motor speed.
- Consequently, the motor speed falls until the back emf in the motor is less than the applied voltage.
- The regenerative action not only controls the speed of the motor but also develops power that may be used elsewhere.