KOM3560
INDUSTRIAL ELECTRONICS

Spring : 2023

Lecture 6

DC DRIVES

Direct current (dc) motors have variable characteristics and are used extensively in variable-speed drives.

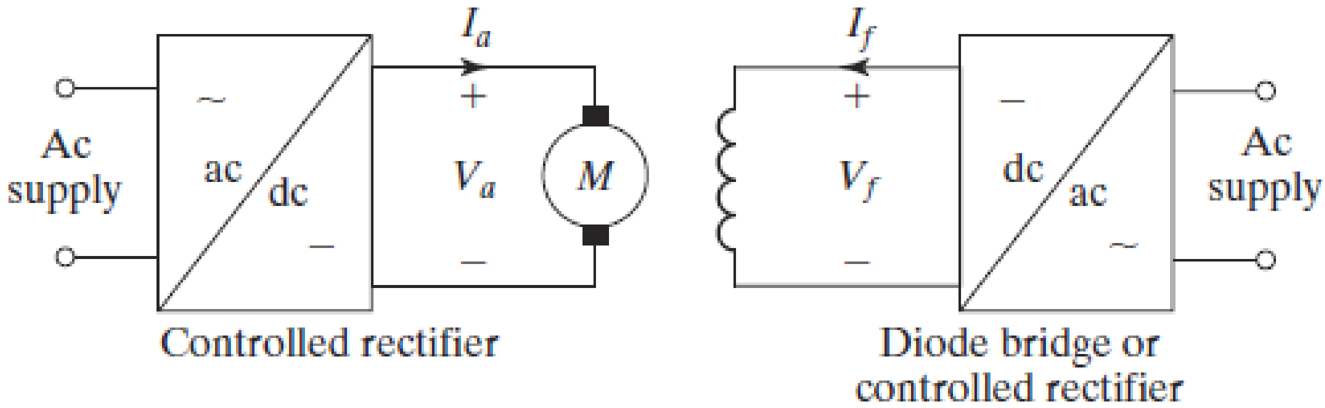
Dc motors can provide a high starting torque and it is also possible to obtain speed control over a wide range. The methods of speed control are normally simpler and less expensive than those of ac drives.

Dc motors play a significant role in modern industrial drives. Both series and separately excited dc motors are normally used in variable-speed drives, but series motors are traditionally employed for traction applications.

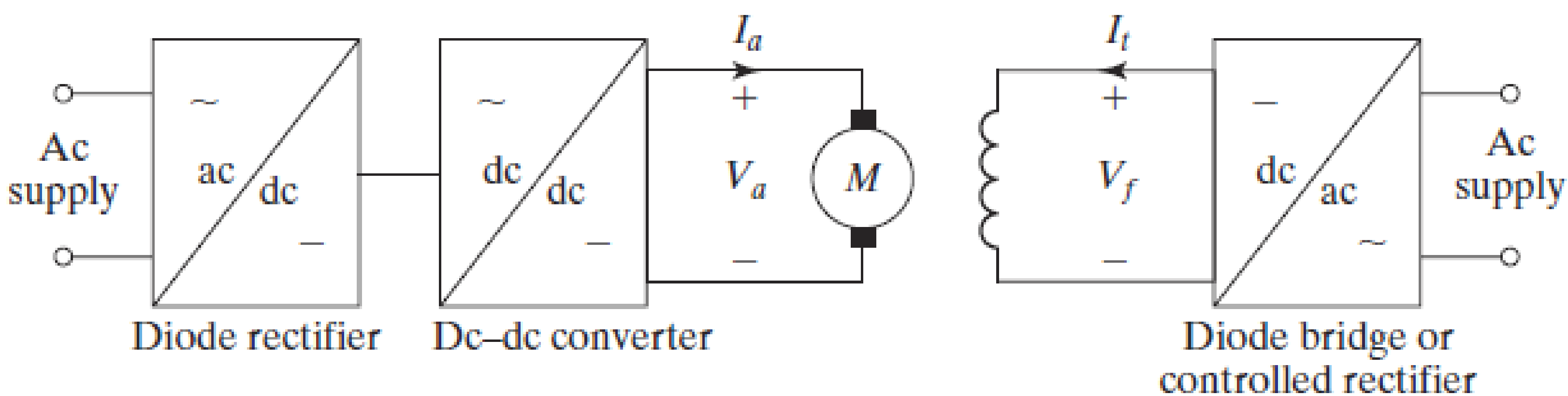
• Speed control over wide range both above and below the rated speed • High starting torque • Accurate steep less speed with constant torque • Quick starting stopping reversing and acceleration • Free from harmonics reactive power consumption…	• High initial cost • Increased operation and maintenance cost due to presence of commutator • Cannot be operated in explosive and hazardous conditions due to sparkings

DC DRIVES

Dc drives can be classified, in general, into two types:



(a) Controlled rectifier-fed drive



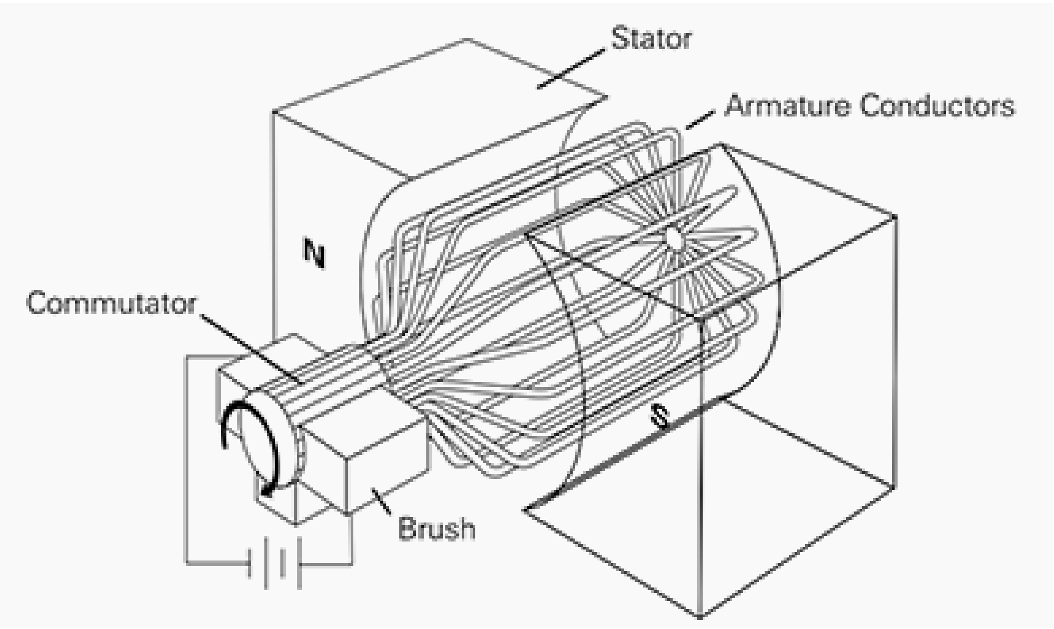
(b) Dc–dc converter-fed drives

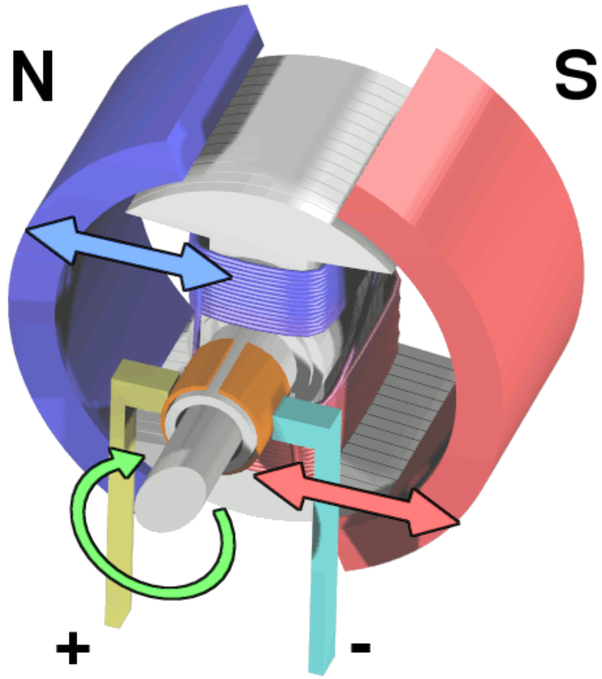
Basic Characteristics of Dc Motors

Dc motors can be classified into two types depending on the type of field winding connections: (i) shunt and (ii) series.

In a shunt-field motor, the field excitation is independent of the armature circuit. The field excitation can be controlled independently and this type of motor is often called the separately excited motor. That is, the armatüre and the field currents are different.

In a series-type motor, the field excitation circuit is connected in series with the armature circuit. That is, the armature and the field currents are the same.





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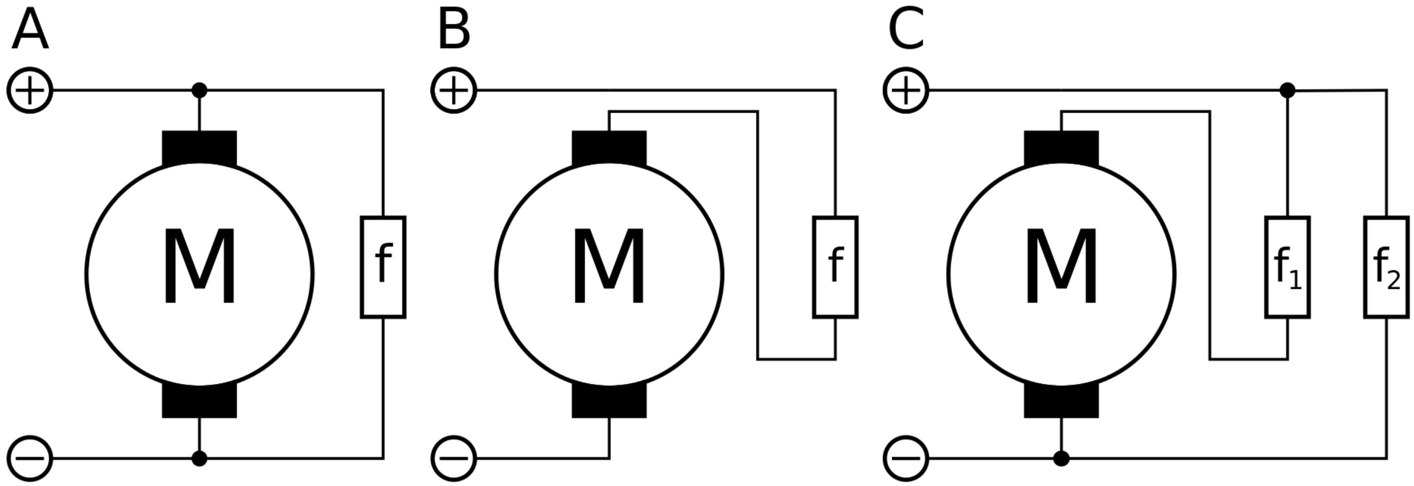
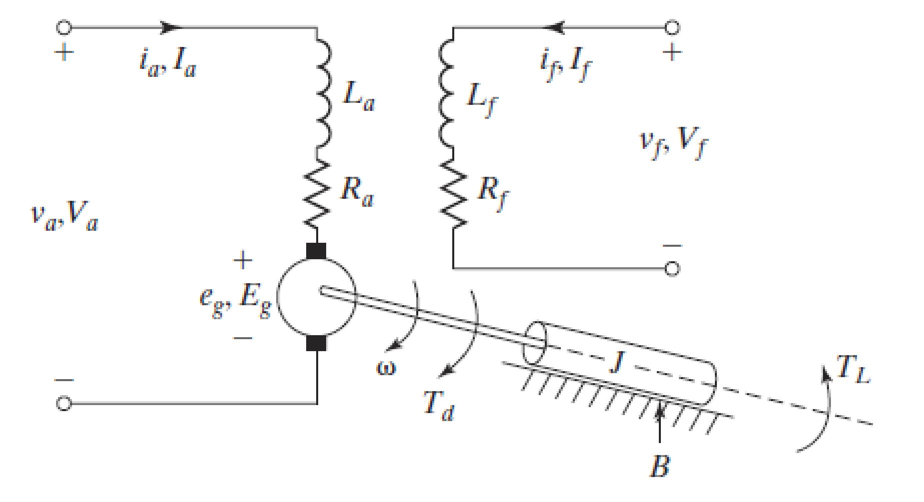


A field coil may be connected in shunt, in series, or in compound with the armature of a DC machine (motor or generator)

Separately Excited Dc Motor



When a separately excited motor is excited by a field current of i_f and an armature current of i_a flows in the armature circuit, the motor develops a back electromotive force (emf) and a torque to balance the load torque at a particular speed. The field current i_f of a separately excited motor is independent of the armature current i_a and any change in the armature current has no effect on the field current. The field current is normally much less than the armature current.

$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$

The motor back emf, which is also known as speed voltage

$$e_g = K_v \omega i_f$$

The torque developed by the motor

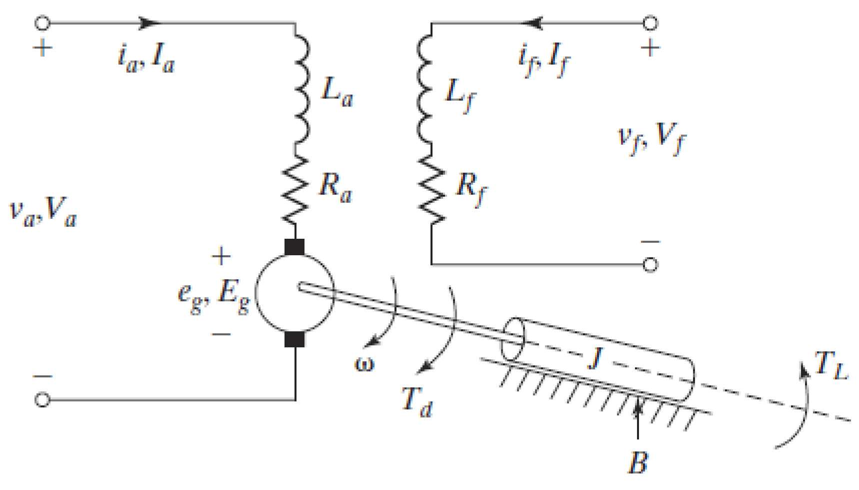
$$T_d = K_t i_f i_a$$

The developed torque must be equal to the load torque:

$$T_d = J\frac{d\omega}{dt} + B\omega + T_L$$

ω = motor angular speed, or rotor angular frequency, rad/s;
B = viscous friction constant, N · m/rad/s;
K_v = voltage constant, V/A-rad/s;
K_t = torque constant, which equals voltage constant, K_v;
L_a = armature circuit inductance, H;
L_f = field circuit inductance, H;
R_a = armature circuit resistance, Ω;
R_f = field circuit resistance, Ω;
T_L = load torque, N · m.

Separately Excited Dc Motor



$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$

$$e_g = K_v \omega i_f$$

$$T_d = K_t i_f i_a$$

Under steady-state conditions, the time derivatives in these equations are zero and the steady-state average quantities are

$$V_f = R_f I_f$$

$$E_g = K_v \omega I_f$$

$$V_a = R_a I_a + E_g = R_a I_a + K_v \omega I_f$$

$$T_d = K_t I_f I_a = B\omega + T_L$$

The developed power is

$$P_d = T_d \omega$$

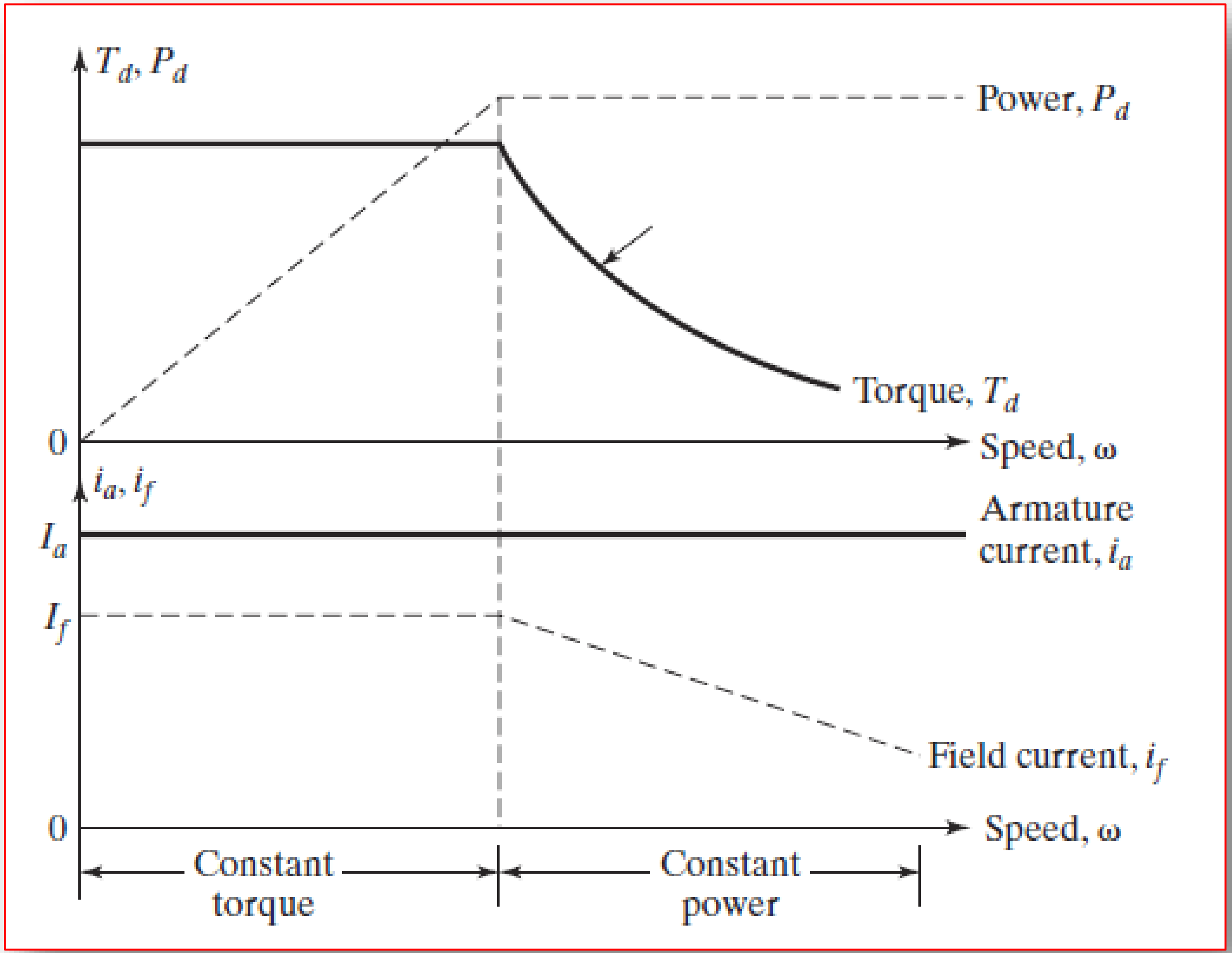
the speed of a separately excited motor can be found from

$$\omega = \frac{V_a - R_a I_a}{K_v I_f} = \frac{V_a - R_a I_a}{K_v V_f / R_f}$$

motor speed can be varied by
(1) Controlling the armature voltage Va, known as voltage control;
(2) controlling the field current If, known as field control; or
(3) torque demand, which corresponds to an armature current Ia, for a fixed field current If.

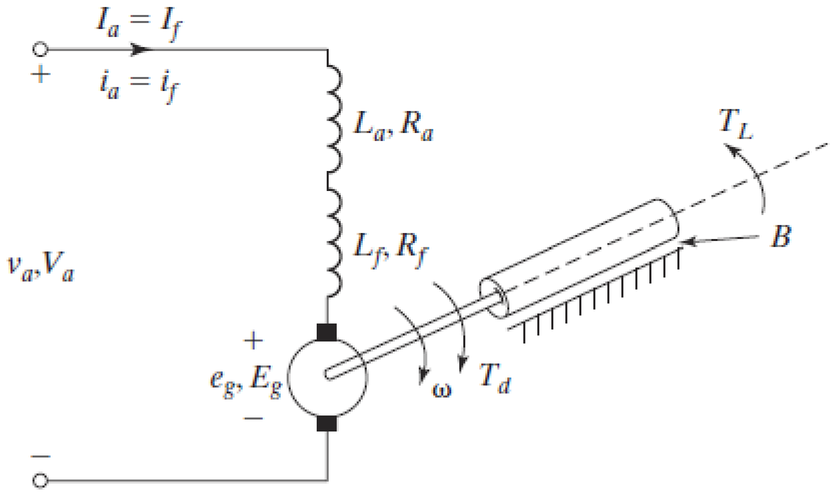
Separately Excited Dc Motor

In practice, for a speed less than the base speed, the armature current and field currents are maintained constant to meet the torque demand, and the armature voltage Va is varied to control the speed. For speed higher than the base speed, the armatüre voltage is maintained at the rated value and the field current is varied to control the speed. However, the power developed by the motor 1 = torque * speed2 remains constant.



Series-Excited Dc Motor

The field of a dc motor may be connected in series with the armature circuit, as shown in Figure, and this type of motor is called a *series motor*.



$$v_f = R_f i_f + L_f \frac{di_f}{dt}$$

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$

$$e_g = K_v \omega i_f$$

$$T_d = K_t i_f i_a$$

The field circuit is designed to carry the armature current. The steady-state average quantities are

$$\begin{aligned} E_g &= K_v \omega I_a \\ V_a &= (R_a + R_f) I_a + E_g \\ &= (R_a + R_f) I_a + K_v \omega I_f \\ T_d &= K_t I_a I_f \\ &= B\omega + T_L \end{aligned}$$

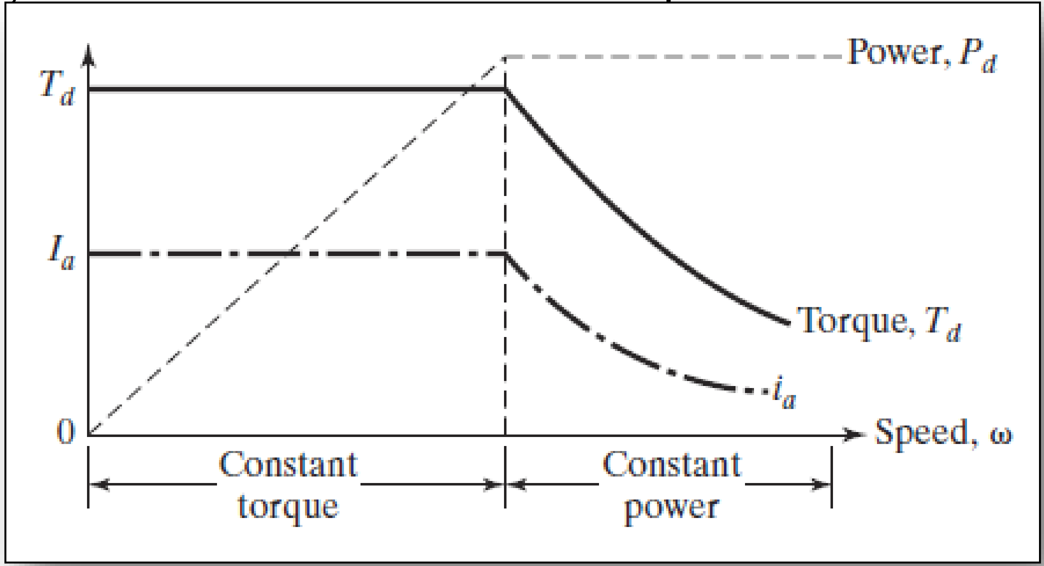
Series-Excited Dc Motor

The speed of a series motor can be determined

$$\omega = \frac{V_a - (R_a + R_f)I_a}{K_v I_f}$$

The speed can be varied by controlling the
(1) armature voltage V_a; or
(2) Armature current, which is a measure of the torque demand.

$$T_d = K_t I_a I_f$$
$$= B\omega + T_L$$

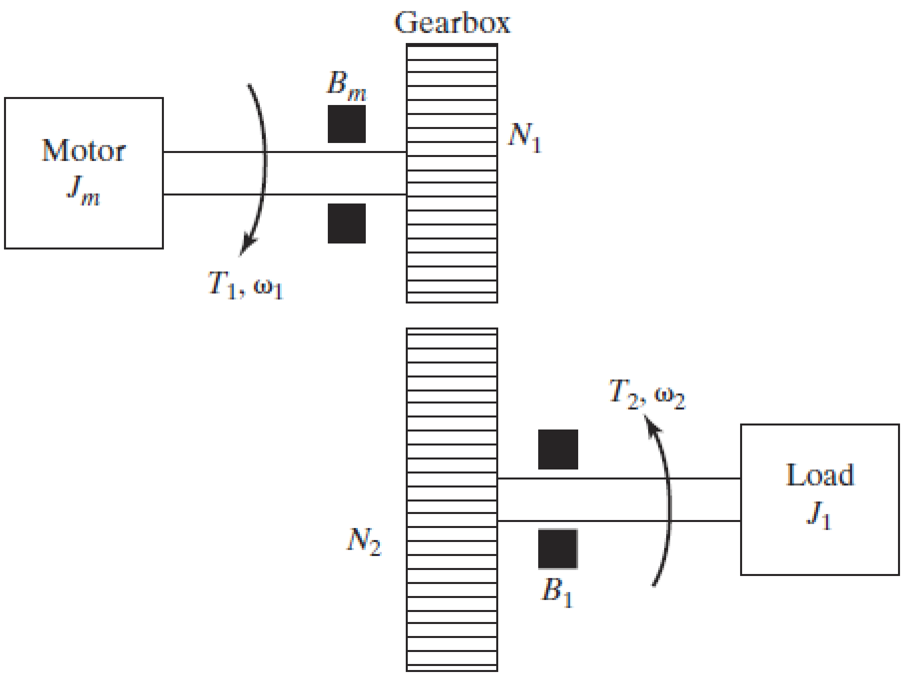


indicates that a series motor can provide a high torque, especially at starting; for this reason, series motors are commonly used in traction applications.
For a speed up to the base speed, the armature voltage is varied and the torque is maintained constant. Once the rated armature voltage is applied, the speed–torque relationship follows the natural characteristic of the motor and the power (= torque * speed) remains constant. As the torque demand is reduced, the speed increases. At a very light load, the speed could be very high and it is not advisable to run a dc series motor without a load.

Gear Ratio

In general, the load torque is a function of speed. For example, the load torque is proportional to speed in frictional systems such as a feed drive. In fans and pumps, the load torque is proportional to the square of the speed. The motor is often connected to the load through a set of gears. The gears have a teeth ratio and can be treated as torque transformers.

The gears are primarily used to amplify the torque on the load side that is at a lower speed compared to the motor speed. The motor is designed to run at high speeds because the higher the speed, the lower is the volume and size of the motor. But most of the applications require low speeds and there is a need for a gearbox in the motor–load connection.



Assuming zero losses in the gearbox, the power handled by the gear is the same on both sides. That is,

$$T_1\omega_1 = T_2\omega_2 \qquad \frac{\omega_1}{\omega_2} = \frac{N_2}{N_1} \qquad T_2 = \left(\frac{N_2}{N_1}\right)^2 T_1$$

Similar to a transformer, the load inertia J1 and the load bearing constant B1 can be reflected to the motor side by

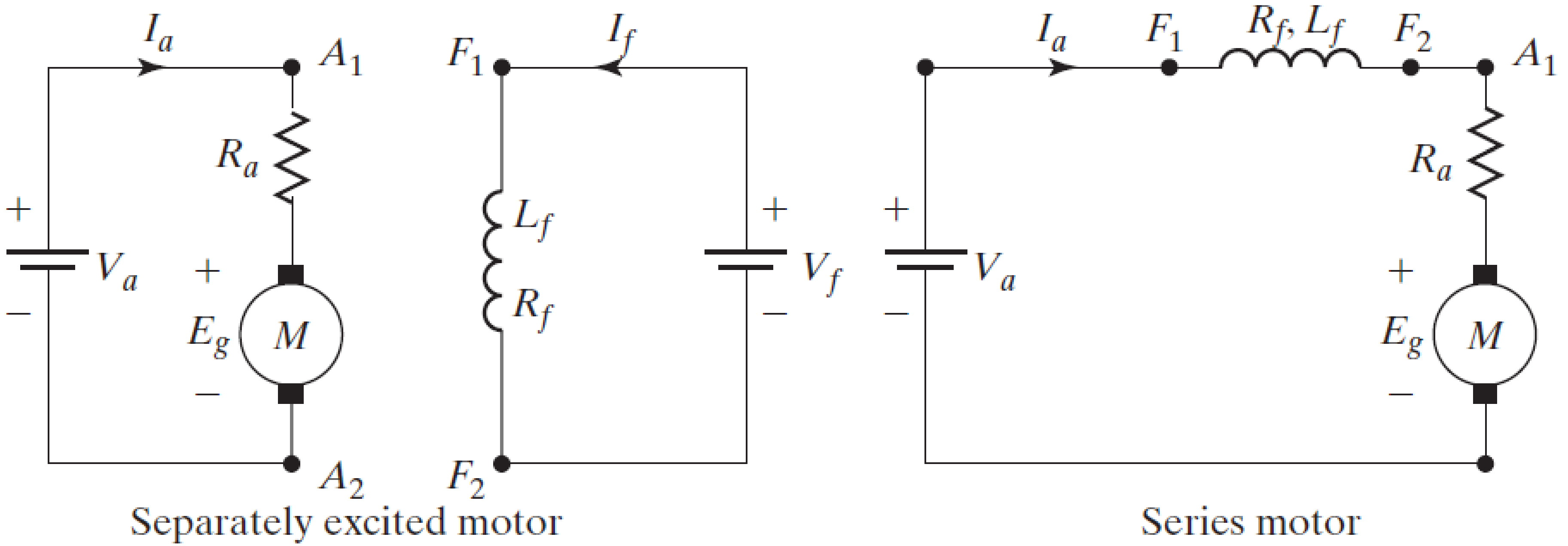
$$J = J_m + \left(\frac{N_1}{N_2}\right)^2 J_1$$

$$B = B_m + \left(\frac{N_1}{N_2}\right)^2 B_1$$

Operating Modes

In variable-speed applications, a dc motor may be operating in one or more modes: motoring, regenerative braking, dynamic braking, plugging, and four quadrants. The operation of the motor in any one of these modes requires connecting the field and armature circuits in different arrangements,

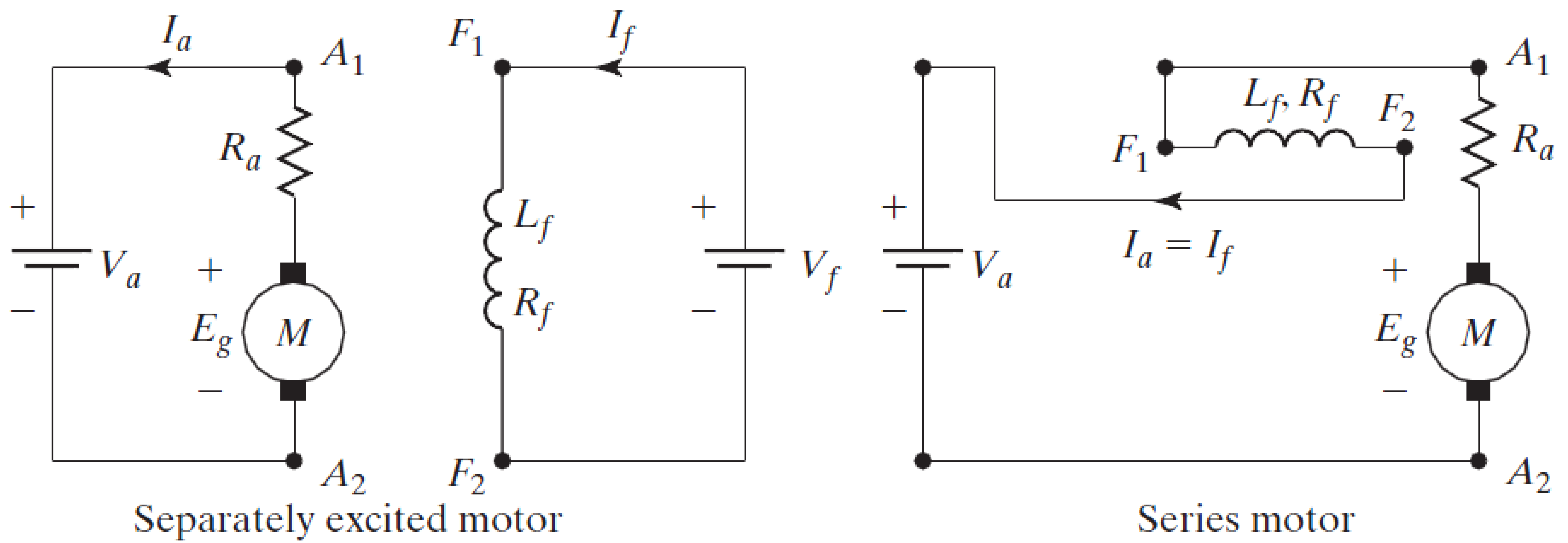
Motoring: Back emf Eg is less than supply voltage Va. Both armature and field currents are positive. The motor develops torque to meet the load demand



(a) Motoring

Operating Modes

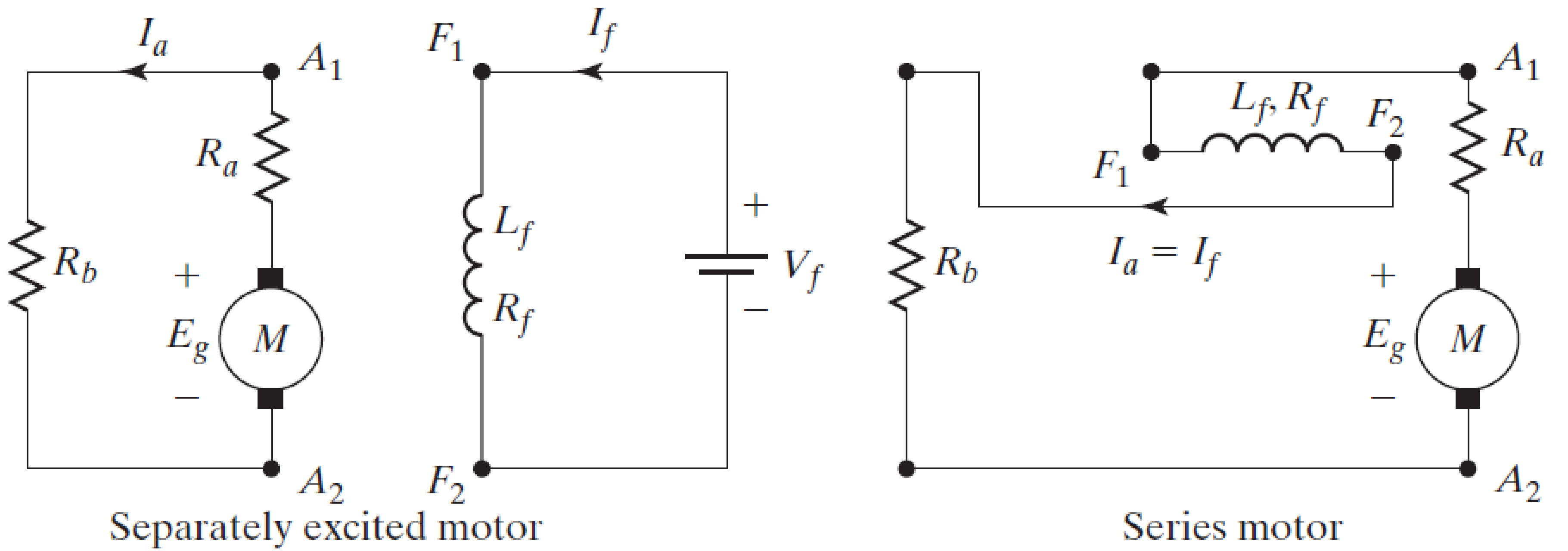
Regenerative braking: The motor acts as a generator and develops an induced voltage Eg. Eg must be greater than supply voltage Va. The armature current is negative, but the field current is positive. The kinetic energy of the motor is returned to the supply. A series motor is usually connected as a self-excited generator. For self-excitation, it is necessary that the field current aids the residual flux. This is normally accomplished by reversing the armature terminals or the field terminals.



(b) Regenerative braking

Operating Modes

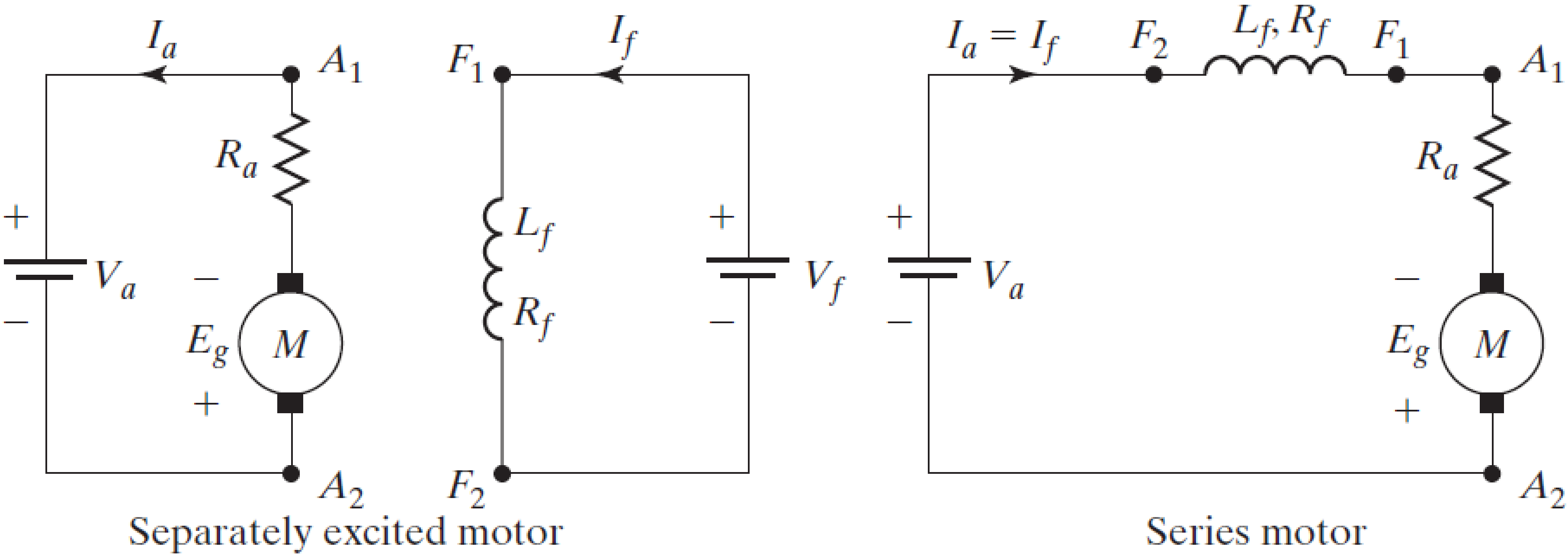
Dynamic braking: The arrangements are similar to those of regenerative braking, except the supply voltage Va is replaced by a braking resistance Rb. The kinetic energy of the motor is dissipated in Rb.



(c) Dynamic braking

Operating Modes

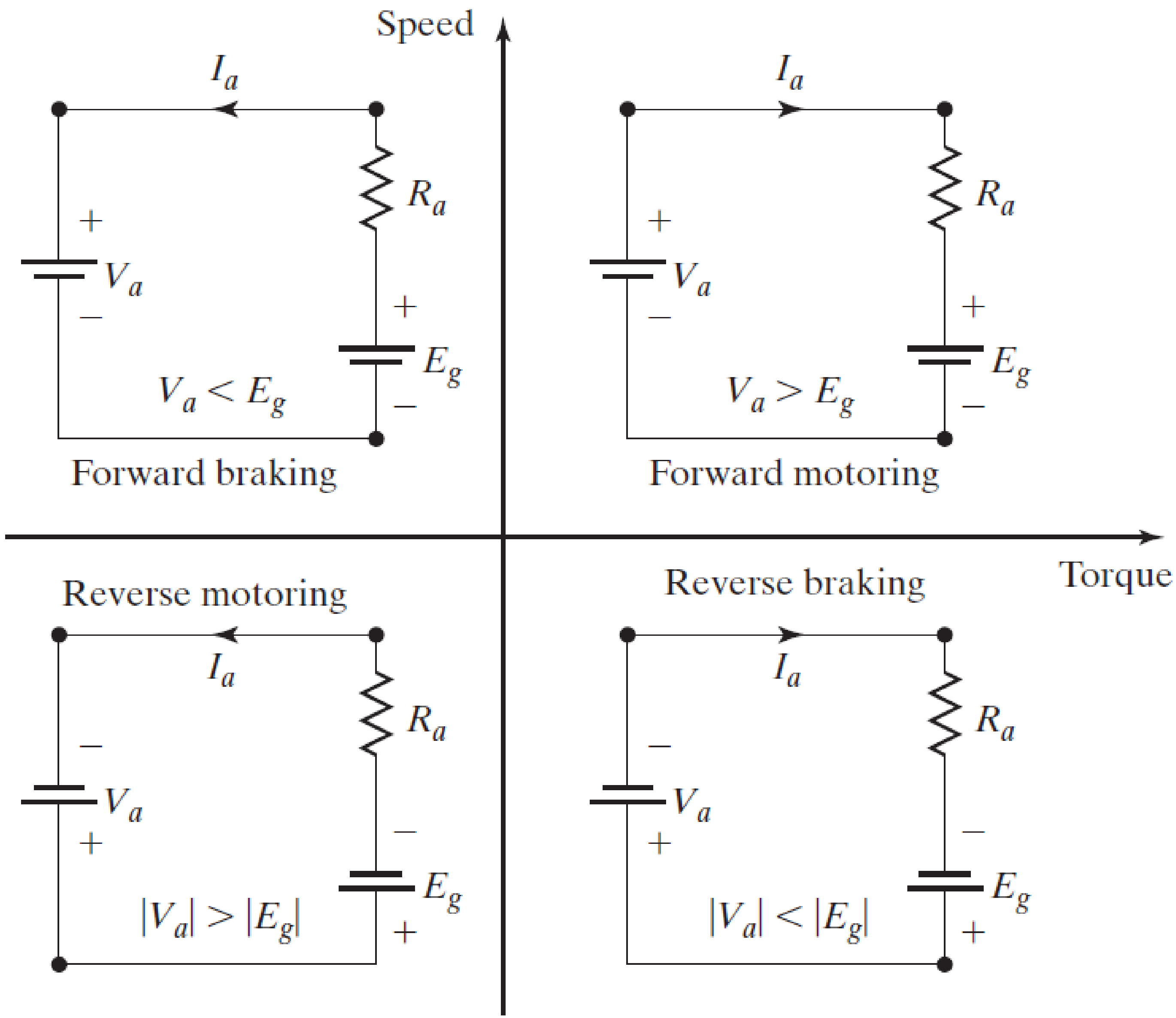
Plugging: Plugging is a type of braking. The connections for plugging are shown İn the Figure. The armature terminals are reversed while running. The supply voltage Va and the induced voltage Eg act in the same direction. The armature current is reversed, thereby producing a braking torque. The field current is positive. For a series motor, either the armature terminals or field terminals should be reversed, but not both.



(d) Plugging

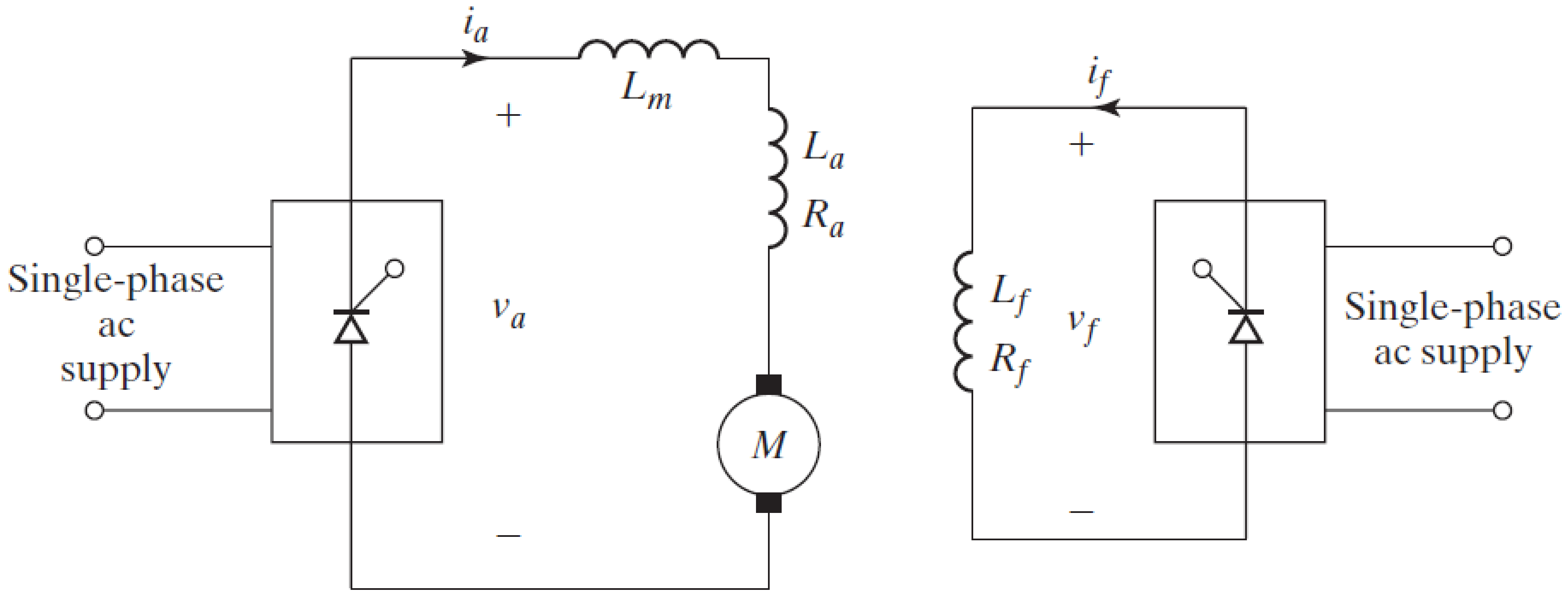
Operating Modes

Conditions for four quadrants.



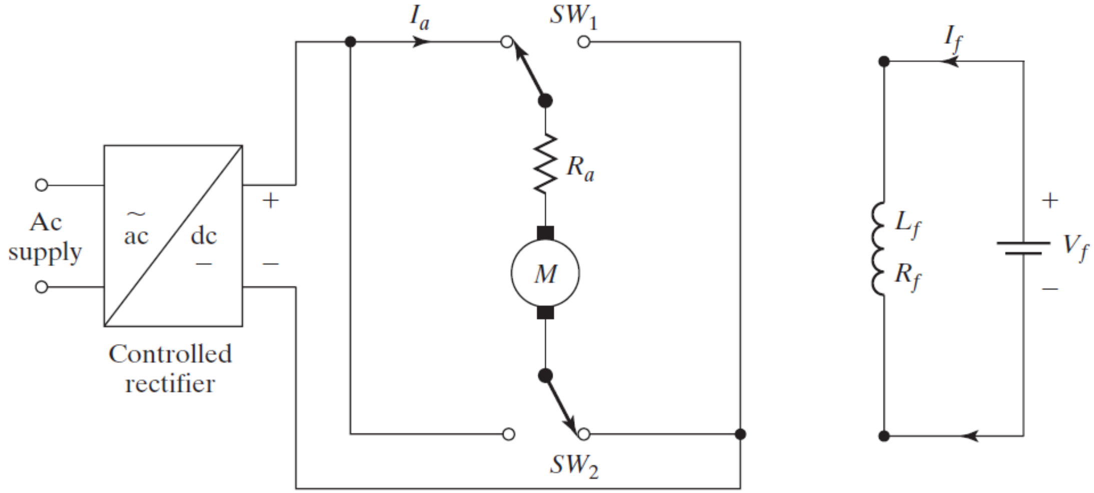
Single-Phase Drives

If the armature circuit of a dc motor is connected to the output of a single-phase Controlled rectifier, the armature voltage can be varied by varying the delay angle of the converter α_a. The forced-commutated ac–dc converters can also be used to improve the power factor (PF) and to reduce the harmonics. The basic circuit agreement for a single-phase converter-fed separately excited motor is shown in Figure

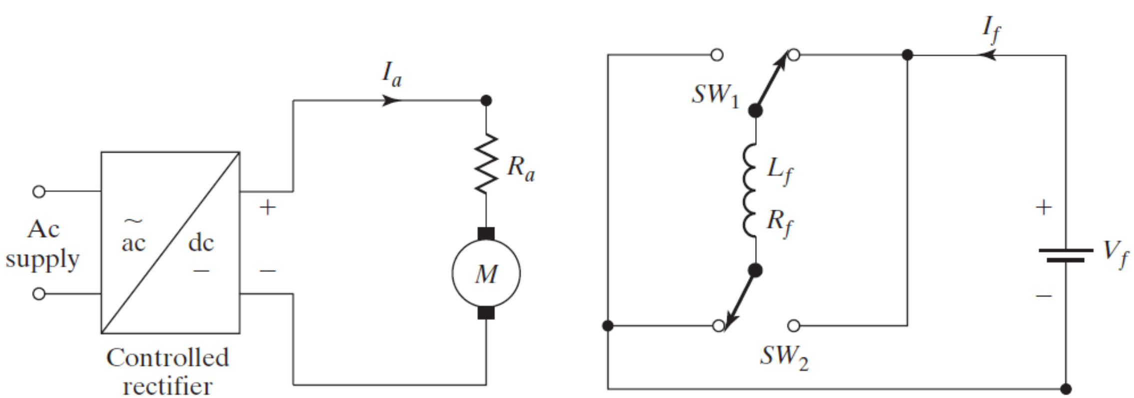


Single-Phase Drives

For operating the motor in a particular mode, it is often necessary to use contactors for reversing the armature circuit, as shown in Figure a, or the field circuit, as shown in Figure b. To avoid inductive voltage surges, the field or the armature reversing is performed at a zero armature current. The delay (or firing) angle is normally adjusted to give a zero current; additionally, a dead time of typically 2 to 10 ms is provided to ensure that the armature current becomes zero.



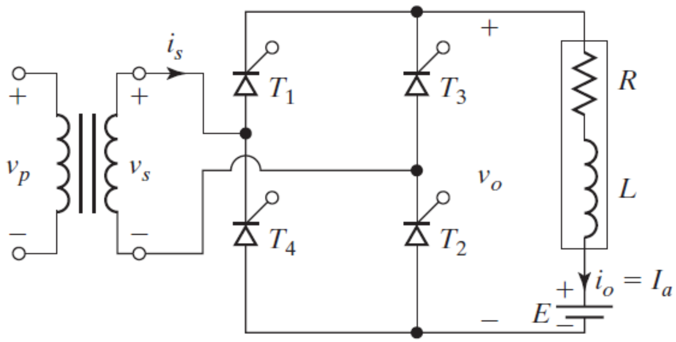
(a) Armature reversal



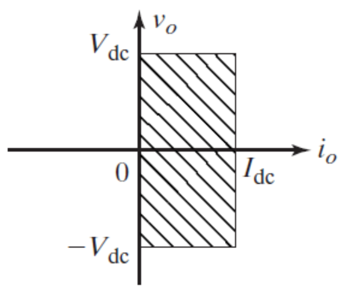
(b) Field reversal

Single-Phase Full Converters

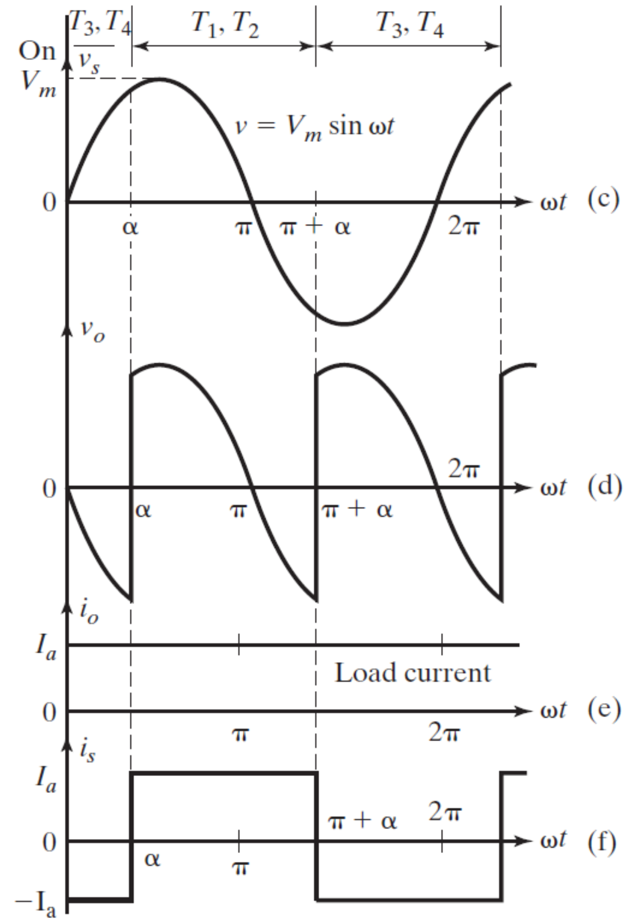
The circuit arrangement of a single-phase full converter is shown in the Figure with a highly inductive load so that the load current is continuous and ripple free. During the positive half-cycle, thyristors T1 and T2 are forward biased; when these two thyristors are turned on simultaneously at ωt = α, the load is connected to the input supply through T1 and T2. Due to the inductive load, thyristors T1 and T2 continue to conduct beyond ωt = π, even though the input voltage is already negative.



(a)

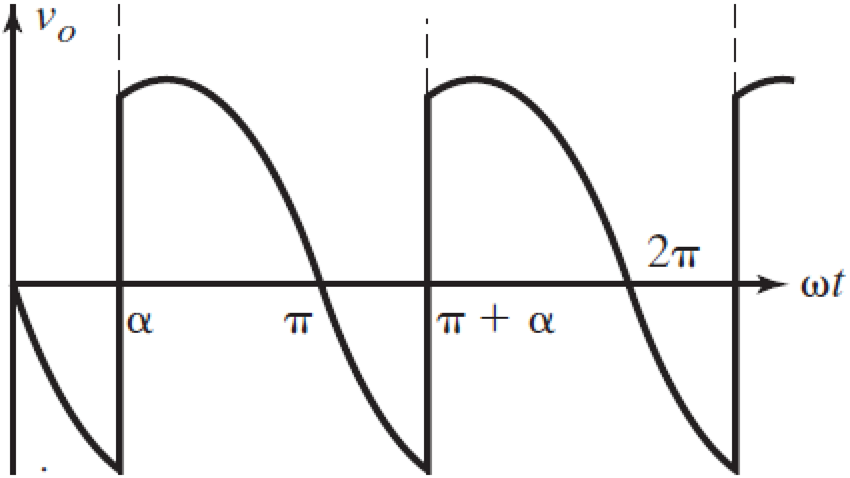


(b)



(a) Circuit,
(b) Quadrant,
(c) Input supply voltage,
(d) Output voltage,
(e) Constant load current,
(f) Input supply current.

Single-Phase Full Converters



The average output voltage can be found from

$$V_{dc} = \frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d(\omega t) = \frac{2V_m}{2\pi}[-\cos \omega t]_{\alpha}^{\pi+\alpha}$$

$$\boxed{= \frac{2V_m}{\pi}\cos \alpha}$$

The rms value of the output voltage is given by

$$V_{rms} = \left[\frac{2}{2\pi}\int_{\alpha}^{\pi+\alpha} V_m^2 \sin^2 \omega t \, d(\omega t)\right]^{1/2} = \left[\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi+\alpha} (1 - \cos 2\omega t) \, d(\omega t)\right]^{1/2}$$

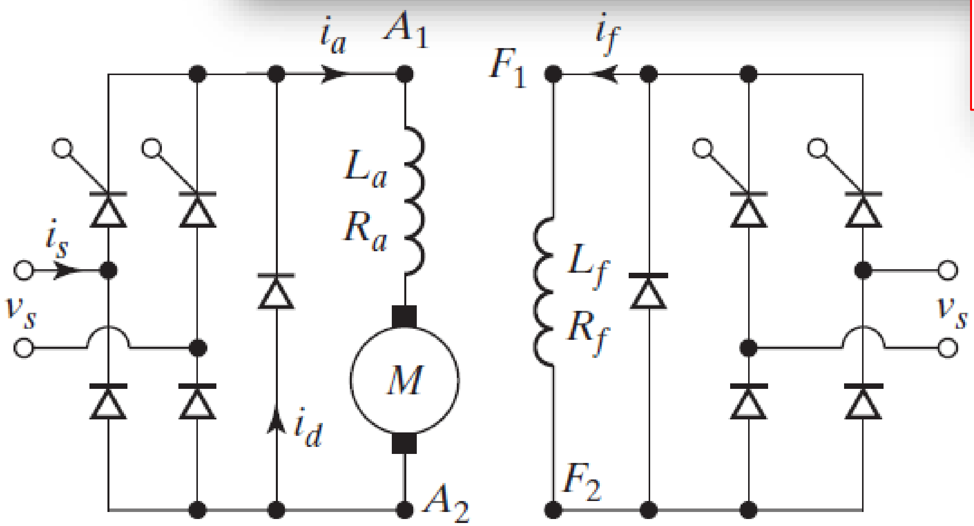
$$\boxed{= \frac{V_m}{\sqrt{2}} = V_s}$$

Single-Phase Semiconverter Drives

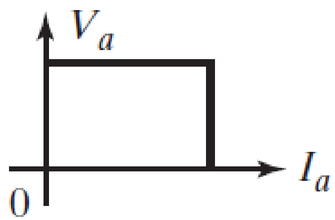
It is a one-quadrant drive, as shown in Figure, and is limited to applications up to 15 kW. The converter in the field circuit can be a semiconverter. With a single-phase semiconverter in the armature circuit, the average armature voltage is can given by

$$V_a = \frac{V_m}{\pi}(1 + \cos \alpha_a) \qquad \text{for } 0 \le \alpha_a \le \pi$$

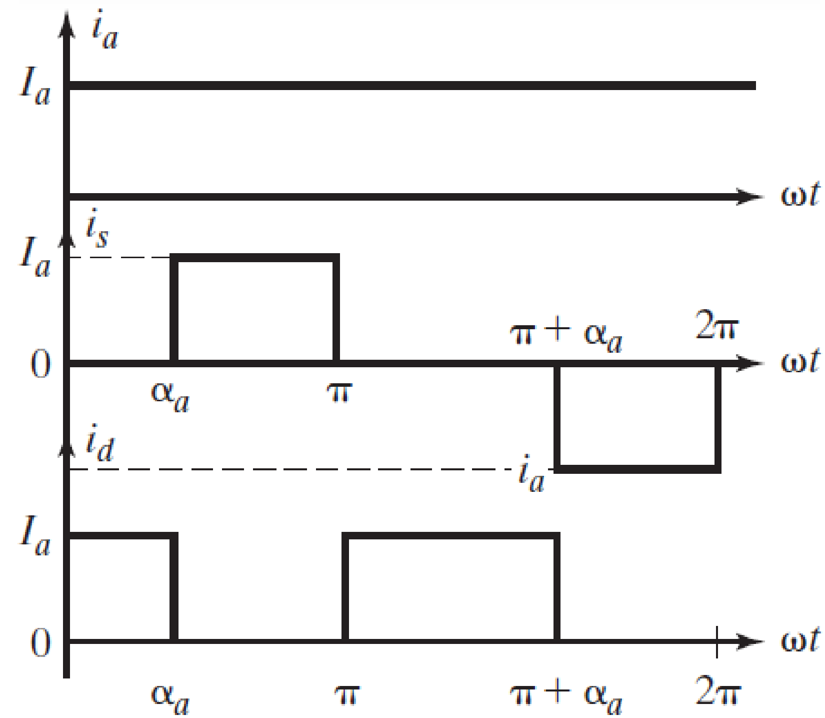
$$V_f = \frac{V_m}{\pi}(1 + \cos \alpha_f) \qquad \text{for } 0 \le \alpha_f \le \pi$$



(a) Circuit



(b) Quadrant



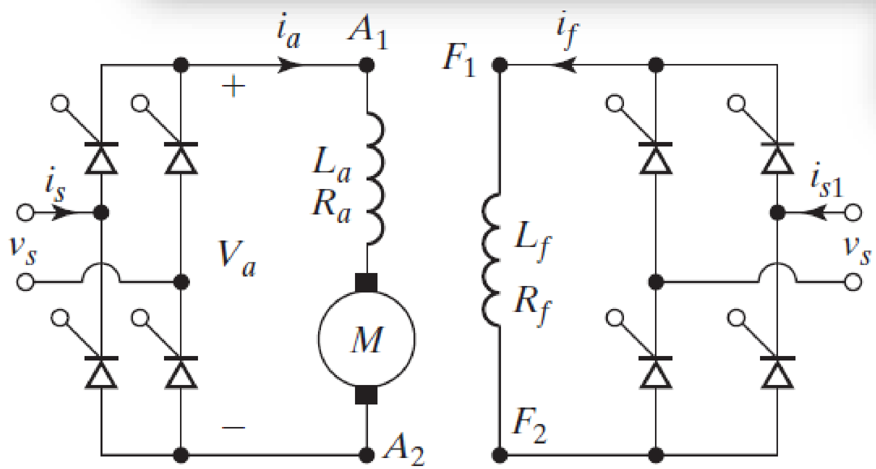
(c) Waveforms

Single-Phase Semiconverter Drives

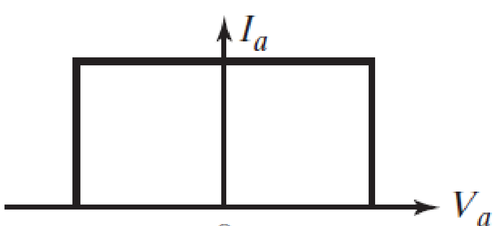
It is a two-quadrant drive, as shown in the Figure, and is limited to applications up to 15 kW. The armature converter gives +Va or -Va, and allows operation in the first and fourth quadrants. During regeneration for reversing the direction of power flow, the back emf of the motor can be reversed by reversing the field excitation. With a single-phase full-wave converter in the armature circuit, equation gives the average armature voltage as

$$\boxed{V_a = \frac{2V_m}{\pi}\cos\alpha_a \qquad \text{for } 0 \le \alpha_a \le \pi}$$

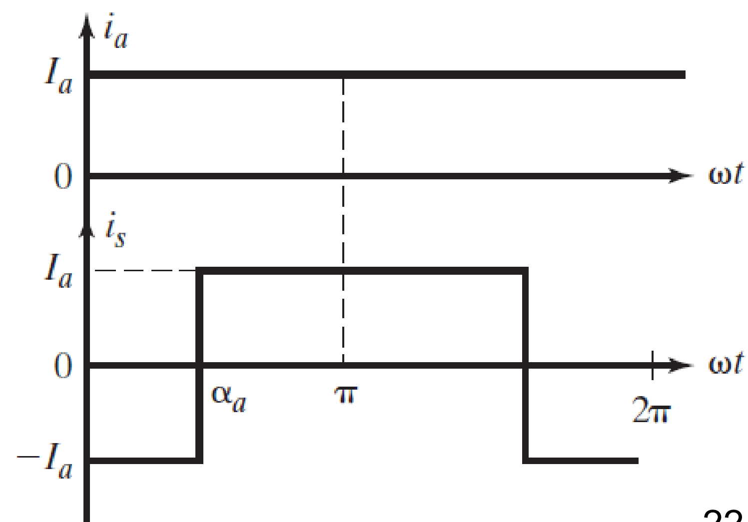
$$\boxed{V_f = \frac{2V_m}{\pi}\cos\alpha_f \qquad \text{for } 0 \le \alpha_f \le \pi}$$



(a) Circuit



(b) Quadrant



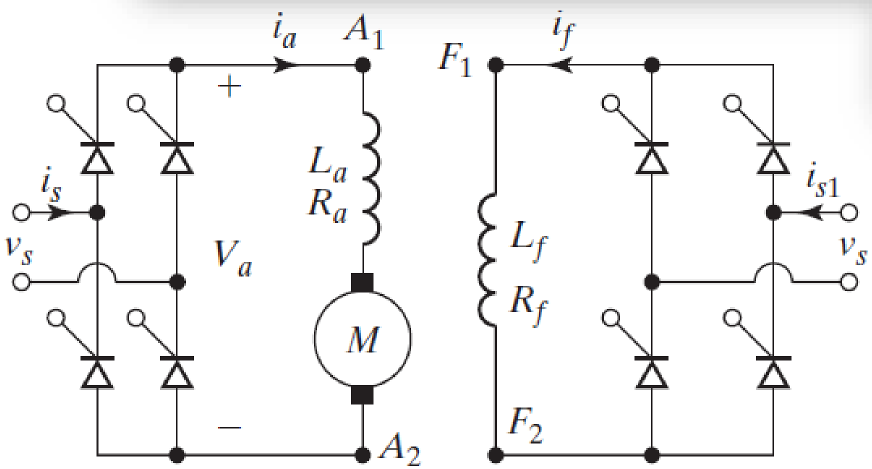
(c) Waveforms

Single-Phase Full-Converter Drives

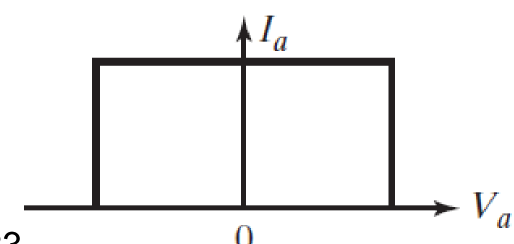
It is a two-quadrant drive, as shown in the Figure, and is limited to applications up to 15 kW. The armature converter gives +Va or -Va, and allows operation in the first and fourth quadrants. During regeneration for reversing the direction of power flow, the back emf of the motor can be reversed by reversing the field excitation. With a single-phase full-wave converter in the armature circuit, equation gives the average armature voltage as

$$\boxed{V_a = \frac{2V_m}{\pi}\cos\alpha_a \qquad \text{for } 0 \le \alpha_a \le \pi}$$

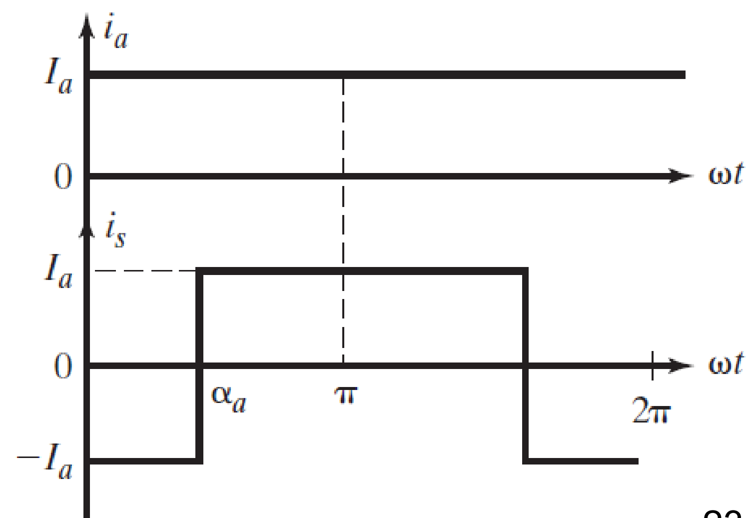
$$\boxed{V_f = \frac{2V_m}{\pi}\cos\alpha_f \qquad \text{for } 0 \le \alpha_f \le \pi}$$



(a) Circuit



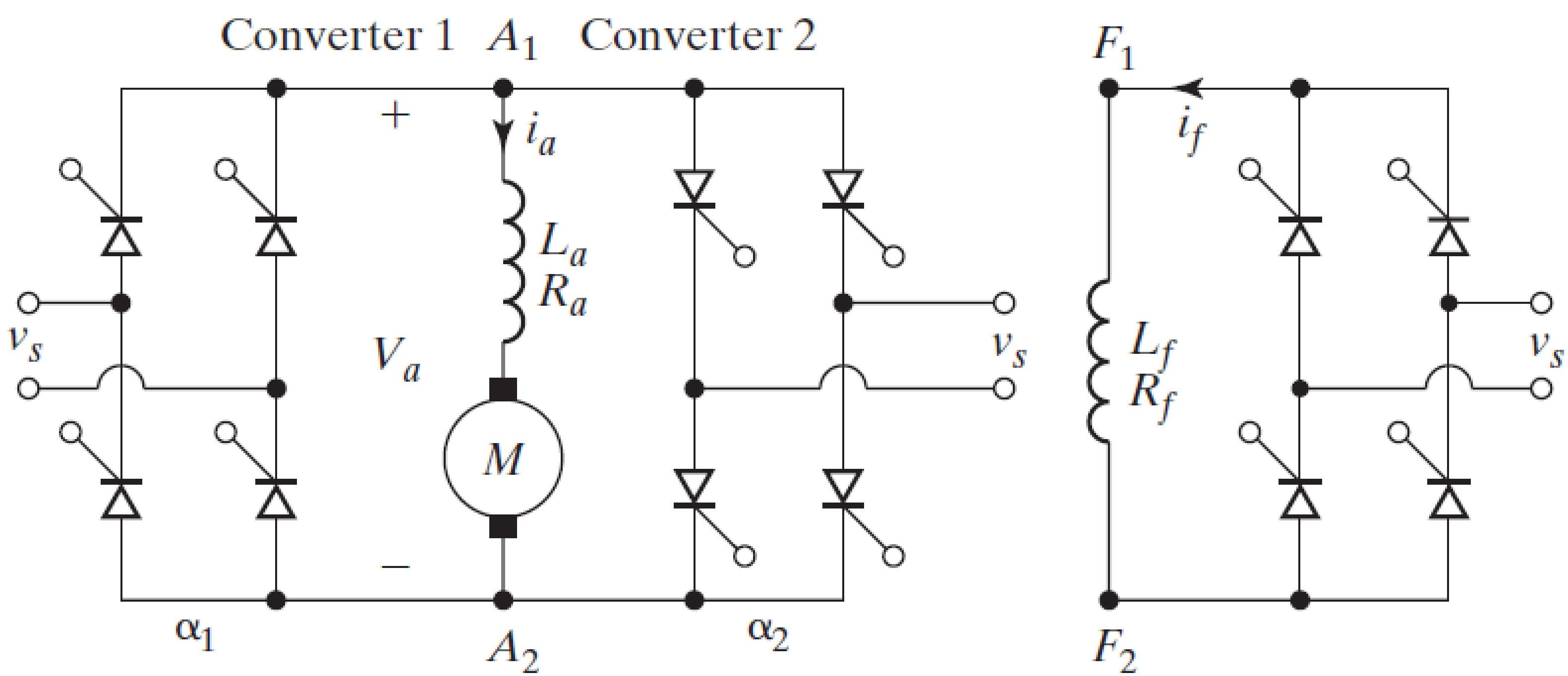
(b) Quadrant



(c) Waveforms

Single-Phase Duall-Converter Drives

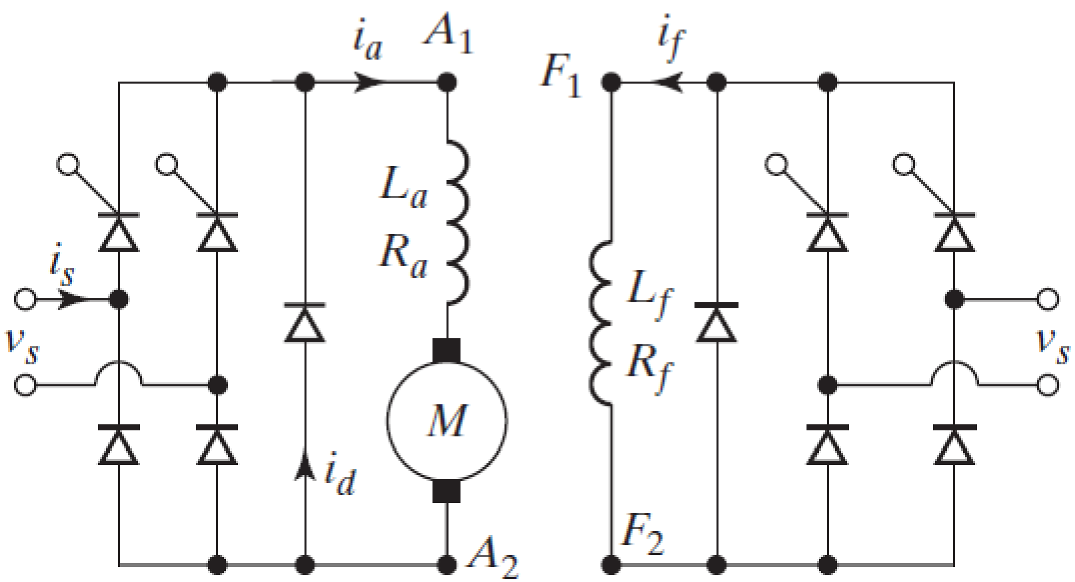
Two single-phase full-wave converters are connected, as shown in the Figure. Either converter 1 operates to supply a positive armature voltage, Va, or converter 2 operates to supply a negative armature voltage, -Va. Converter 1 provides operation in the first and fourth quadrants, and converter 2, in the second and third quadrants. It is a four-quadrant drive and permits four modes of operation: forward powering, forward braking (regeneration), reverse powering, and reverse braking (regeneration). It is limited to applications up to 15 kW. The field converter could be a full-wave, a semi-, or a dual converter.



Single-Phase Converter Drives

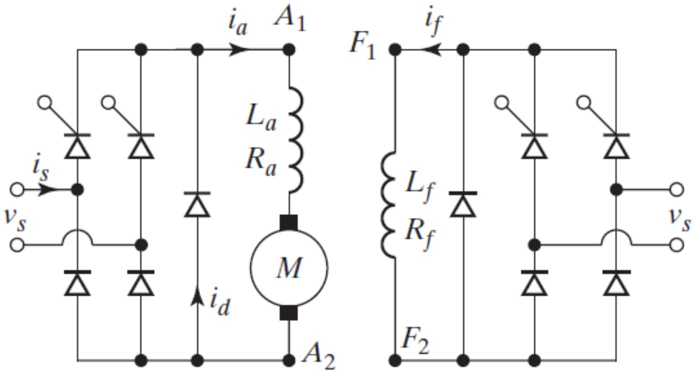
Example

The speed of a separately excited motor is controlled by a single-phase semiconverter in the Figure. The field current, which is also controlled by a semiconverter, is set to the maximum possible value. The ac supply voltage to the armature and field converters is one phase, 208 V, 60 Hz. The armature resistance is Ra = 0.25Ω, the field resistance is Rf = 147Ω, and the motor voltage constant is Kv = 0.7032 V/A rad/s. The load torque is TL = 45 Nm at 1000 rpm. The viscous friction and no-load losses are negligible. The inductances of the armature and field circuits are sufficient enough to make the armature and field currents continuous and ripple free.
Determine (a) the field current If; (b) the delay angle of the converter in the armature circuit, and (c) the input power factor of the armature circuit converter.



Single-Phase Converter Drives

Example



$$V_s = 208\text{ V},\qquad V_m = \sqrt{2}\times 208 = 294.16\text{ V},$$

$$R_a = 0.25\ \Omega,\ R_f = 147\ \Omega,$$

$$T_d = T_L = 45\text{ N}\cdot\text{m},$$

$$K_v = 0.7032\text{ V/A rad/s},$$

$$\omega = 1000\,\pi/30 = 104.72\text{ rad/s}.$$

(a) the maximum field voltage (and current) is obtained for a delay angle of $\alpha_f = 0$

$$\boxed{V_f = \frac{V_m}{\pi}(1 + \cos\alpha_f)\qquad \text{for } 0 \le \alpha_f \le \pi}$$

$$V_f = \frac{2V_m}{\pi} = \frac{2\times 294.16}{\pi} = 187.27\text{ V}\qquad I_f = \frac{V_f}{R_f} = \frac{187.27}{147} = 1.274\text{ A}$$

(b) the delay angle of the converter in the armature circuit

$$\boxed{T_d = K_t I_f I_a}\qquad I_a = \frac{T_d}{K_v I_f} = \frac{45}{0.7032\times 1.274} = 50.23\text{ A}$$

$$\boxed{E_g = K_v\omega I_f} = 0.7032\times 104.72\times 1.274 = 93.82\text{ V}$$

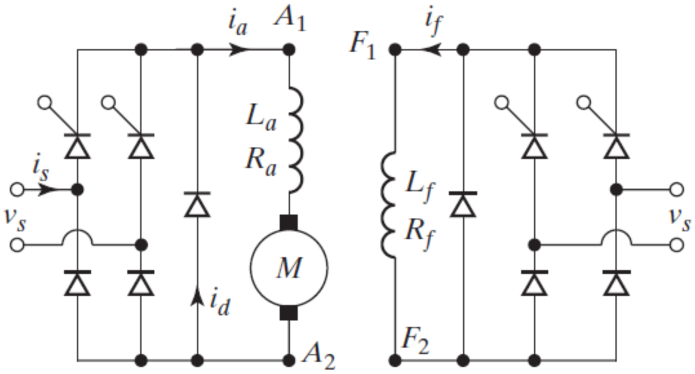
$$V_a = 93.82 + I_a R_a = 93.82 + 50.23\times 0.25 = 93.82 + 12.56 = 106.38\text{ V}$$

$$V_a = 106.38 = (294.16/\pi)\times(1 + \cos\alpha_a)$$

$$\alpha_a = 82.2^\circ.$$

Example

Single-Phase Converter Drives



$V_s = 208$ V, $\quad V_m = \sqrt{2} \times 208 = 294.16$ V,

$R_a = 0.25\ \Omega$, $R_f = 147\ \Omega$,

$T_d = T_L = 45$ N·m,

$K_v = 0.7032$ V/A rad/s,

$\omega = 1000\ \pi/30 = 104.72$ rad/s.

(c) If the armature current is constant and ripple free, the output power is

$$P_o = V_a I_a = 106.38 \times 50.23 = 5343.5 \text{ W}$$

If the losses in the armature converter are neglected, the power from the supply is

$$P_a = P_o = 5343.5 \text{ W}.$$

The rms input current

$$I_{sa} = \left(\frac{2}{2\pi}\int_{\alpha_a}^{\pi} I_a^2\, d\theta\right)^{1/2} = I_a\left(\frac{\pi - \alpha_a}{\pi}\right)^{1/2}$$

$$= 50.23\left(\frac{180 - 82.2}{180}\right)^{1/2} = 37.03 \text{ A}$$

the input volt–ampere (VA) rating is

$$VI = V_s I_{sa} = 208 \times 37.03 = 7702.24.$$

the input PF is approximately

$$PF = \frac{P_o}{VI} = \frac{5343.5}{7702.24} = 0.694 \text{ (lagging)}$$

$$PF = \frac{\sqrt{2}(1 + \cos\alpha)}{\sqrt{\pi(\pi + \cos\alpha)}}$$

$$PF = \frac{\sqrt{2}(1 + \cos 82.2^\circ)}{[\pi(\pi - 82.2^\circ)]^{1/2}} = 0.694 \text{ (lagging)}$$

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