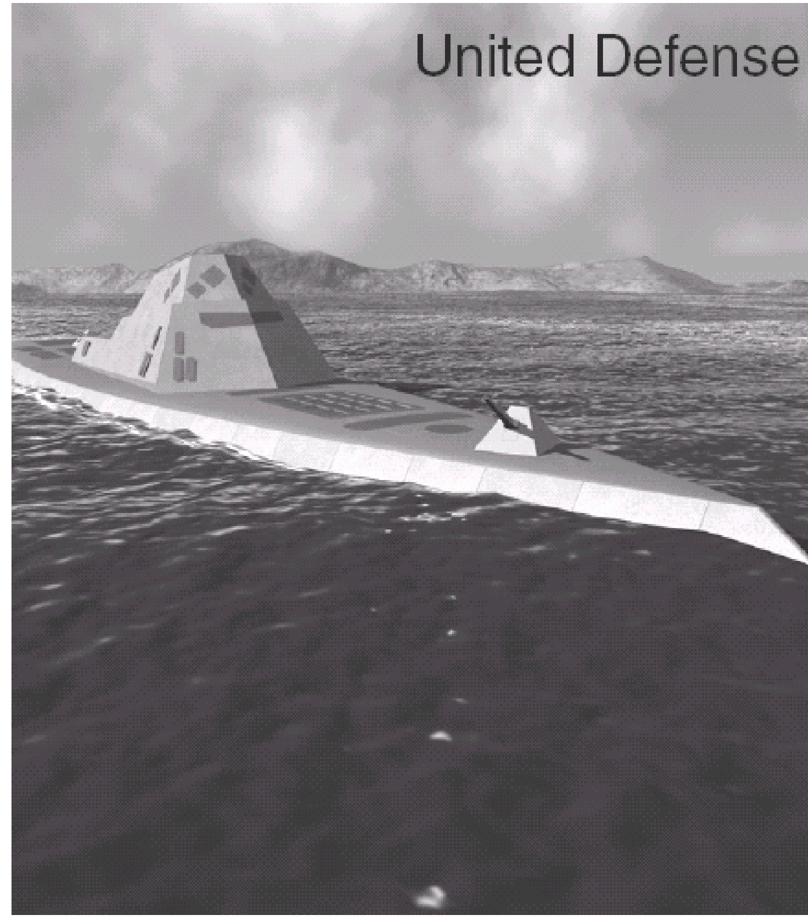
DC MACHINES

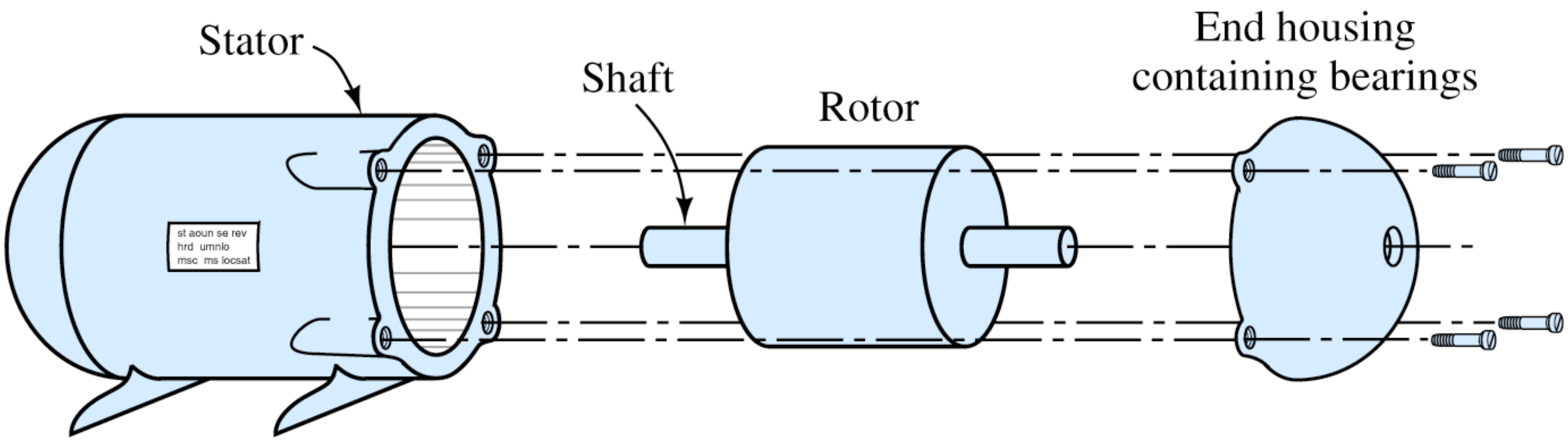
DC Machines

1. Select the proper motor type for various applications.
2. State how torque varies with speed for various motors.
3. Compute electrical and mechanical quantities using the equivalent circuit for dc motors.
4. Use motor nameplate data.
5. Understand the operation and characteristics of shunt-connected dc motors, series-connected dc motors, and universal motors.

The DD(X) class of destroyers currently under development by the United States Navy will use an electrical propulsion system. Similarly enhanced electrical-power systems are being developed to provide the electrical power needed for drive-by-wire systems in automobiles.



Basic Construction of Motors



Characteristics of AC Electrical Motors

	Type	Power Range (hp)	Rotor	Stator	Comments and Applications
Three phase	Induction	1–5000	Squirrel cage	Three-phase armature windings	Simple rugged construction; very common; fans, pumps
			Wound field		Adjustable speed using rotor resistance; cranes, hoists
	Synchronous	1–5	Permanent magnet		Precise speed; transport sheet materials
		1000–50,000	Dc field winding		Large constant loads; potential for power-factor correction
Single phase	Induction	$\frac{1}{3}$–5	Squirrel cage	Main and auxiliary windings	Several types: split phase, capacitor start, capacitor run; simple and rugged; many household applications: fans, water pumps, refrigerators
	Synchronous	$\frac{1}{10}$ or less	Reluctance or hysteresis	Armature winding	Low torque, fixed speed; timing applications

Characteristics of DC Electrical Motors

Wound field	Shunt connected	10–200	Armature winding	Field winding	Industrial applications, grinding, machine tools, hoists
	Series connected				High torque at low speed; dangerous if not loaded; drills, automotive starting motors, (universal motor used for single-phase ac has high power/weight ratio)
	Compound connected				Can be designed to tailor torque–speed characteristic; traction motors
Permanent-magnet field		$\frac{1}{20}$–10	Armature winding	Permanent magnets	Servo applications, machine tools, computer peripherals, automotive fans, window motors

Armature and Field Windings

The purpose of the field winding is to set up the magnetic field required to produce torque.

The armature windings carry currents that vary with mechanical load. When the machine is used as a generator, the output is taken from the armature windings.

AC Motors

- Single phase or three phase
- Types:
  - Induction motors
    - Most common
    - Simple rugged construction
    - Good operating characteristics
  - Synchronous motors
    - Constant speed regardless of load torque
    - Used as generators
  - Special-purpose
- 70% of energy consumed by motors (half of which are induction motors)

DC Motors

- Powered from DC sources
- AC distribution => Rectifier/converter
- Automotive application
- Direction of current in armature conductors on rotor is reversed periodically during rotation.
  - Using brushes on stator and commutator on shaft
  - Brushes in sliding contact with commutator
  - Subject to wear, need for maintenance
- Advantage: Speed and direction can be controlled more easily

Losses, Power Ratings and Efficiency

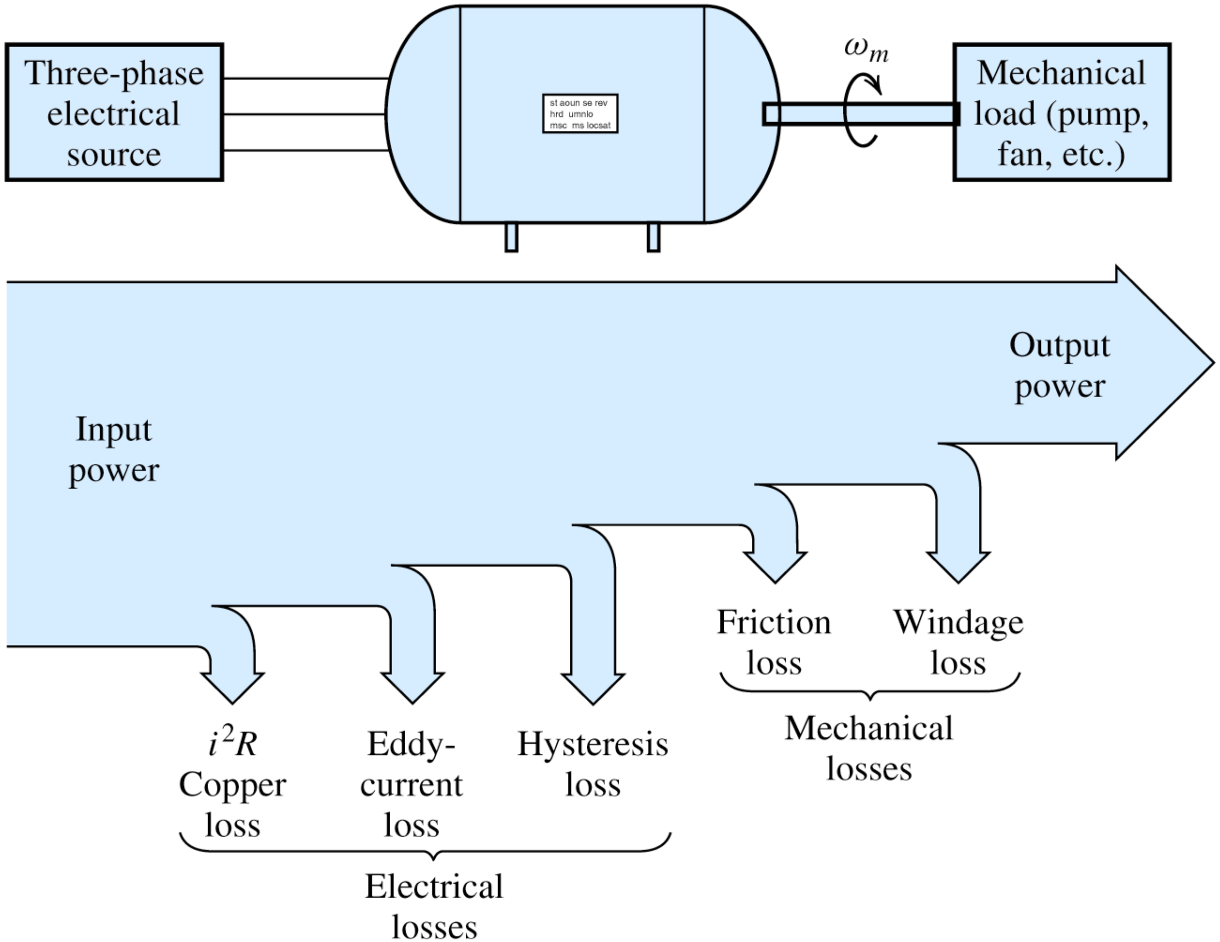


Figure 16.2 Power flows left to right from a three-phase electrical source into an induction motor and then to a mechanical load. Some of the power is lost along the way due to various causes.

Losses, Power Ratings and Efficiency

$$P_{in} = \sqrt{3} V_{rms} I_{rms} \cos(\theta)$$

$$P_{out} = T_{out} \omega_m$$

$$\omega_m = n_m \frac{2\pi}{60}$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

Power rating of a motor is the output power that the motor can safely produce on a continuous basis.

Torque-Speed Characteristics

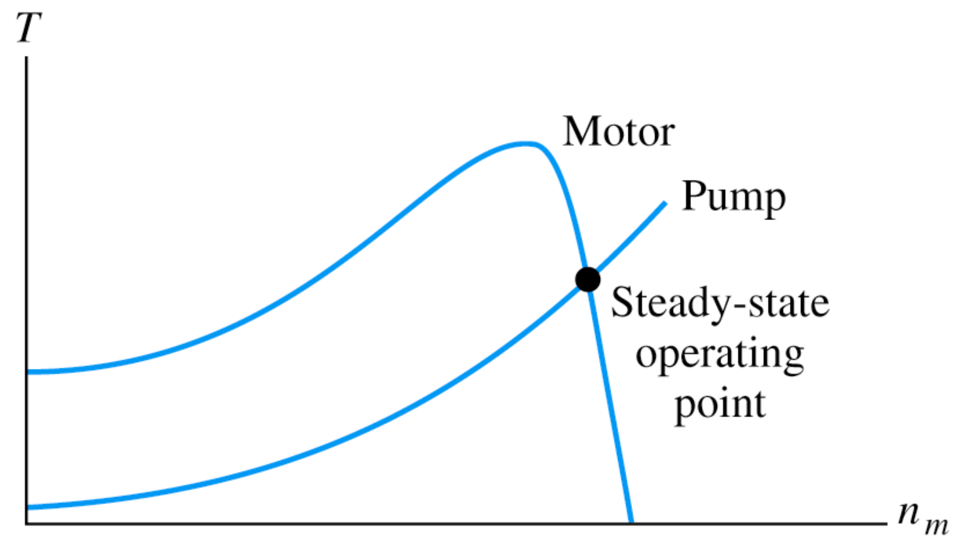


Figure 16.3 The torque–speed characteristics of an induction motor and a load consisting of a pump. In steady state, the system operates at the point for which the torque produced by the motor equals the torque required by the load.

Torque-Speed Characteristics

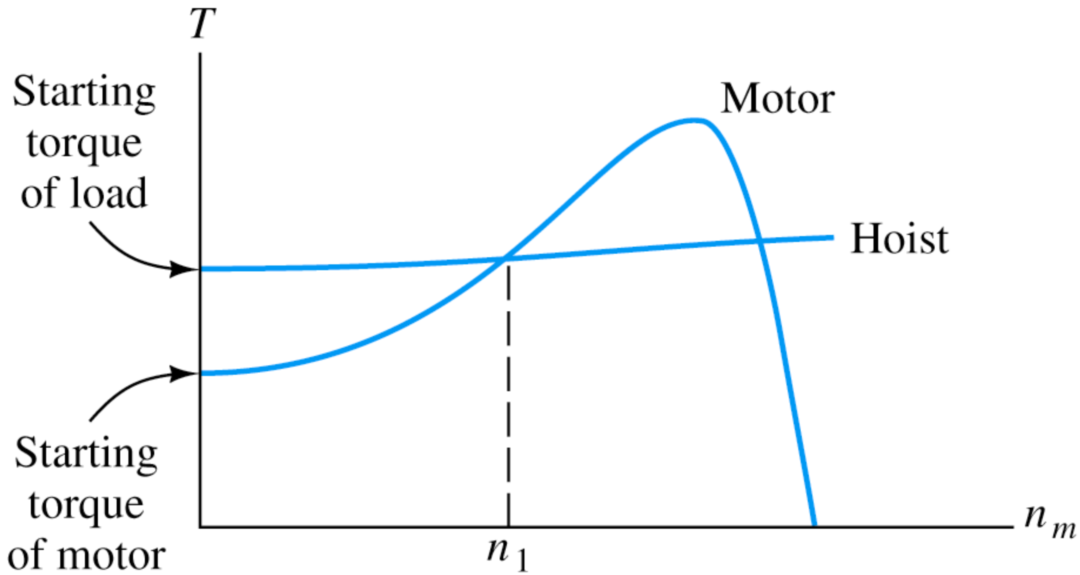


Figure 16.4 This system will not start from a standstill because the motor cannot supply the starting torque demanded by the load.

Torque-Speed Characteristics

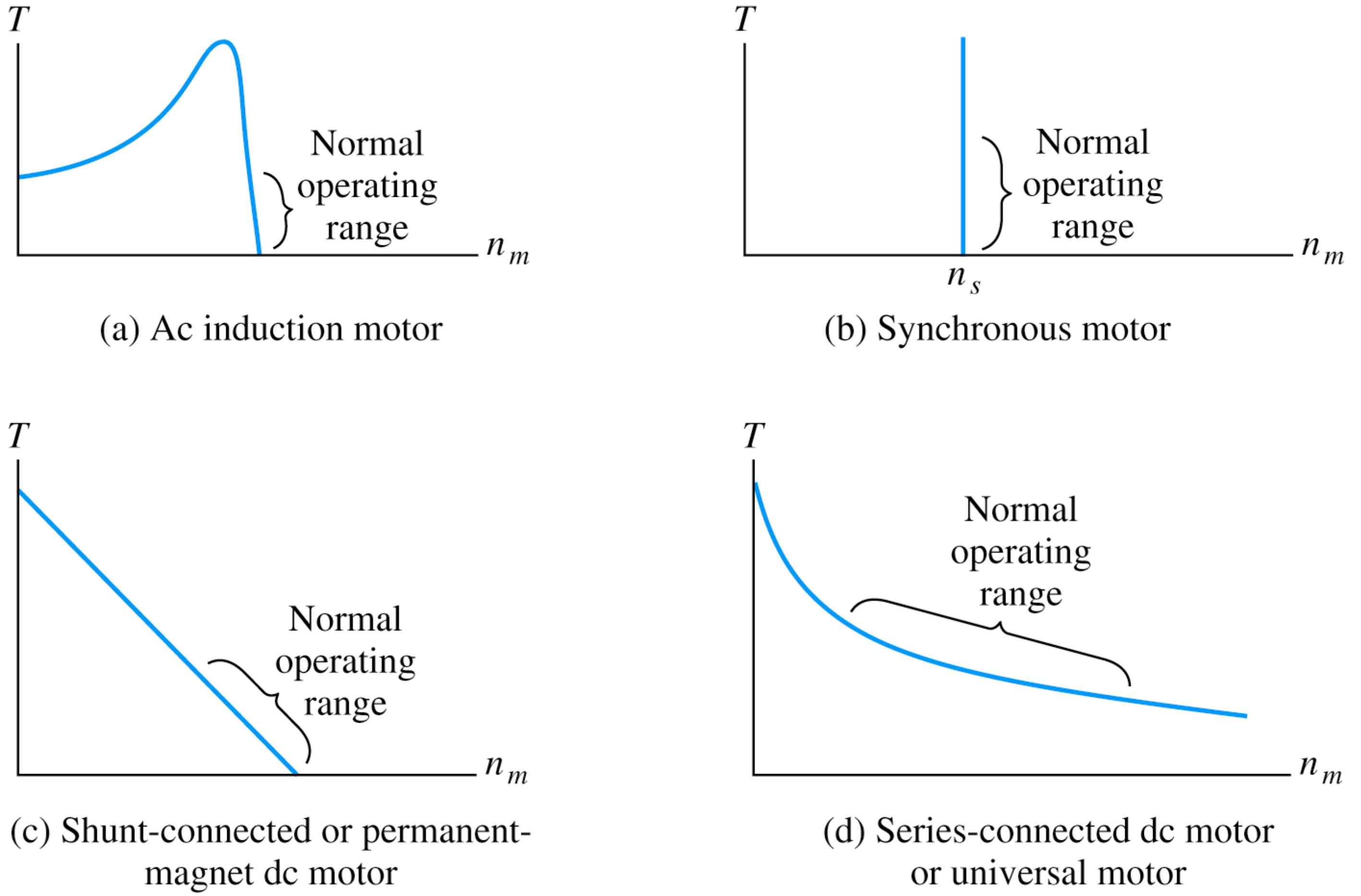


Figure 16.5 Torque versus speed characteristics for the most common types of electrical motors.

Speed Regulation

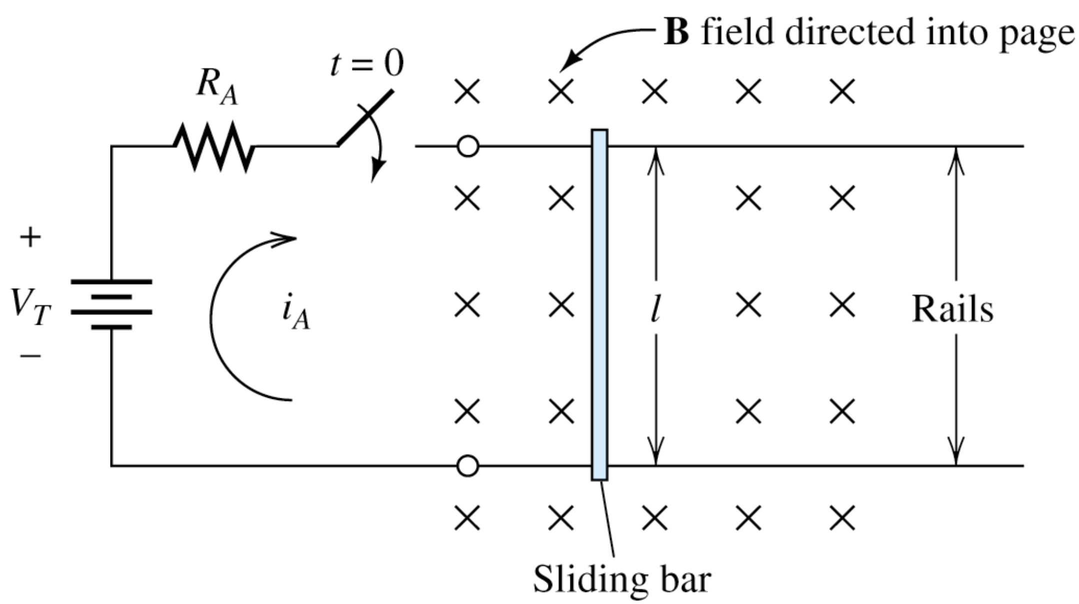
$$speed\ regulation = \frac{\eta_{no-load} - \eta_{full-load}}{\eta_{full-load}} \times 100\%$$

Example Exercise

A certain 5 hp three phase induction motor operates from a 440 V rms (line-to-line) three phase source and draws a line current of 6.8 A rms at a power factor of 0.78 lagging nder rated full-load conditions. The full-load speed is 1150 rpm. Under no-load conditions, the speed is 1195 rpm, and the line current is 1.2 A rms at a pf of 0.3 lagging. Find the power loss and efficiency with full load, the input power with no load and the speed regulation.

PRINCIPLES OF DC MACHINES

Study of the idealized linear dc machine demonstrates how the principles of electromagnetism apply to dc machines in general.

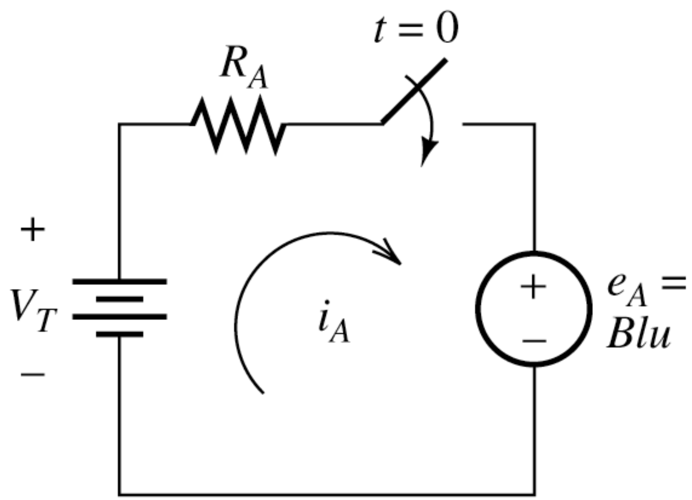


Operation as Motor

$$f = i_A l B$$

$$e_A = Blu$$

$$i_A = \frac{V_T - e_A}{R_A}$$



Operation as Generator

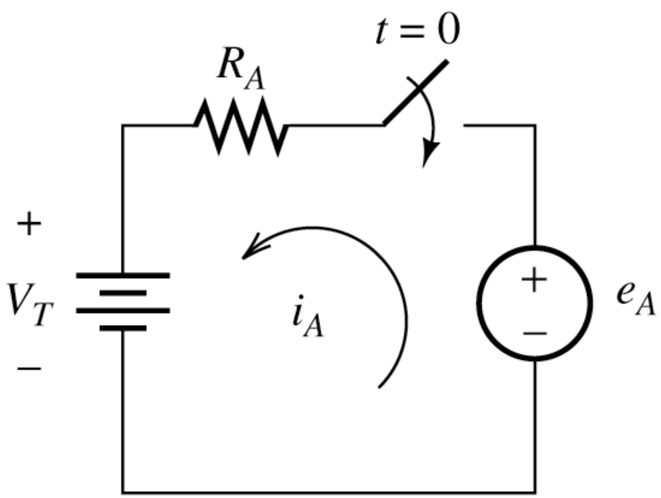


Figure 16.8 Equivalent circuit for the linear machine operating as a generator.

Example Exercise

Suppose that for the linear machine, the B=1 T, l=0.3 m, vT=2 V, R=0.05 ohm. a. Assuming that the bar is stationary at t=0, compute the initial current and initial force on the bar. Also, determine the final steady state speed. B. Now suppose that a mechanical load of 4 N directed to the left is applied to the moving bar. In steady-state, determine the speed, power delivered by vT, power delivered to the load, power lost to heat and the efficiency. C. Now suppose that a mechanical puling force of 2 N directed to the right is applied to the moving bar. In steady-state, determine the speed, power taken from the mechanical source, power delivered to the battery, power lost to heat and the efficiency.

ROTATING DC MACHINES

The basic principles of rotating dc machines are the same as those of the linear dc machine.

DC Machines

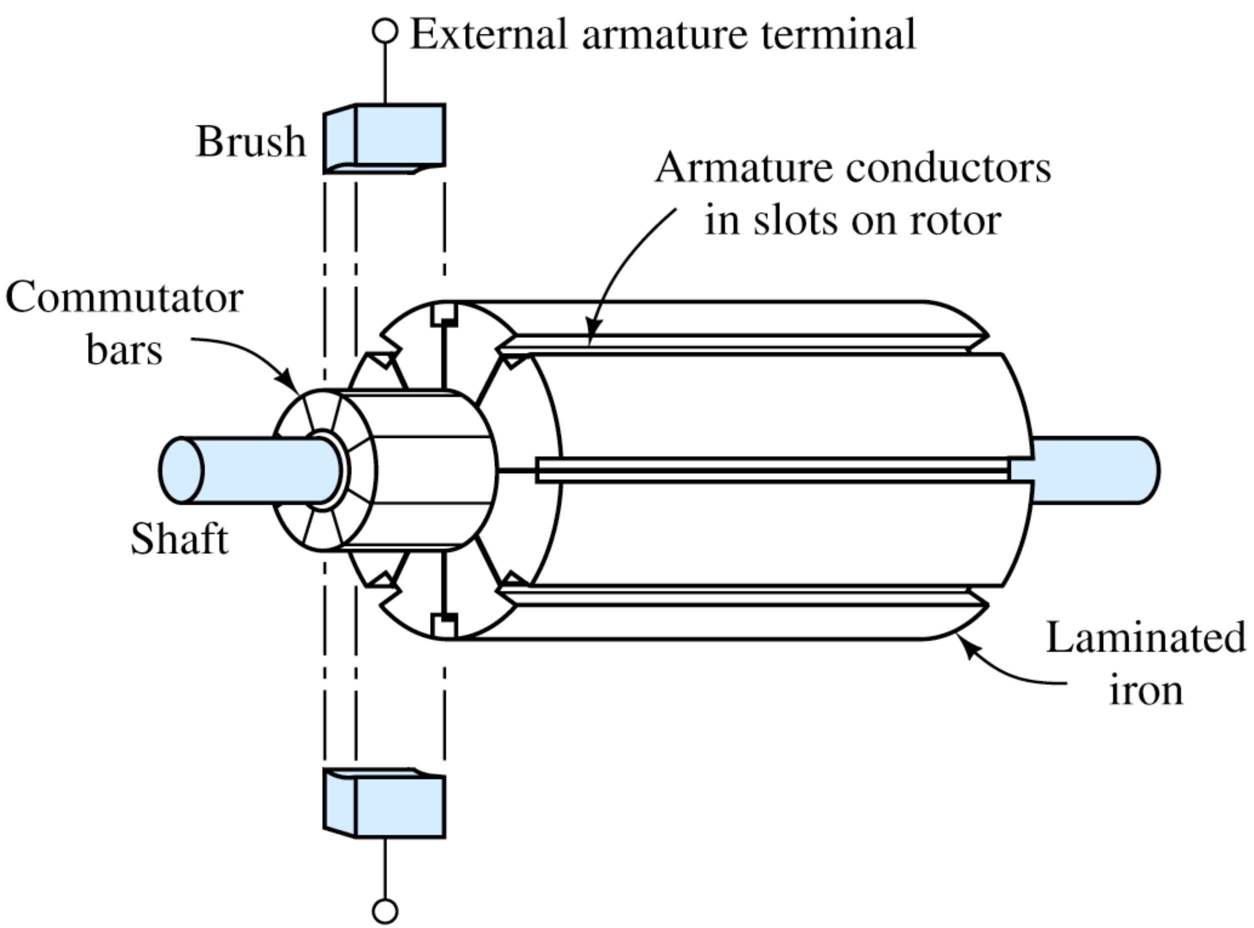


Figure 16.9 Rotor assembly of a dc machine.

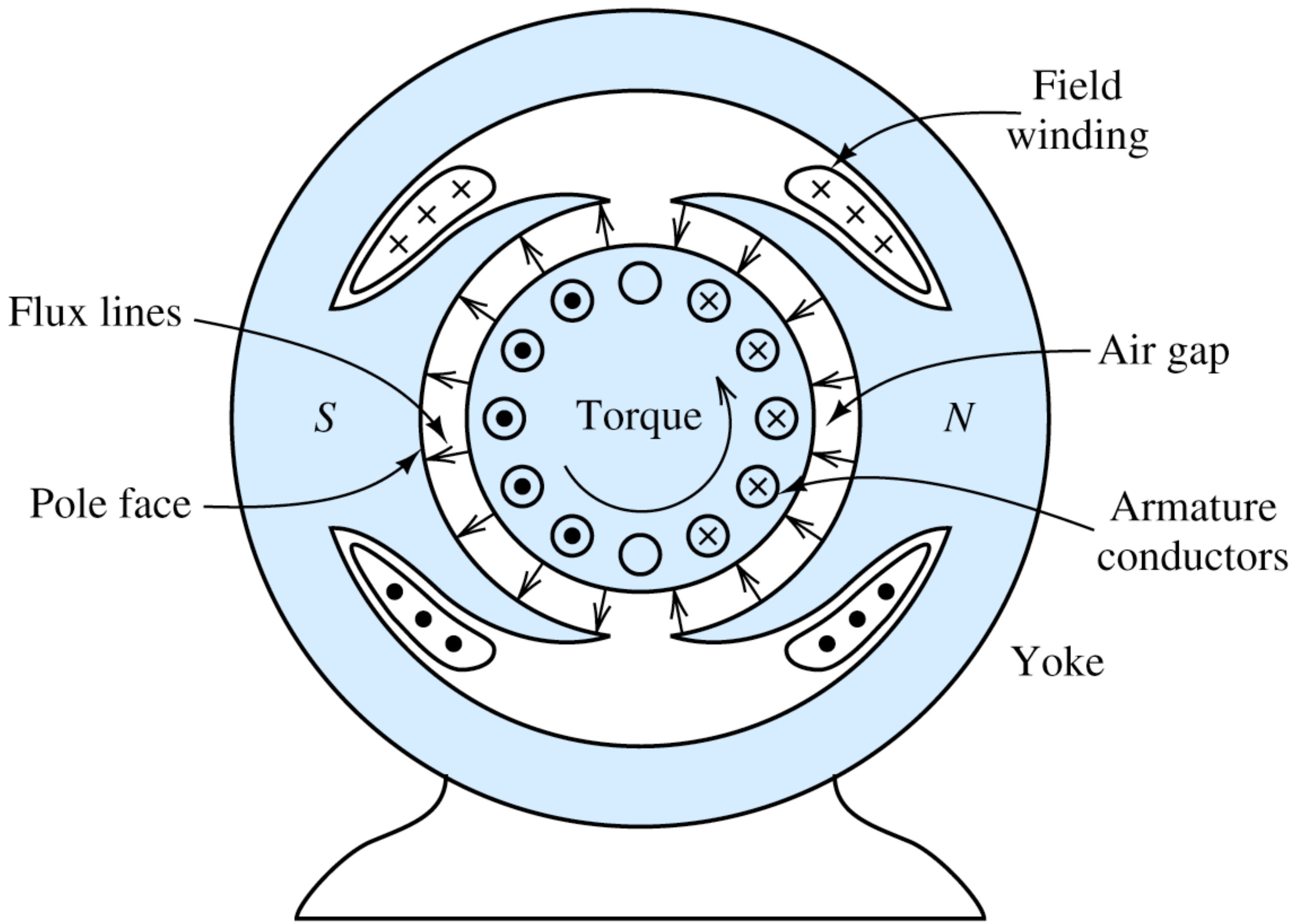


Figure 16.10 Cross section of a two-pole dc machine.

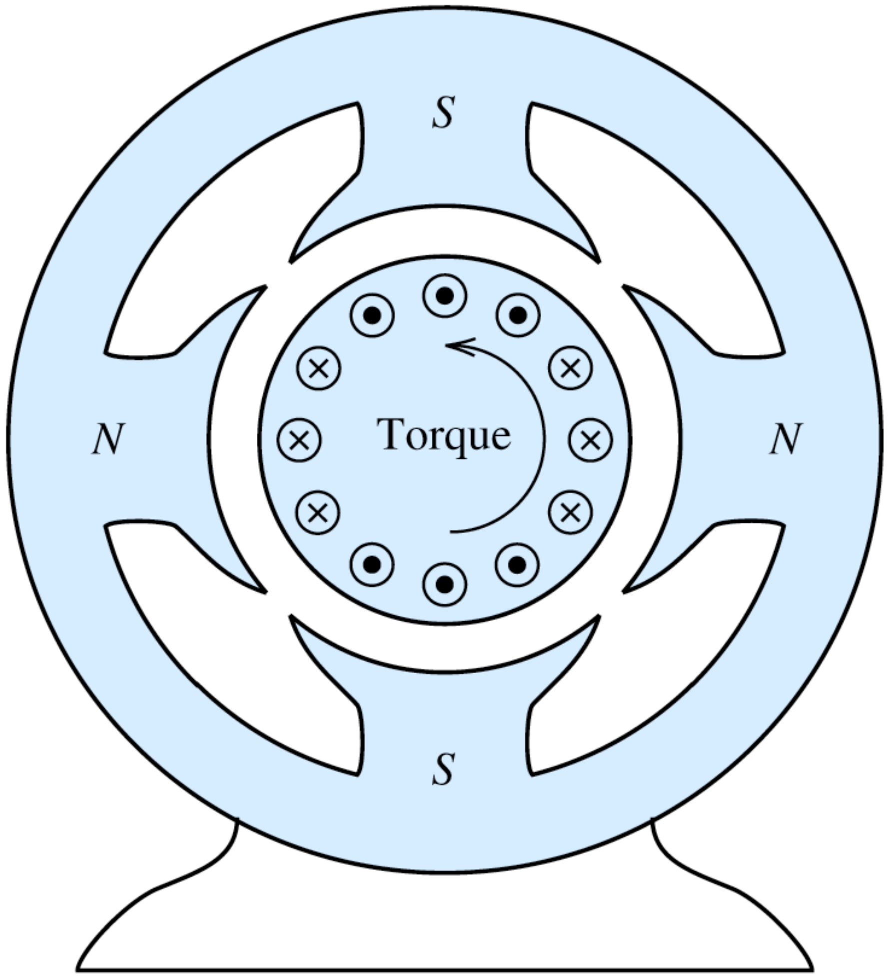


Figure 16.11 Cross section of a four-pole dc machine.

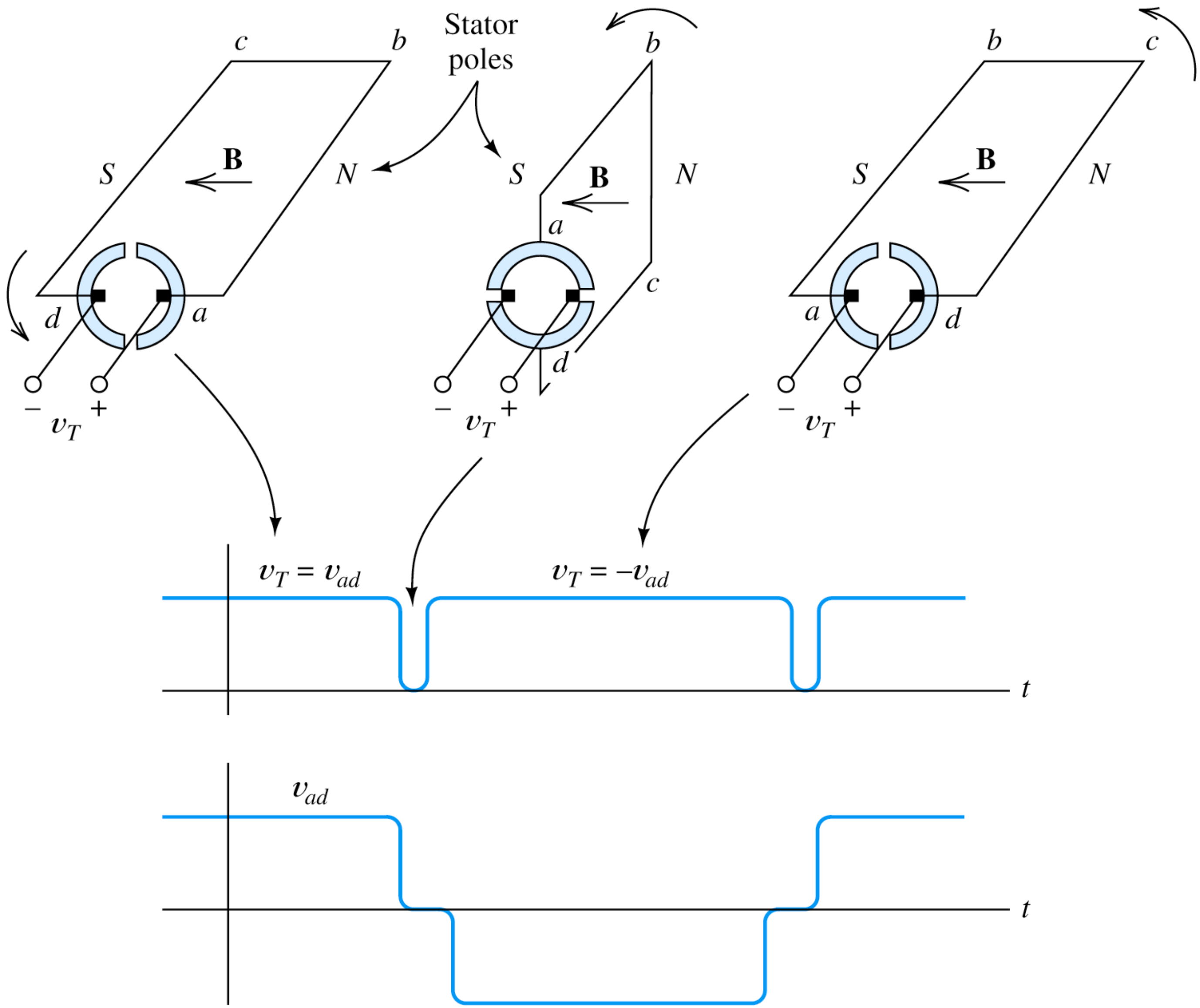


Figure 16.12 Commutation for a single armature winding.

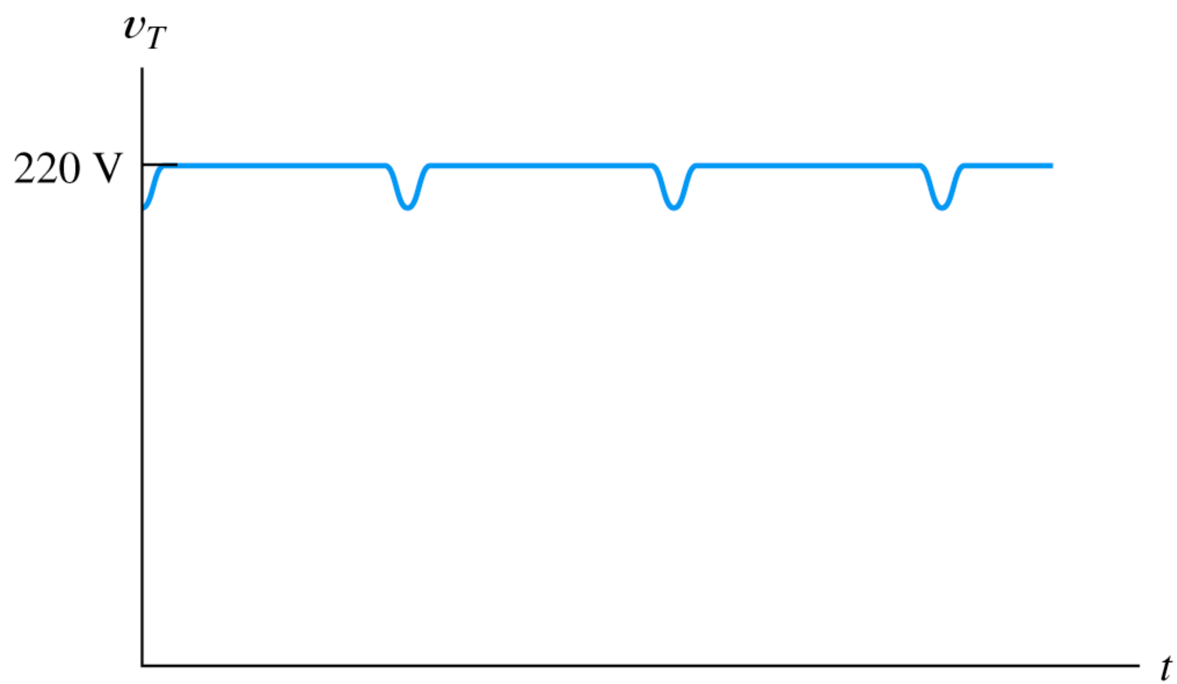
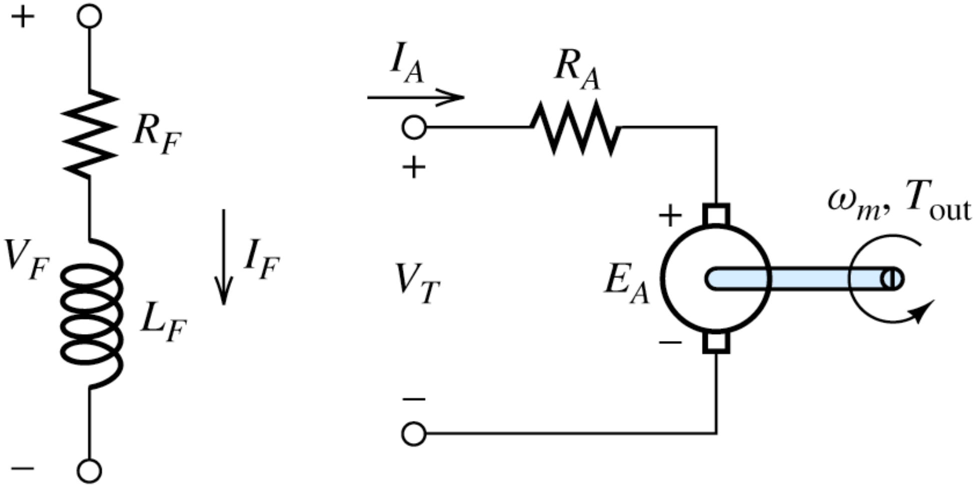


Figure 16.13 Voltage produced by a practical dc machine. Because only a few (out of many) conductors are commutated (switched) at a time, the voltage fluctuations are less pronounced than in the single-loop case illustrated in Figure 16.12.

Equivalent Circuit of the DC Motor

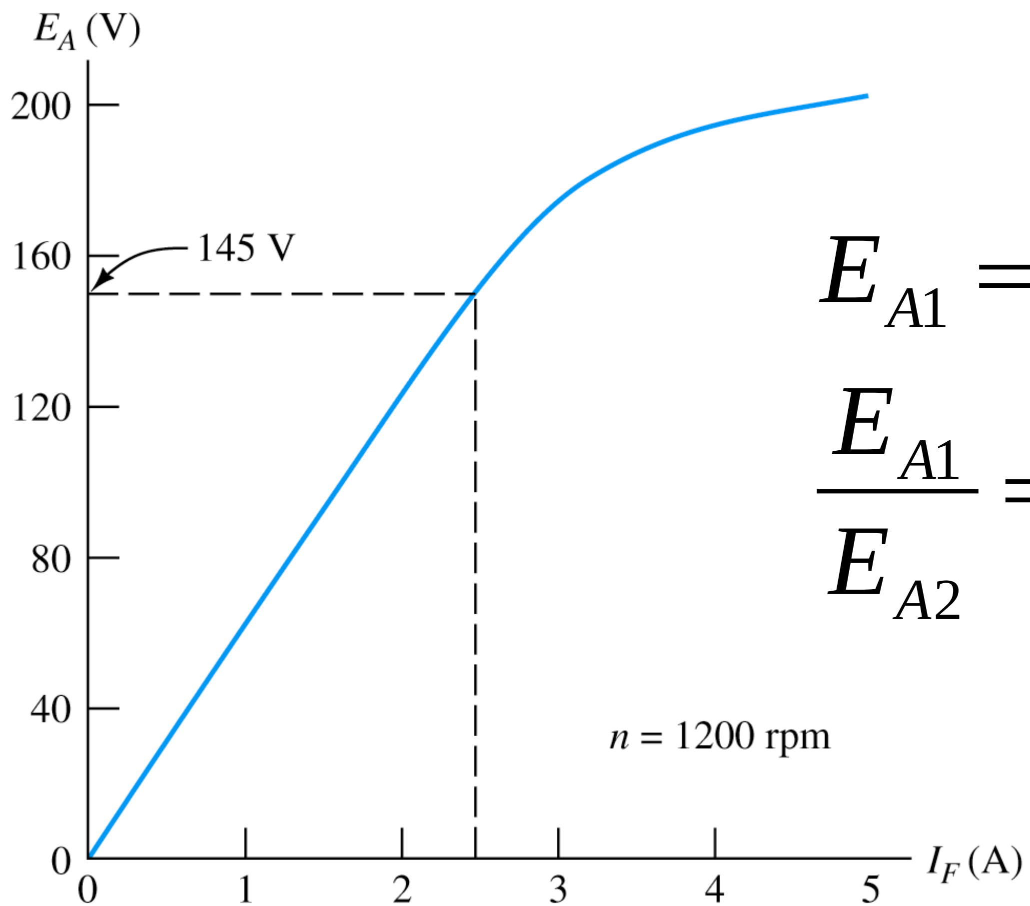


$$V_F = R_F I_F \qquad T_{\text{dev}} = K\phi I_A$$

$$E_A = K\phi\omega_m \qquad P_{\text{dev}} = \omega_m T_{\text{dev}}$$

$$P_{\text{dev}} = E_A I_A$$

Magnetization Curve



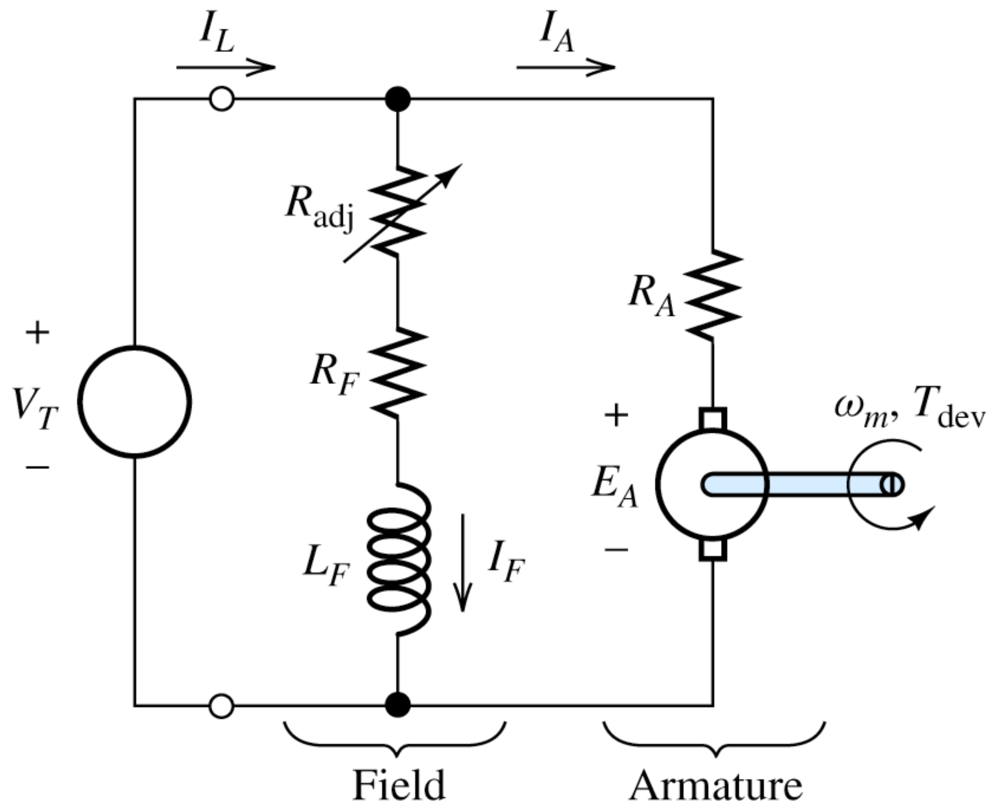
$$E_{A1} = K\phi\omega_{m1}$$

$$\frac{E_{A1}}{E_{A2}} = \frac{n_1}{n_2} = \frac{\omega_1}{\omega_2}$$

Example Exercise

A machine having the magnetization curve on previous slide is operating as a motor at a speed of 800 rpm with IA=30 A and IF=2.5 A. The armature resistance is 0.3 ohms and field resistance is 50 ohms. Find the voltage VF applied to the field circuit, VT applied to armature, developed torque and developed power.

SHUNT-CONNECTED DC MOTORS



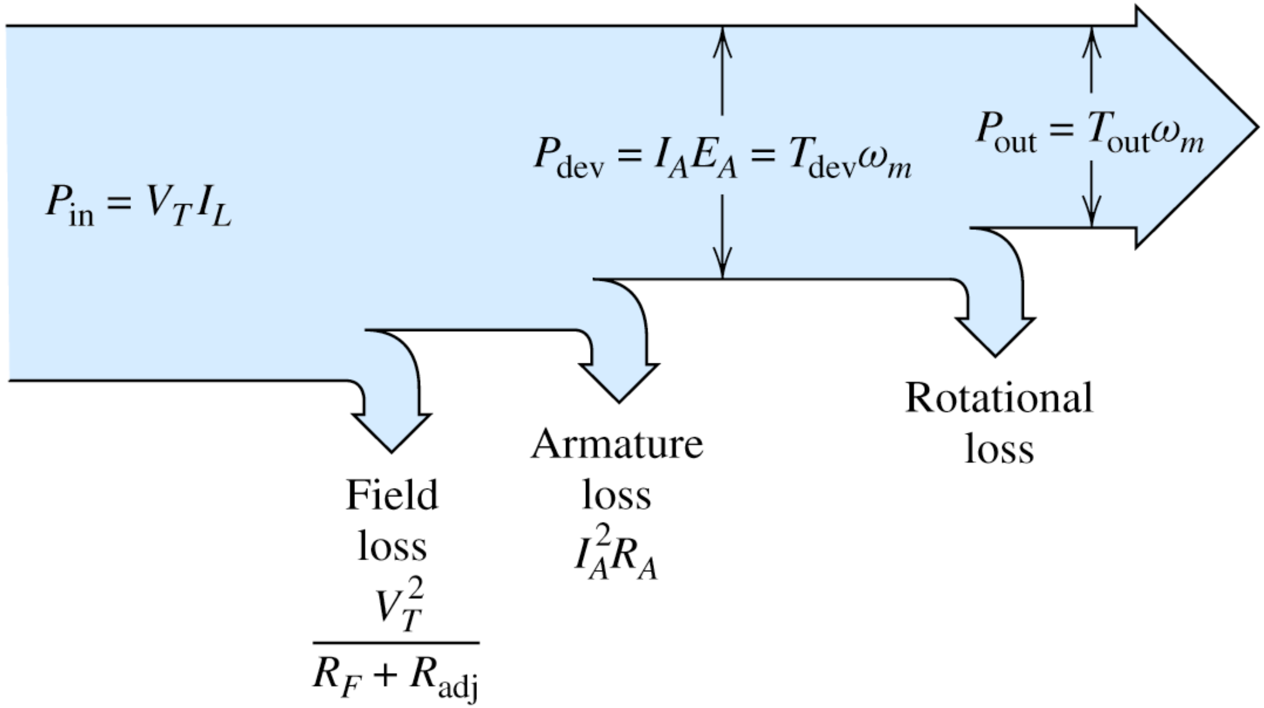


Figure 16.17 Power flow in a shunt-connected dc motor.

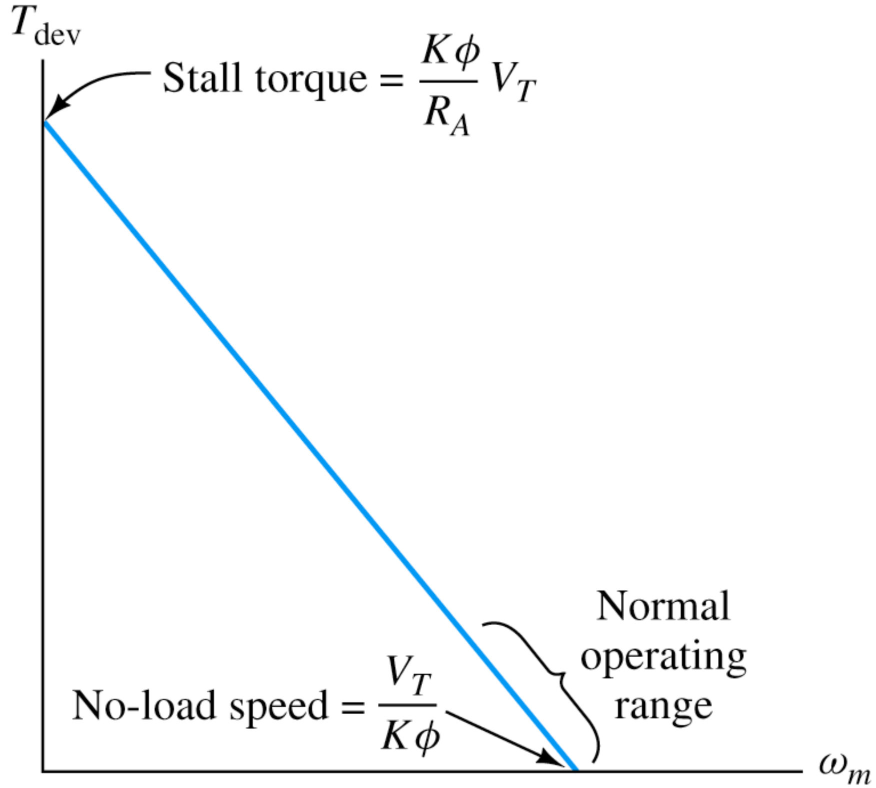
$$P_{\text{in}} = V_T I_L$$

$$P_{\text{field-loss}} = \frac{V_T^2}{R_F + R_{\text{adj}}} = V_T I_F$$

$$P_{\text{arm-loss}} = I_A^2 R_A$$

$$P_{\text{dev}} = I_A E_A = \omega_m T_{\text{dev}}$$

Torque–Speed Characteristic



$$T_{dev} = \frac{K\phi}{R_A}\left(V_T - K\phi\omega_m\right)$$

Example Exercise

50 hp shunt connected DC motor has magnetization curve shown below. VT=240 V dc supply. RA=0.065 ohm, RF=10 ohms and Radj=14 ohms. At a speed of 1200 rpm, rotational loss is 140 W. If this motor drives a hoist that demands a torque of Tout=250 Nm independent of speed, determine the motor speed and efficiency.

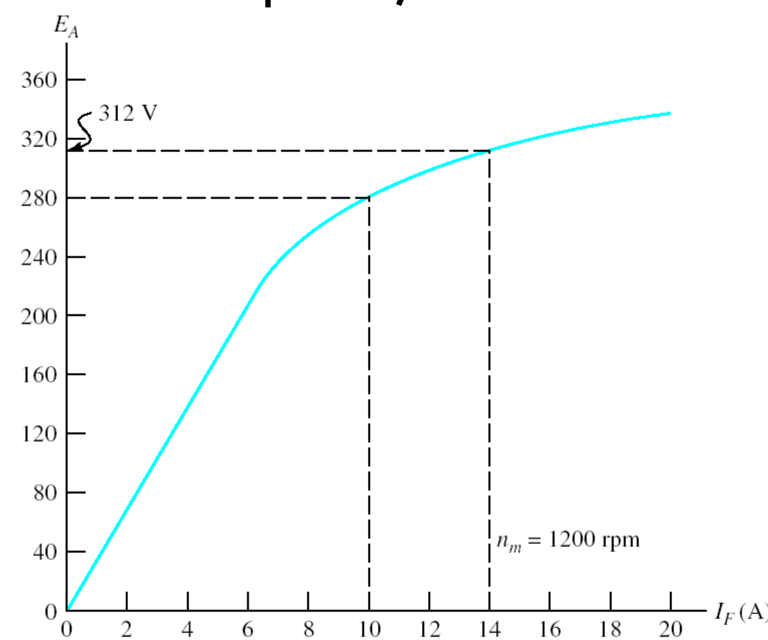


Figure 16.19 Magnetization curve for the motor of Example 16.4.

Equivalent Circuit

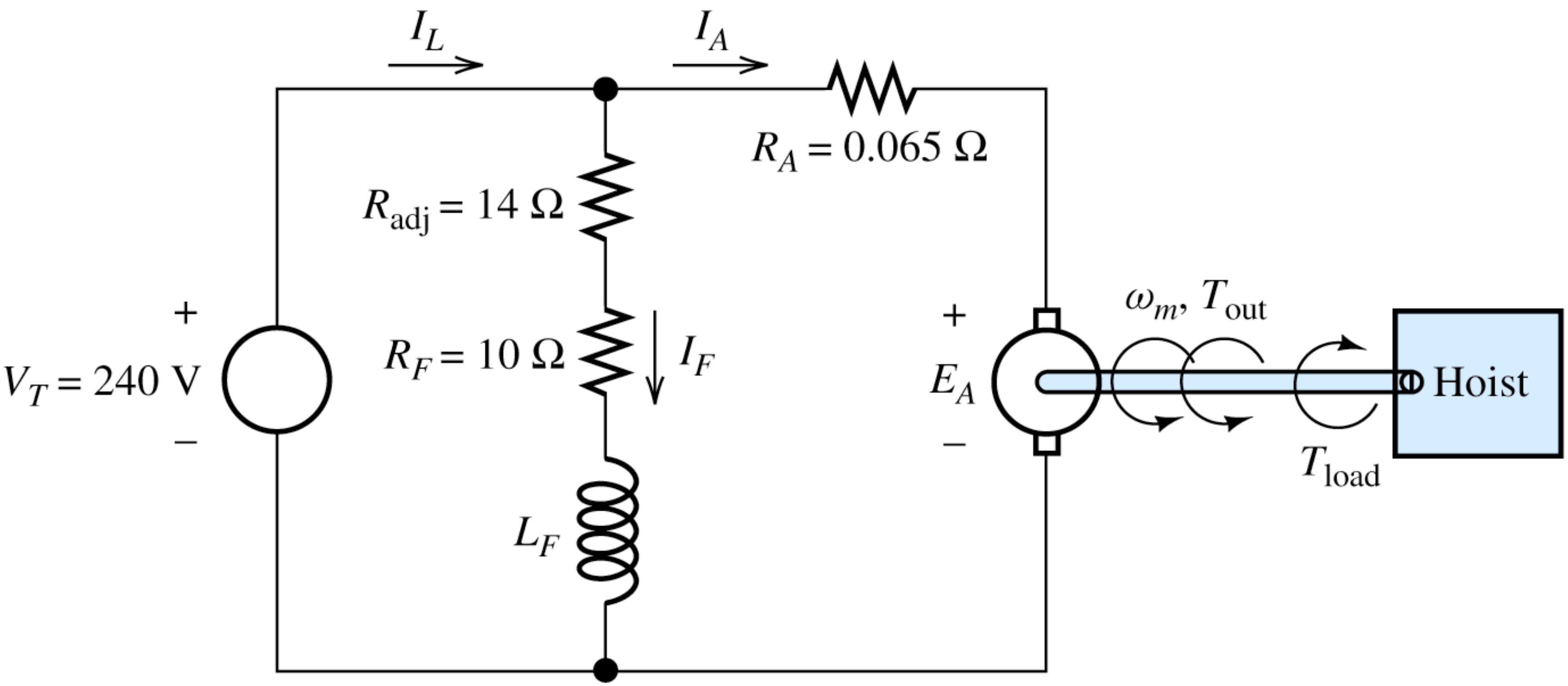
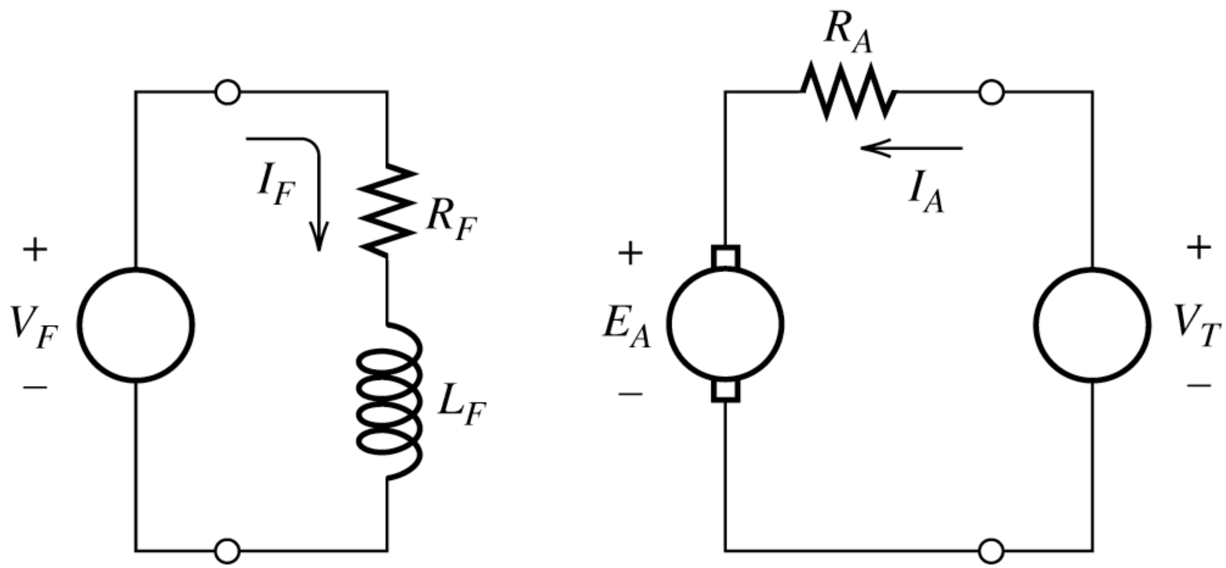


Figure 16.20 Equivalent circuit for Example 16.4.

Question

- What is the effect of increasing Radj?

Separately Excited DC Motors

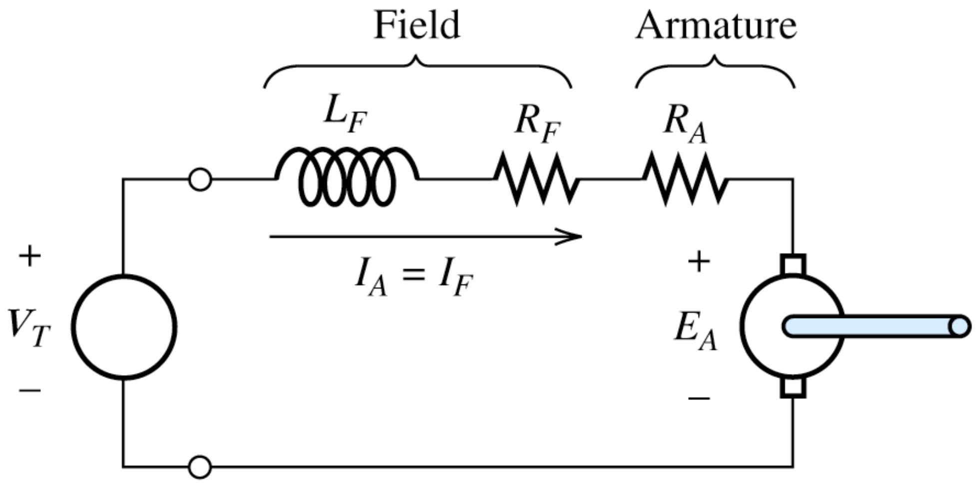


Permanent-Magnet Motors

Separately excited and permanent-magnet motors have similar characteristics to those of shunt-connected motors.

SERIES-CONNECTED DC MOTORS

Field windings are designed differently for series-connected machines than they are for shunt-connected machines.



$$\phi = K_F I_F$$

$$T_{\text{dev}} = \frac{K K_F V_T^2}{\left(R_A + R_F + K K_F \omega_m\right)^2}$$

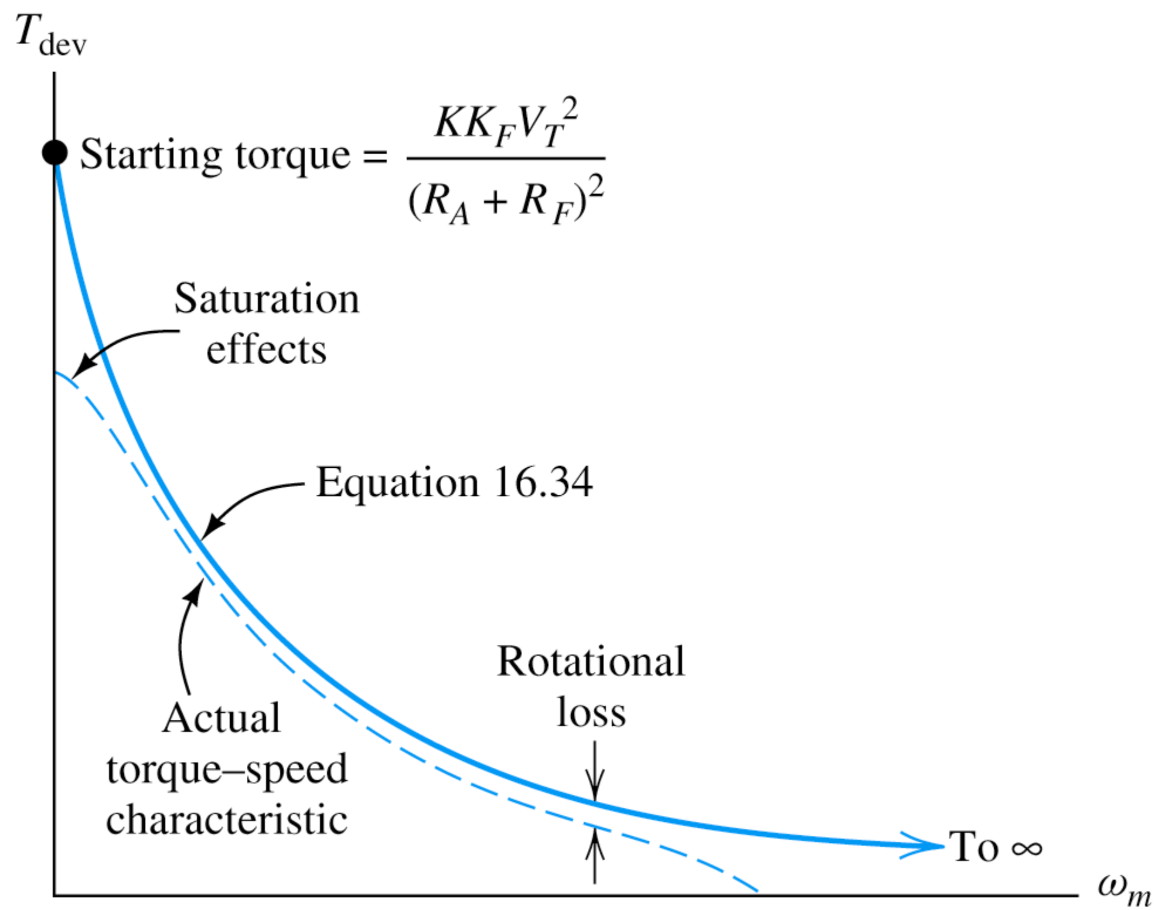


Figure 16.23 Torque–speed characteristic of the series-connected dc motor.

Universal Motors Advantages

1. For a given weight, universal motors produce more power than other types.
2. The universal motor produces large starting torque without excessive current.
3. When load torque increases, the universal motor slows down. Thus, the power produced is relatively constant, and the current magnitude remains within reasonable bounds.
4. Universal motors can be designed to operate at very high speeds, whereas we will see that other types of ac motors are limited to 3600 rpm, assuming a 60-Hz source.

SPEED CONTROL OF DC MOTORS

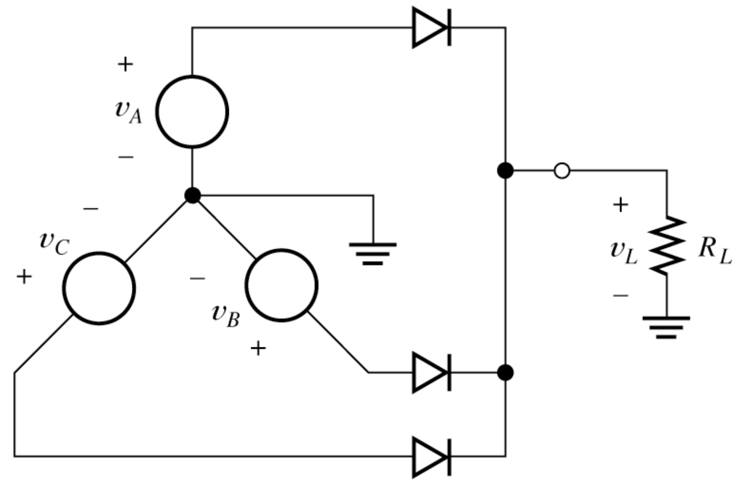
1. Vary the voltage supplied to the armature circuit while holding the field constant.
2. Vary the field current while holding the armature supply voltage constant.
3. Insert resistance in series with the armature circuit.

Speed Control

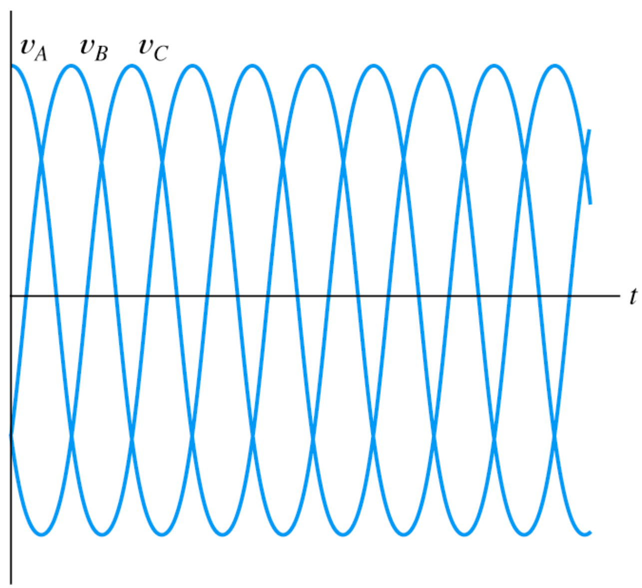
Motor Type	Speed Control Technique
Separately excited and PM	Variation of supply voltage VT
Separately excited and shunt connected	Variation of field current
All	Variation of Armature Resistance

Variation of VT

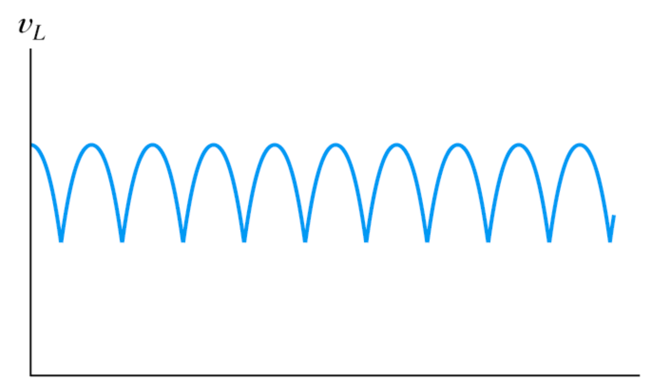
- Not useful for shunt motors
- Speed approximately proportional to source voltage
- Variable DC voltage source:



(a) Circuit diagram



(b) Three-phase ac voltages



(c) Rectified output voltage

Figure 16.24 Three-phase half-wave rectifier circuit used to convert ac power to dc.

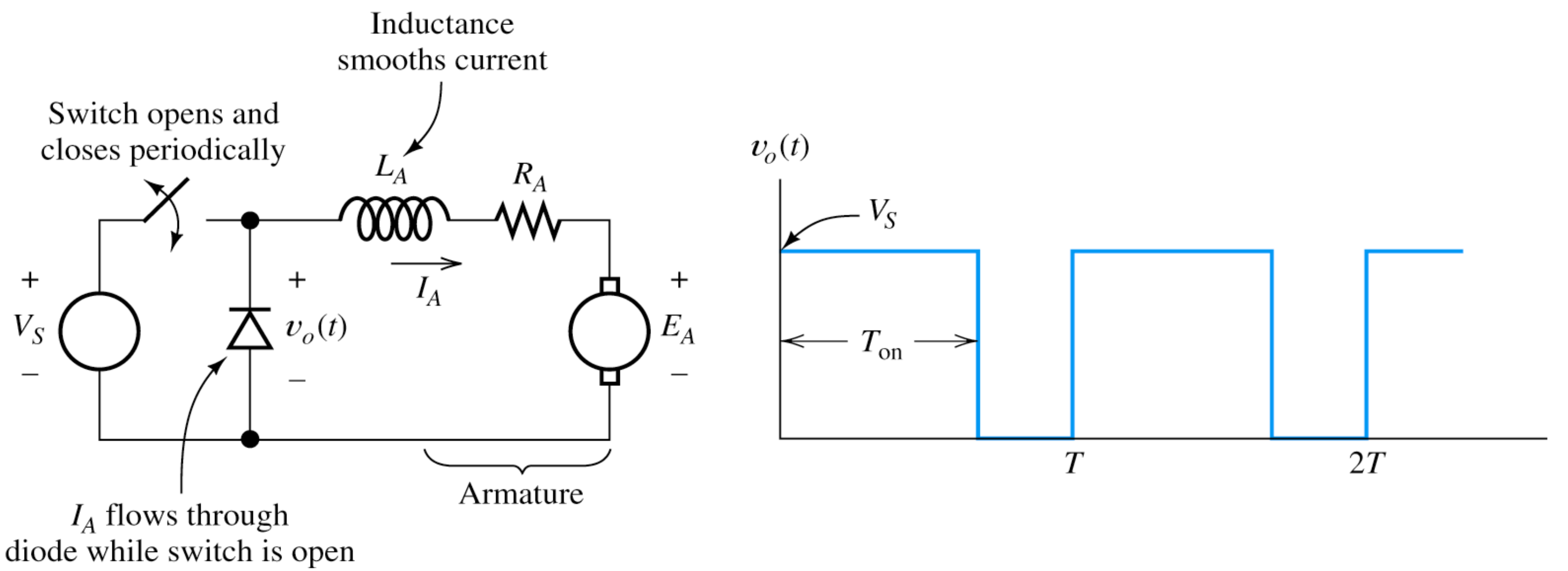


Figure 16.25 An electronic switch that opens and closes periodically can efficiently supply a variable dc voltage to a motor from a fixed dc supply voltage.

Variation of Field Current

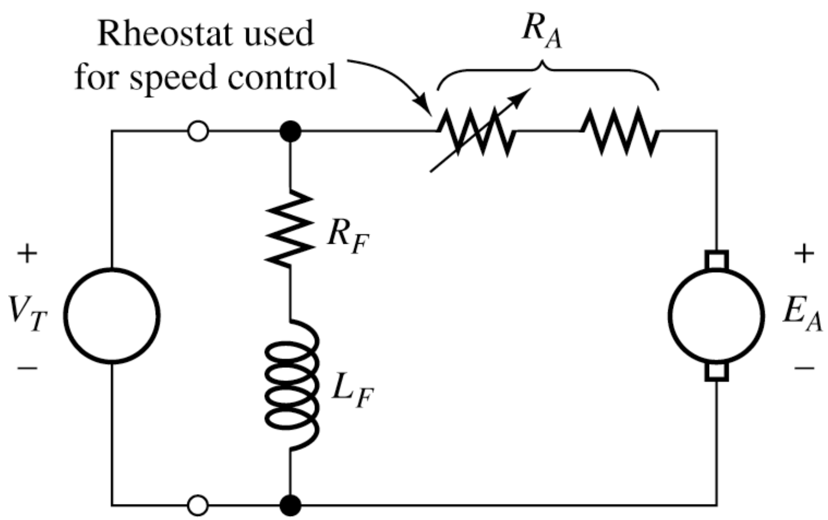
- Rheostat
- Not good for PM or series connected motors
- Reducing IF reduces flux, reducing EA, increasing IA.

$$T_{\text{dev}} = K\phi I_A$$

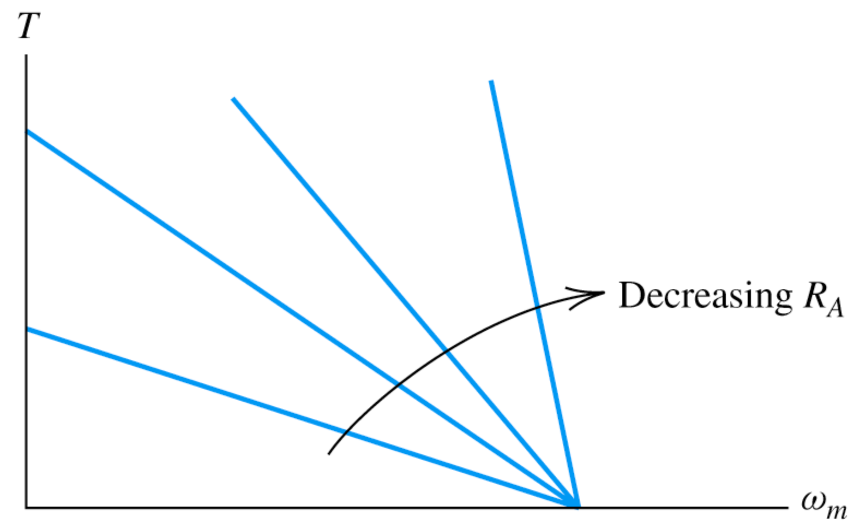
- Change in IA much greater than reduction in phi.

Resistance in Series with Armature

- Useful for all motor types.
- Wasteful of energy.



(a) Circuit diagram



(b) Torque–speed characteristic

Figure 16.26 Speed can be adjusted by varying a rheostat that is in series with the armature.

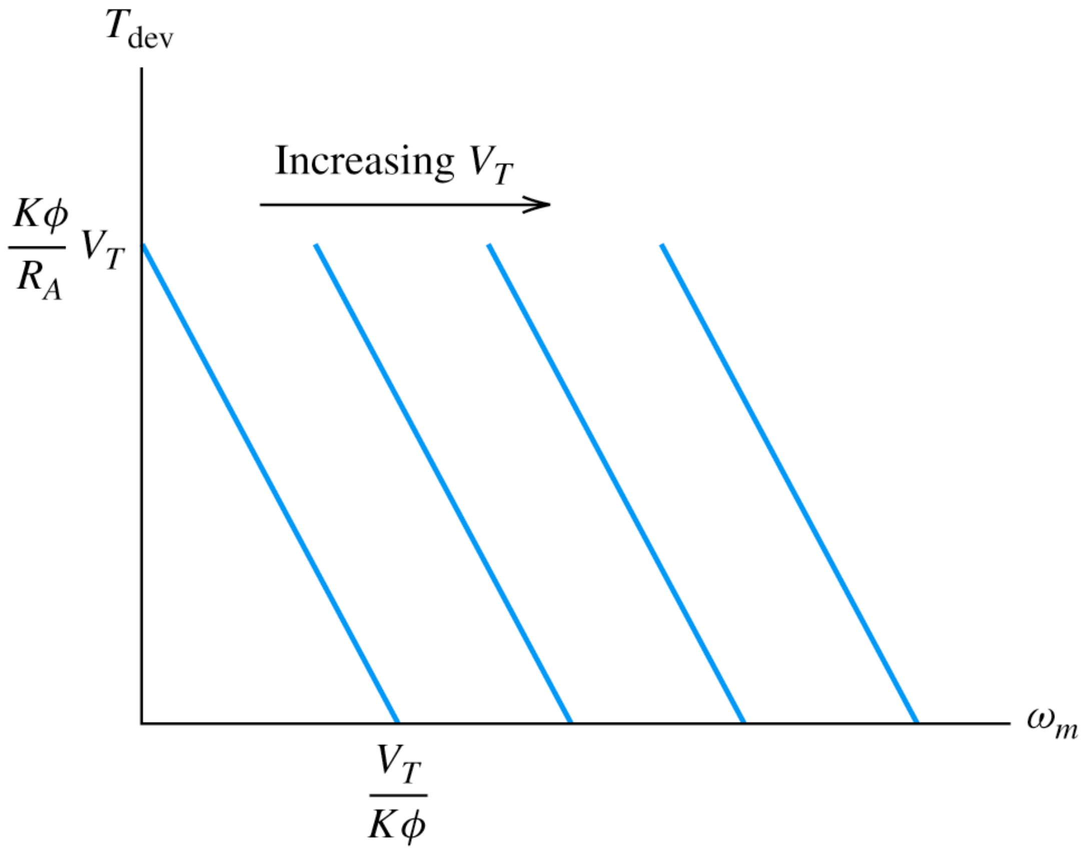


Figure 16.27 Torque versus speed for the separately excited dc motor for various values of armature supply voltage V_T.

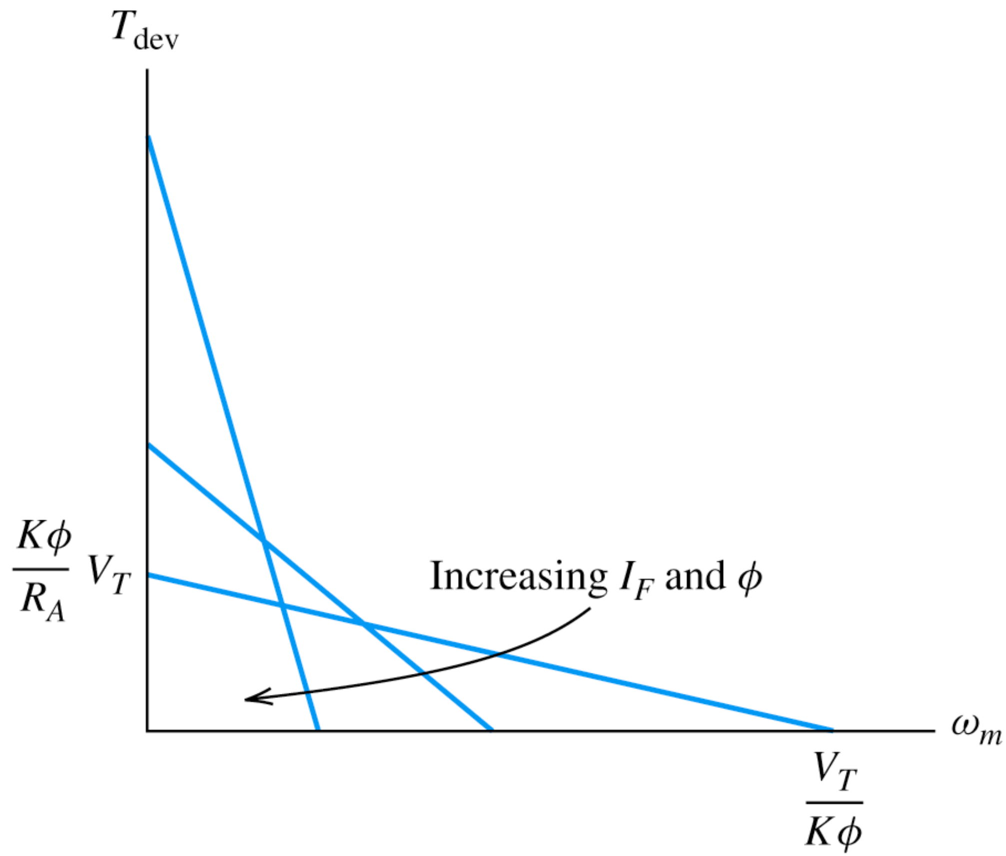
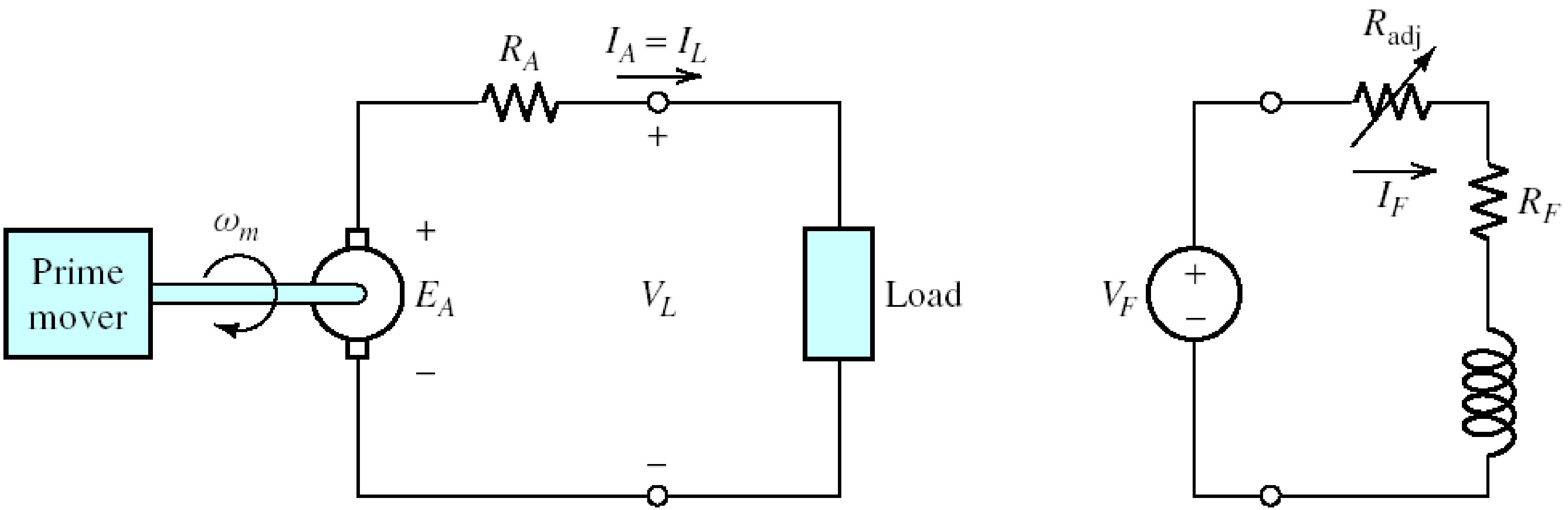


Figure 16.28 Effect of varying I_F on the torque–speed characteristics of the shunt-connected or separately excited dc motor.

Separately Excited DC Generator



(a) Separately excited

Separately Excited DC Generator

$$\text{voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

$$E_A = K\phi\omega_m$$

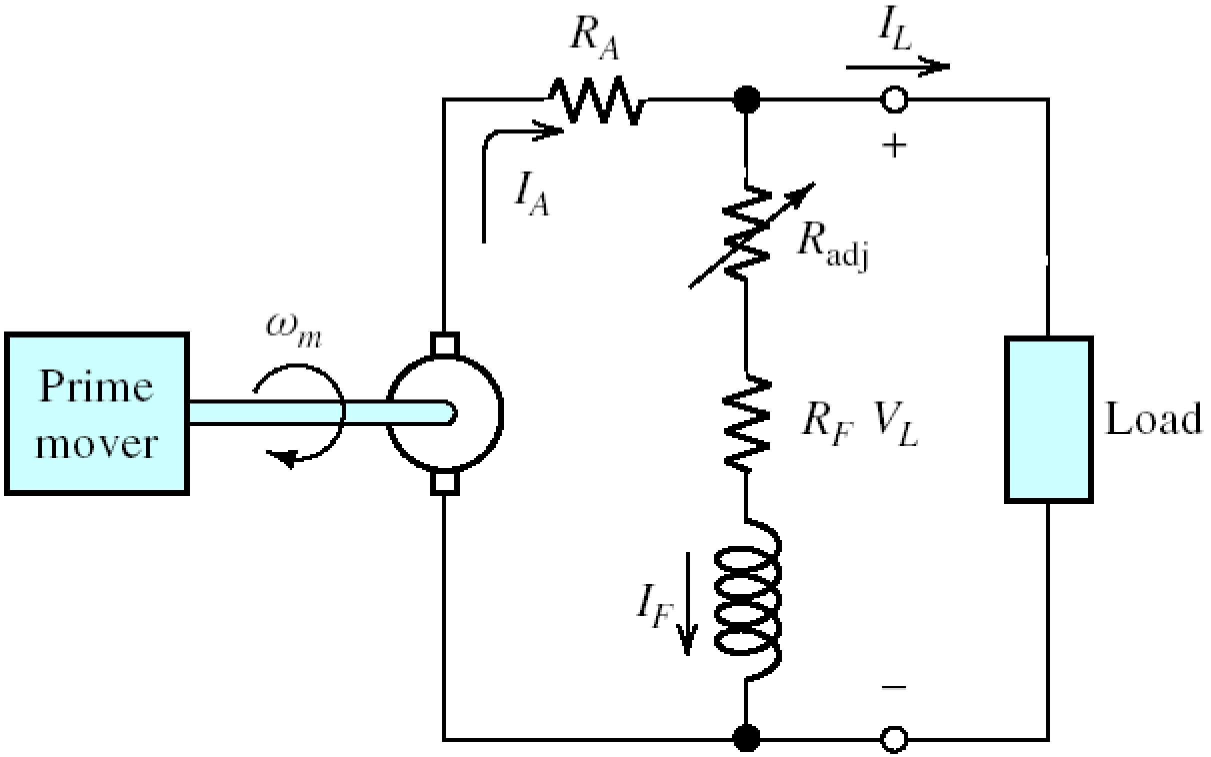
$$T_{\text{dev}} = K\phi\omega_m$$

$$E_A = R_A I_A + V_L$$

$$V_F = \left(R_F + R_{\text{adj}}\right) I_F$$

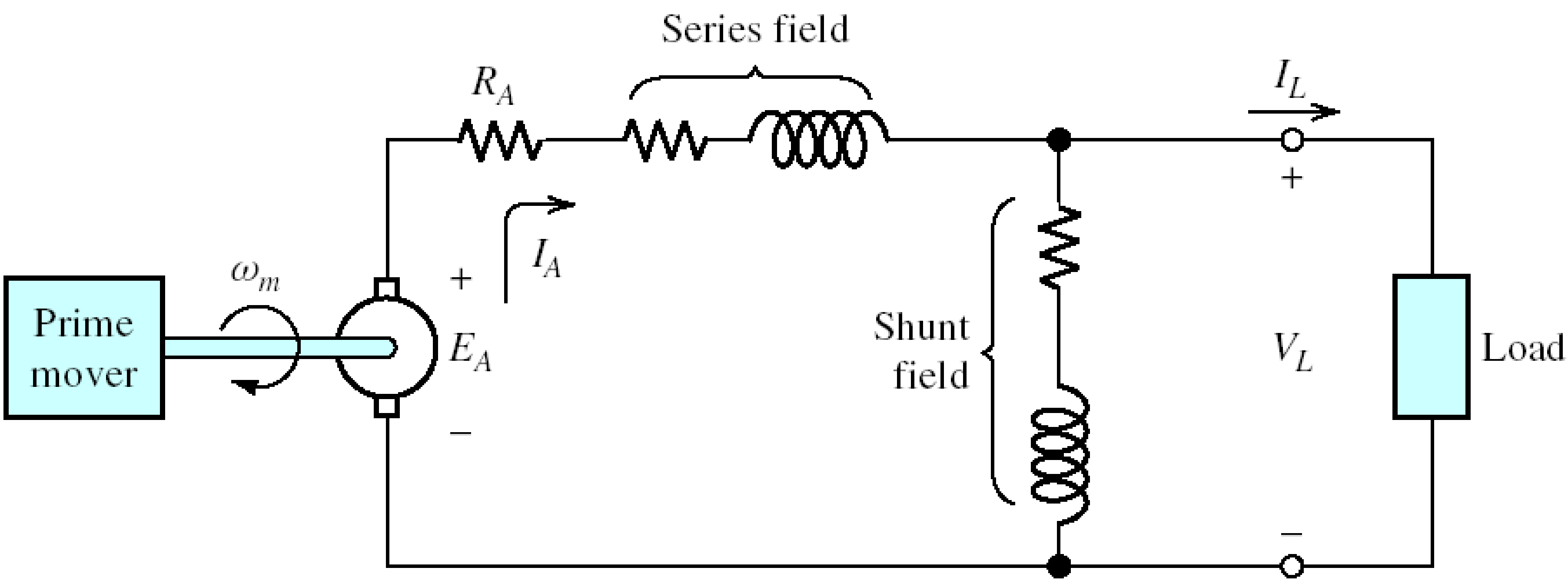
$$\text{efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

Shunt Connected DC Generator



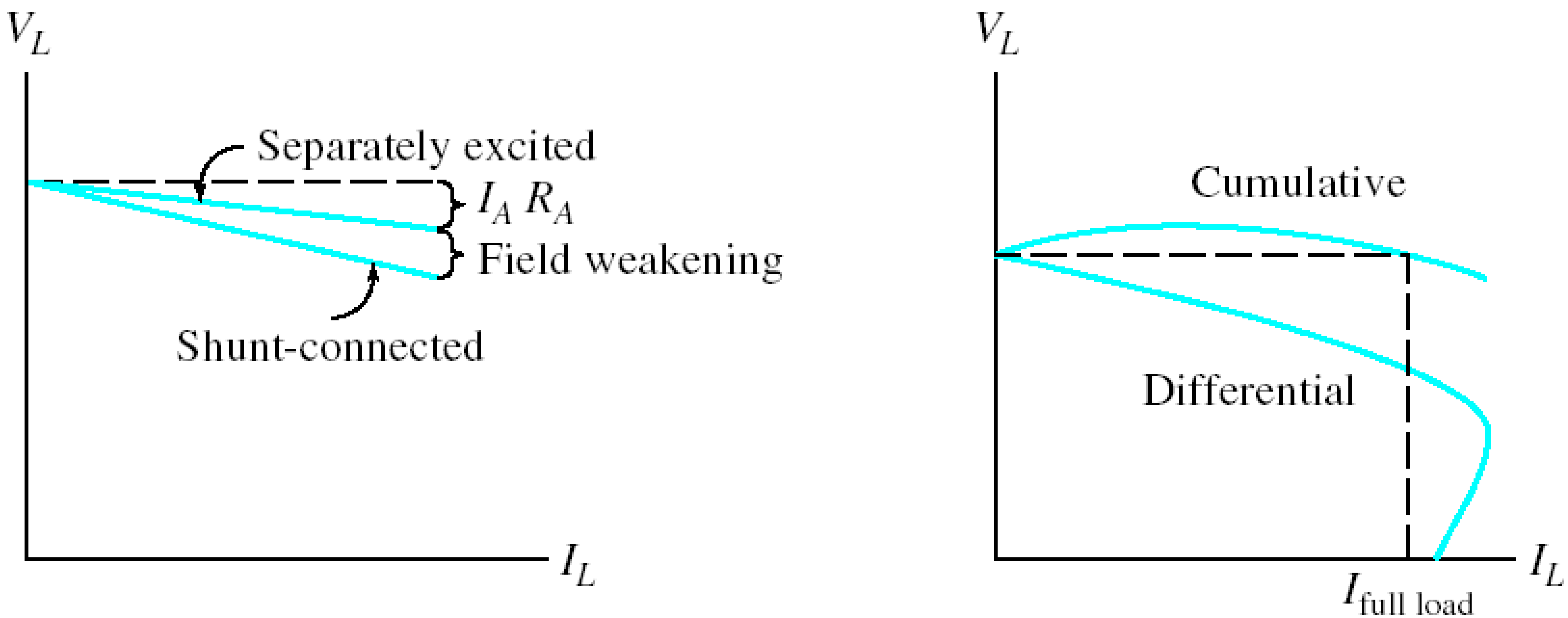
(b) Shunt connected

Compound Connected



(c) Compound connected

Long shunted vs. Short Shunted
Cumulative vs. Differential Shunted



(a) Separately excited and shunt-connected (b) Compound connected

Figure 16.30 Load voltage versus load current for various dc generators.

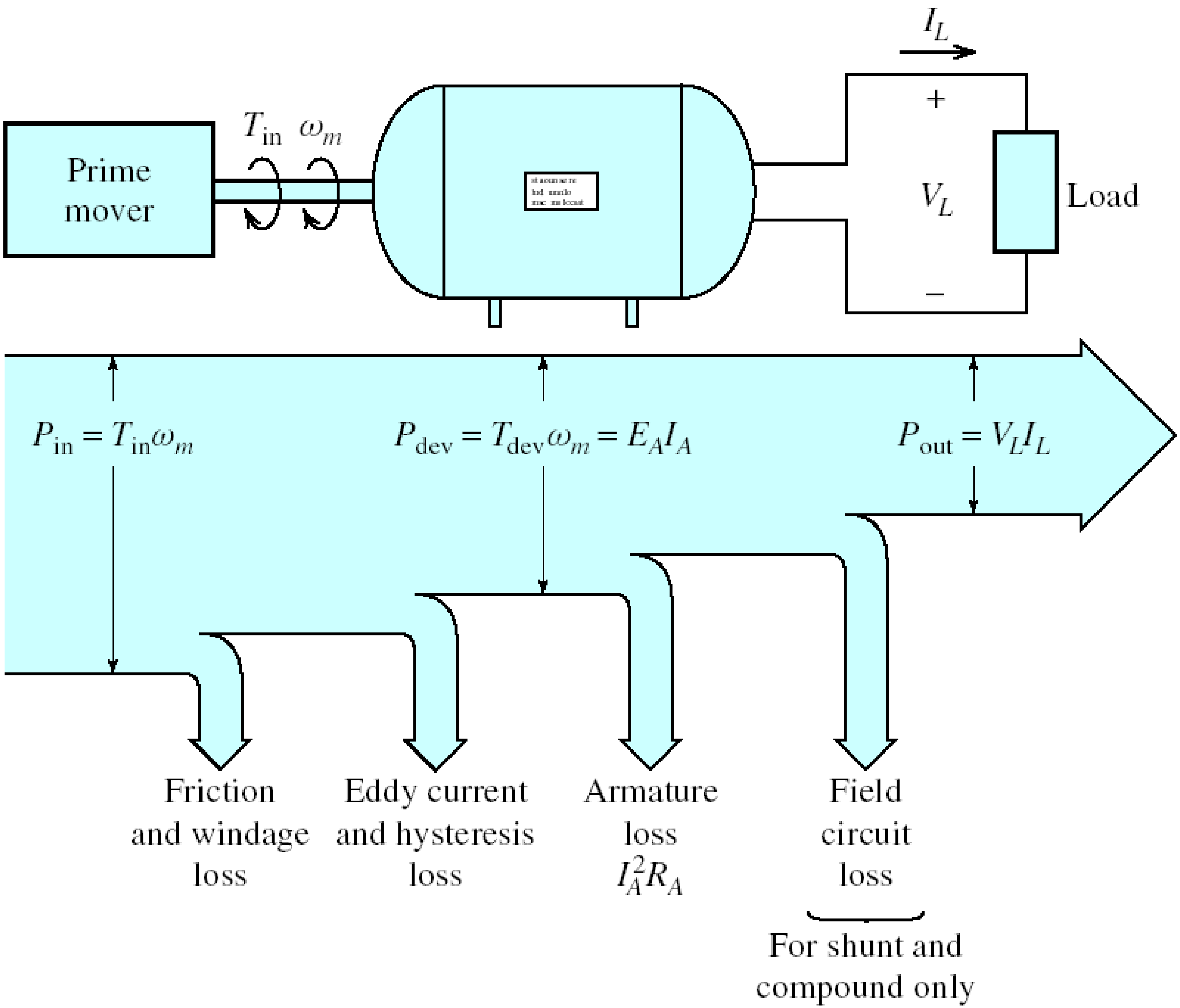


Figure 16.31 Power flow in dc generators.

Example

- A separately excited DC generator has VF=140 V, RF=10 ohms, Radj=4 ohms, RA=0.065 ohms. The prime mover rotates the armature at a speed of 1000 rpm. The magnetization curve is shown in the slides earlier. Determine the field current, no-load voltage, full-load voltage, voltage regulation for a full-load current of 200 A. Assuming overall efficiency is 85%, determine input torque, developed torque and losses.