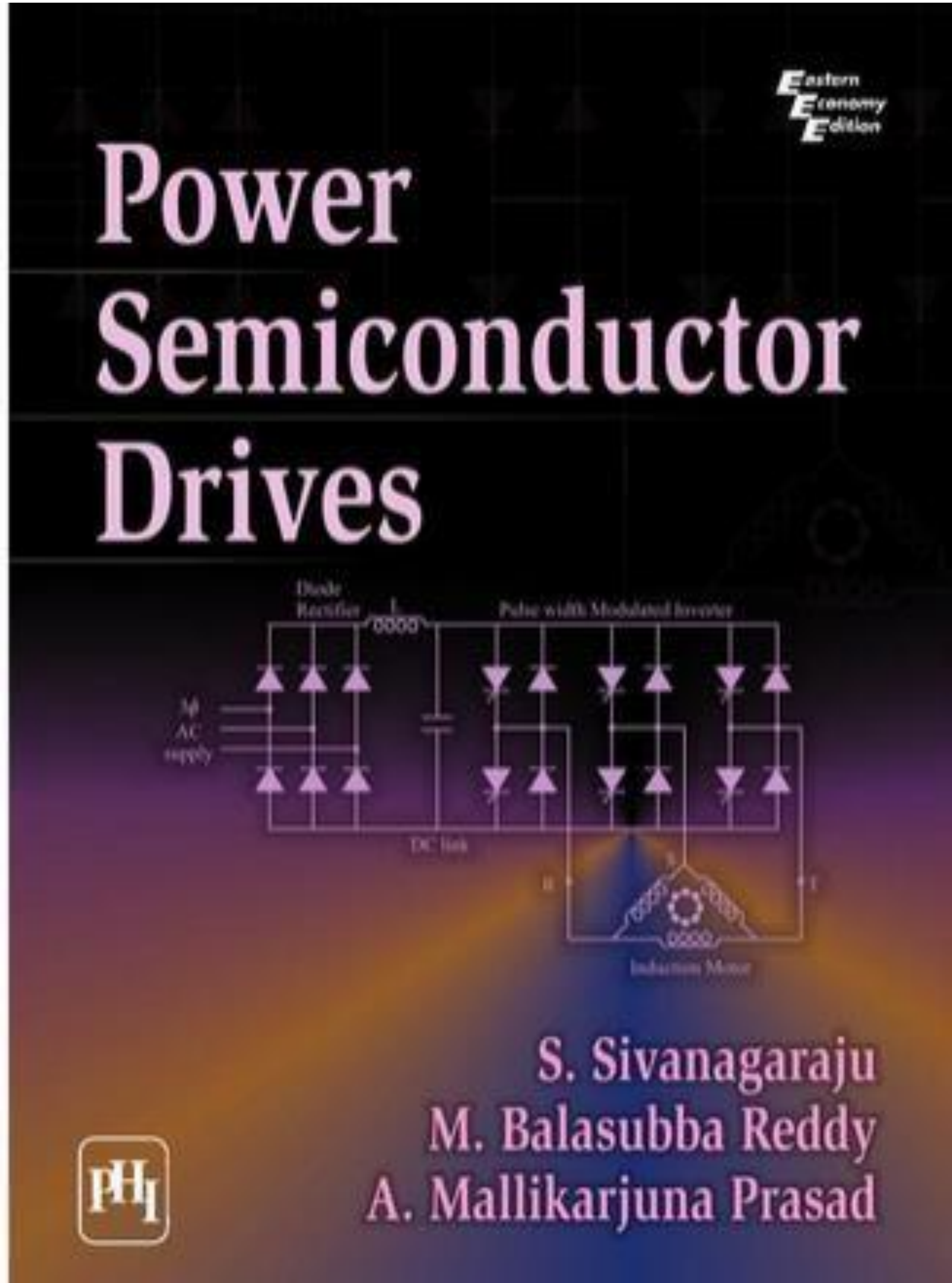
Book Exactly Matching to Syllabus



Electrical Drives

Drives are systems employed for **motion control**

↓

Require **prime movers**

↓

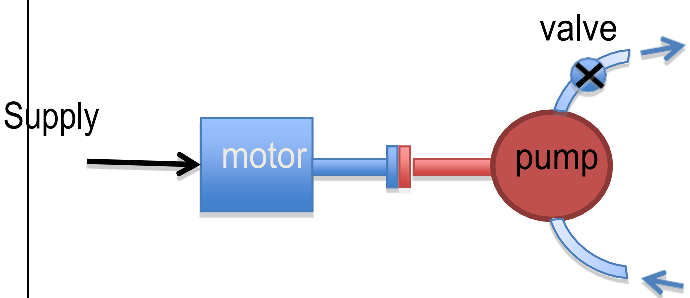
Drives that employ **electric motors** as
prime movers are known as Electrical Drives

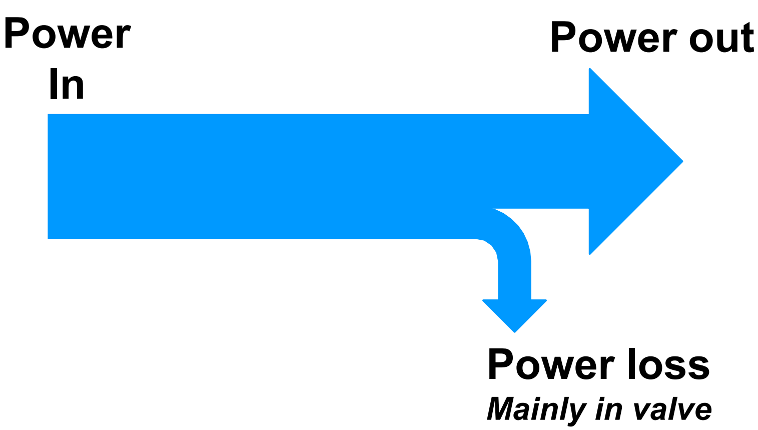
Electrical Drives

- About 50% of electrical energy used for drives
- Can be either used for fixed speed or variable speed
  - 75% - constant speed, 25% variable speed (expanding)

Example on VSD application

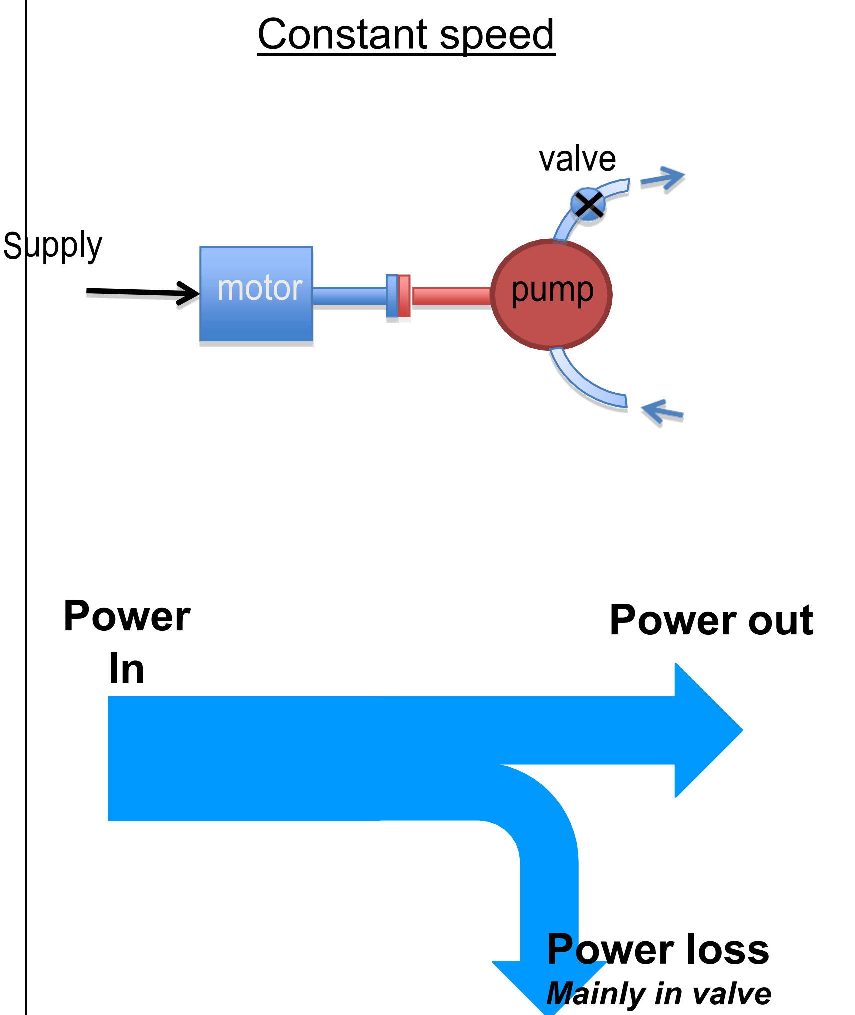
Constant speed

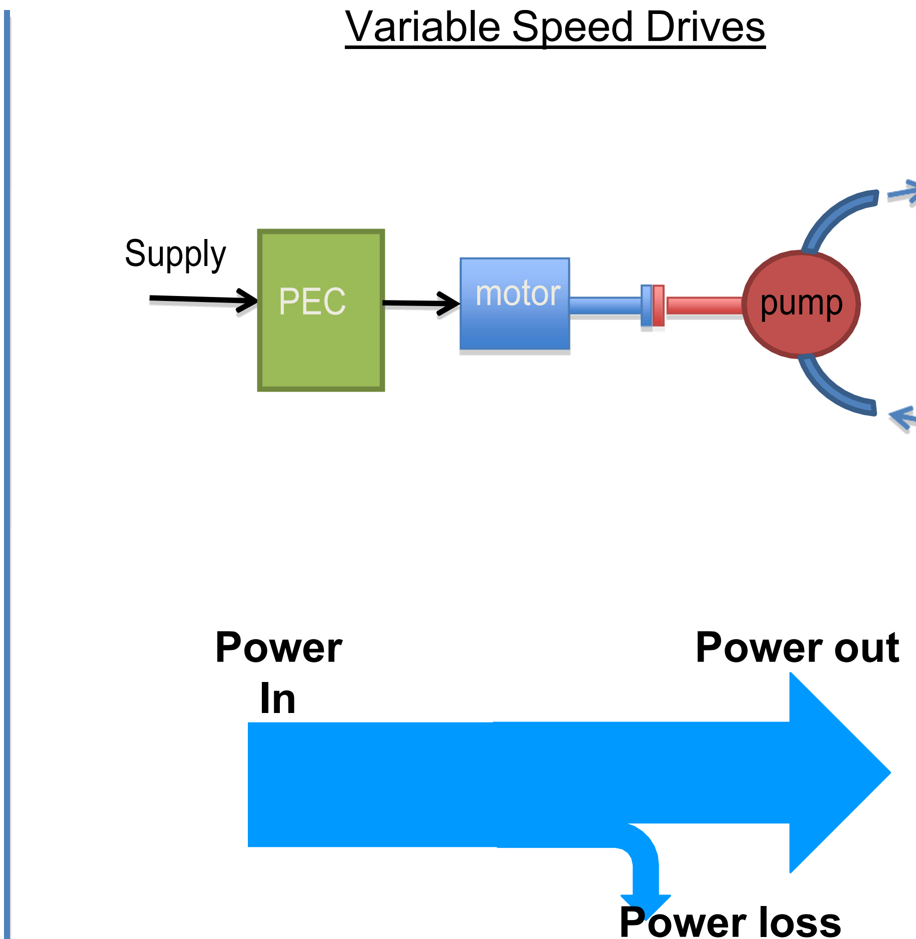




Variable Speed Drives

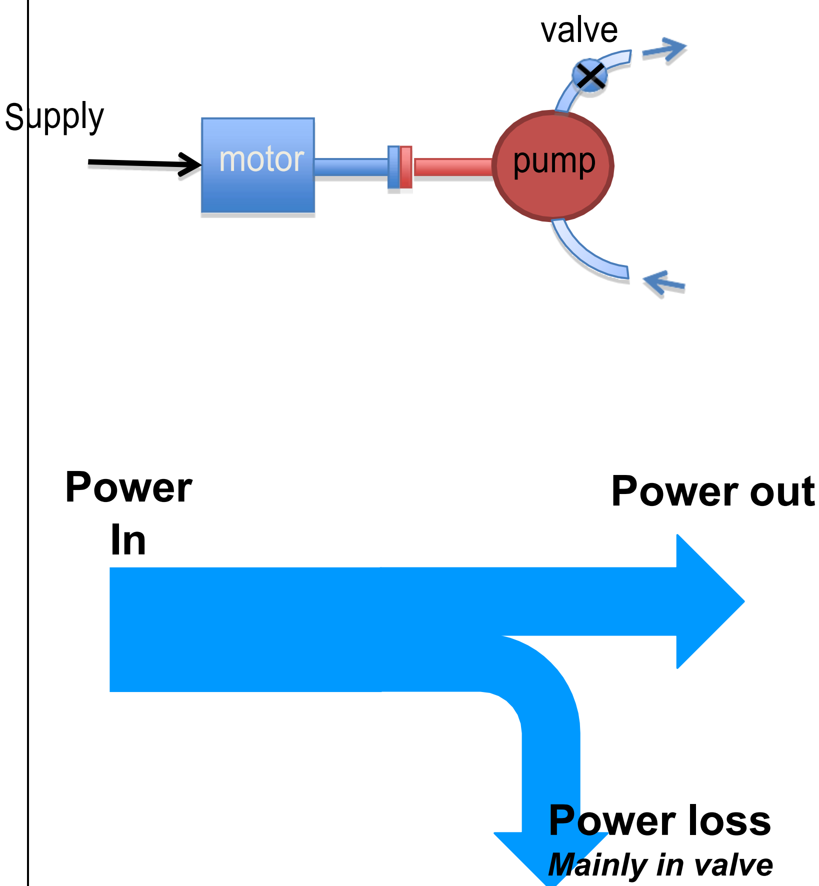
Example on VSD application



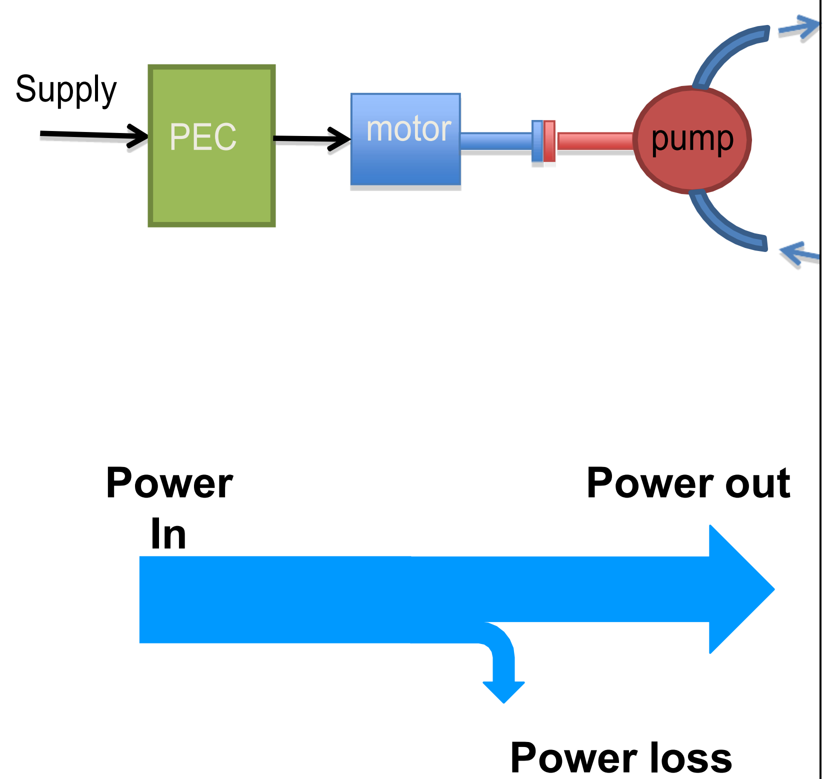


Example on VSD application

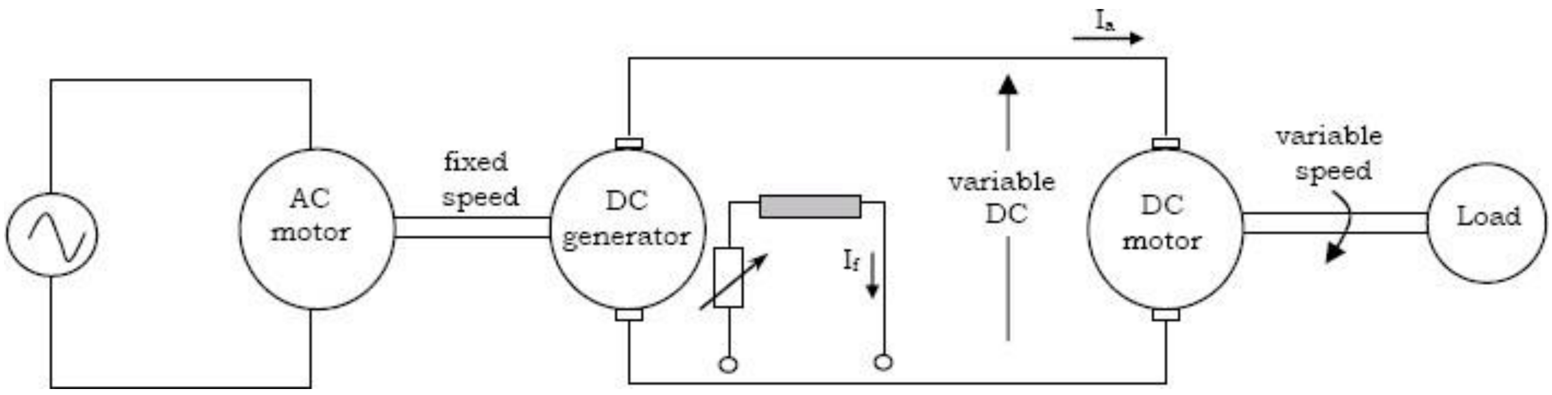
Constant speed



Variable Speed Drives

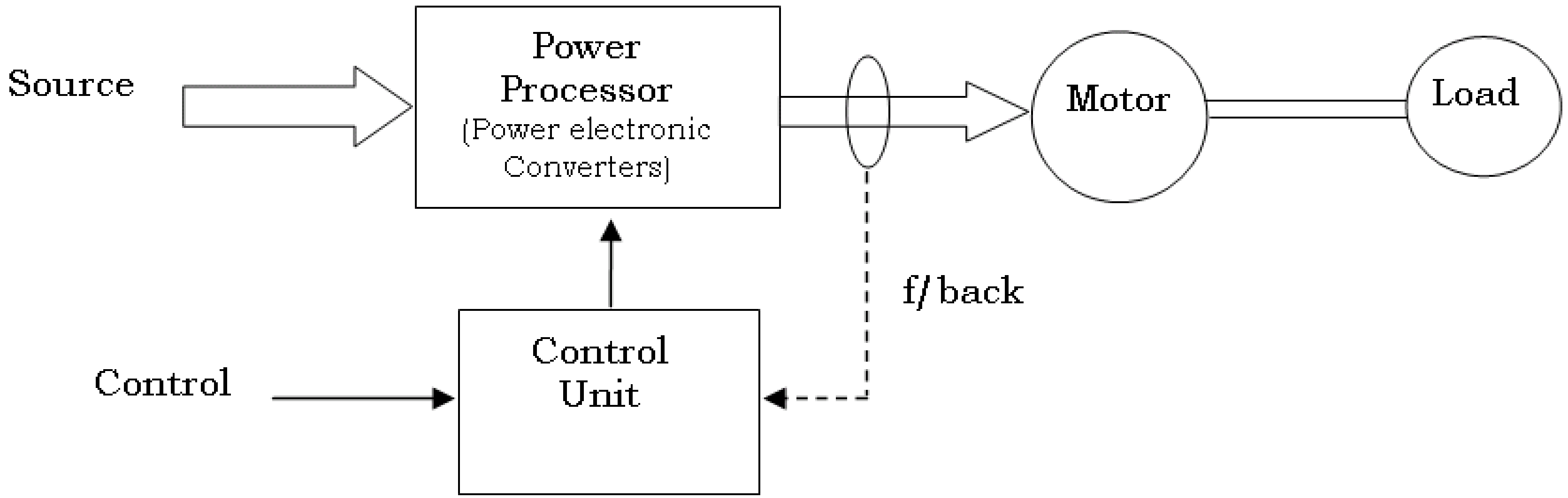


Conventional electric drives (variable speed)



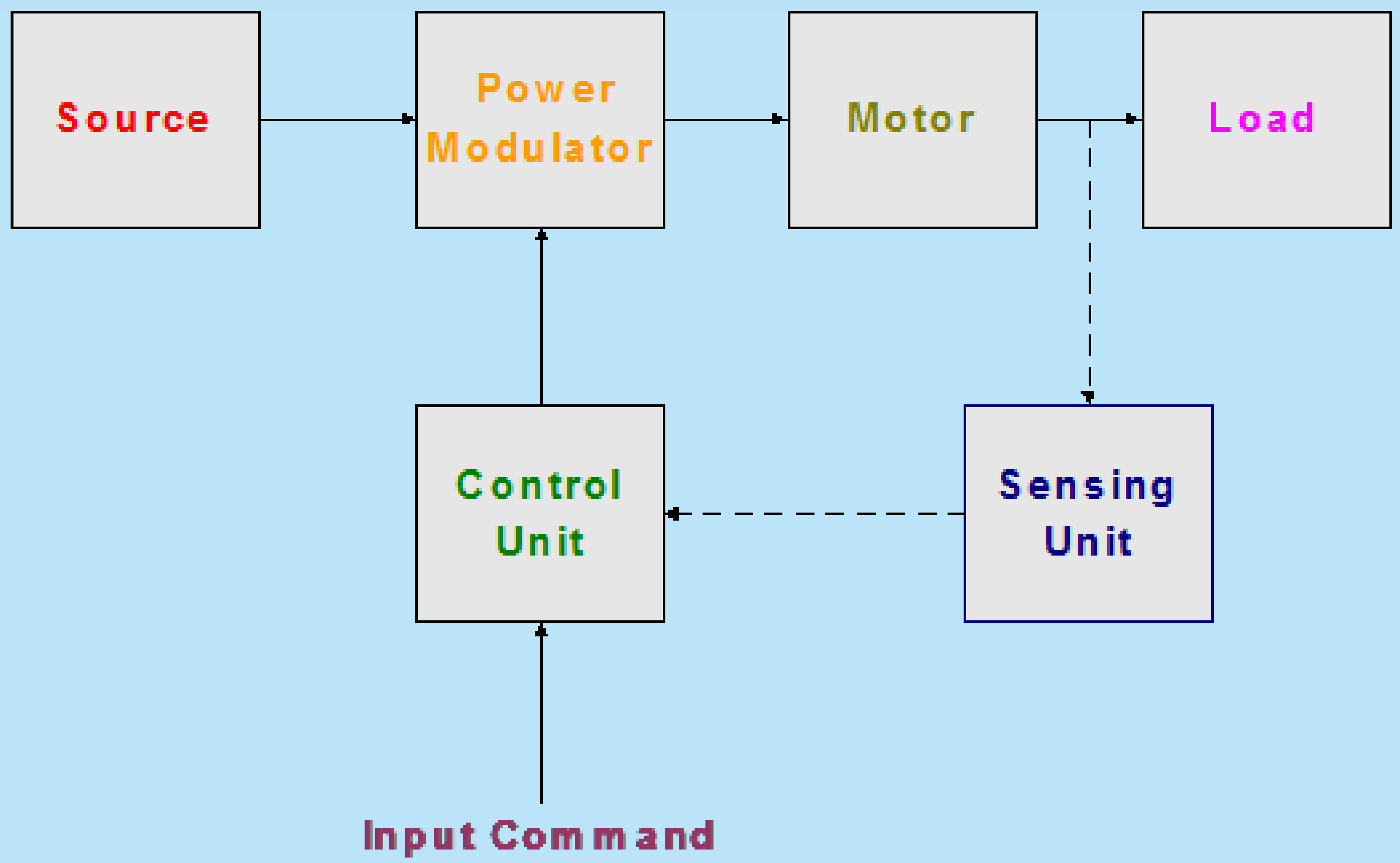
- Bulky
- Inefficient
- inflexible

Modern electric drives (With power electronic converters)



- Small
- Efficient
- Flexible

BLOCK DIAGRAM OF ELECTRIC DRIVE



Components in electric drives

Motors

- DC motors - permanent magnet – wound field
- AC motors – induction, synchronous (IPMSM, SMPSM), brushless DC
- Applications, cost, environment

Power sources

- DC – batteries, fuel cell, photovoltaic - unregulated
- AC – Single- three- phase utility, wind generator - unregulated

Power processor

- To provide a regulated power supply
- Combination of power electronic converters
  - More efficient
  - Flexible
  - Compact
  - AC-DC DC-DC DC-AC AC-AC

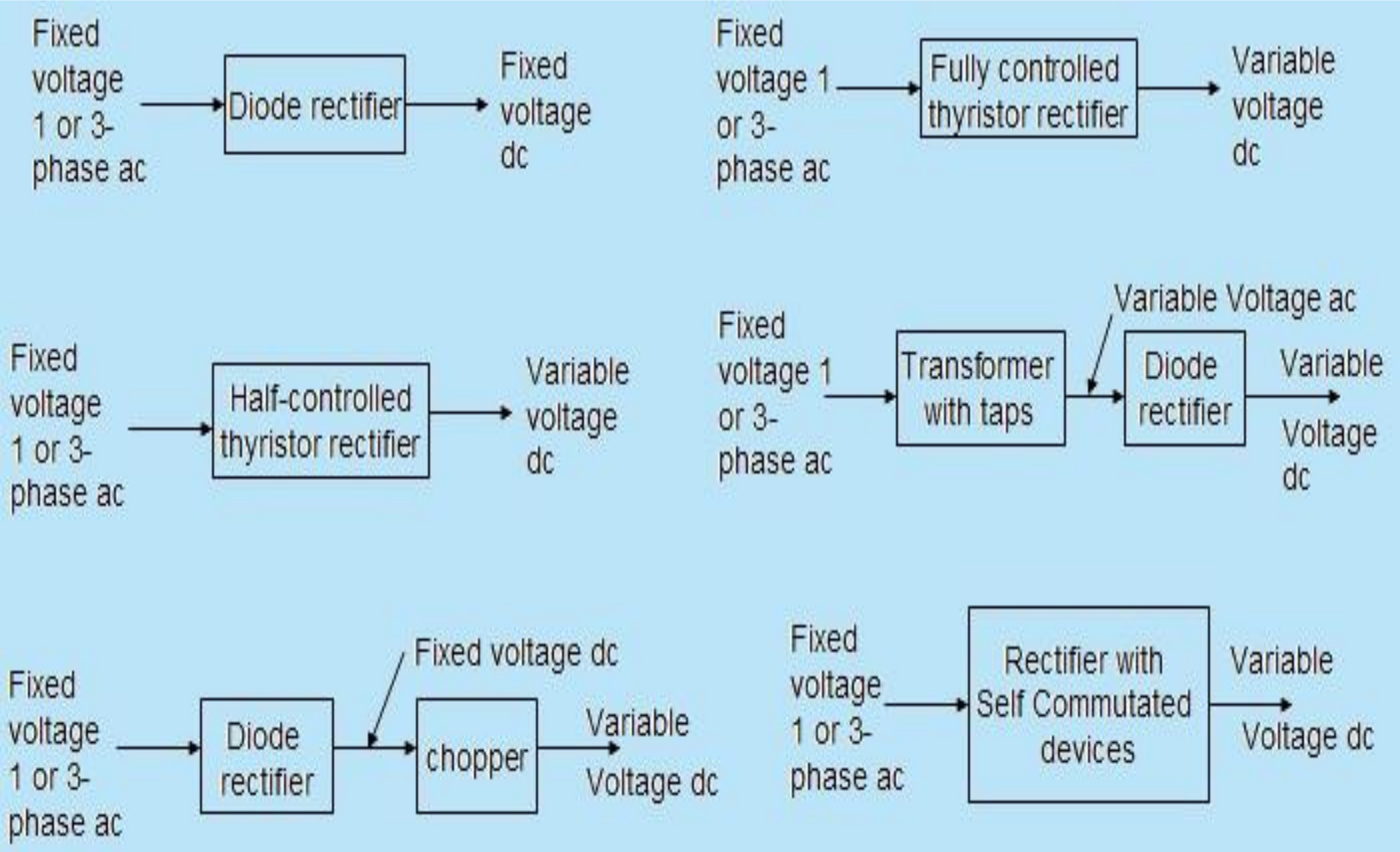
Components in electric drives

Control unit

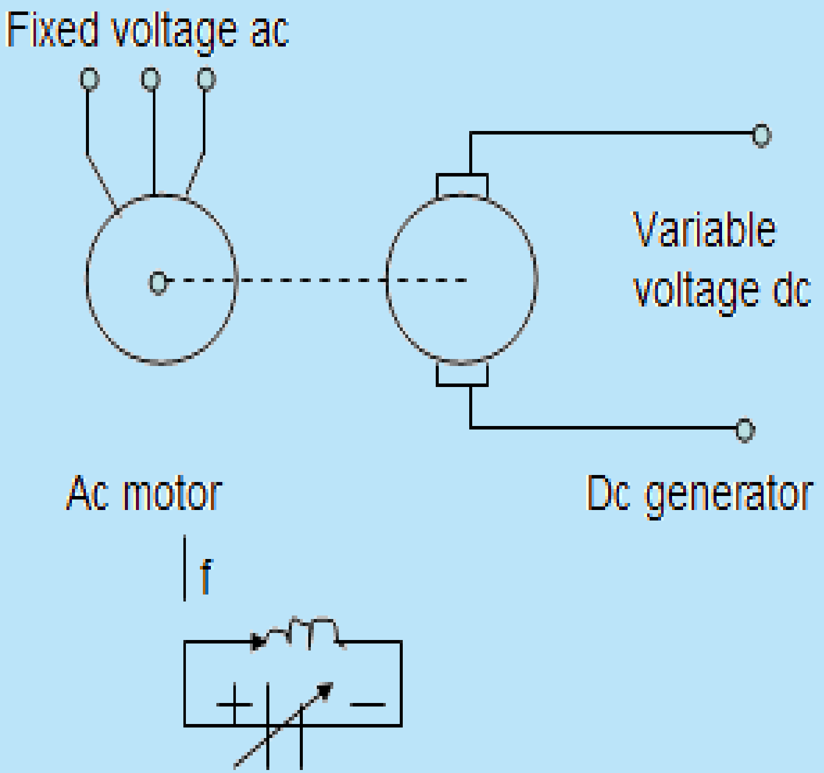
- Complexity depends on performance requirement
- analog- noisy, inflexible, ideally has infinite bandwidth.
- digital – immune to noise, configurable, bandwidth is smaller than the analog controller's
- DSP/microprocessor – flexible, lower bandwidth - DSPs perform faster operation than microprocessors (multiplication in single cycle), can perform complex estimations

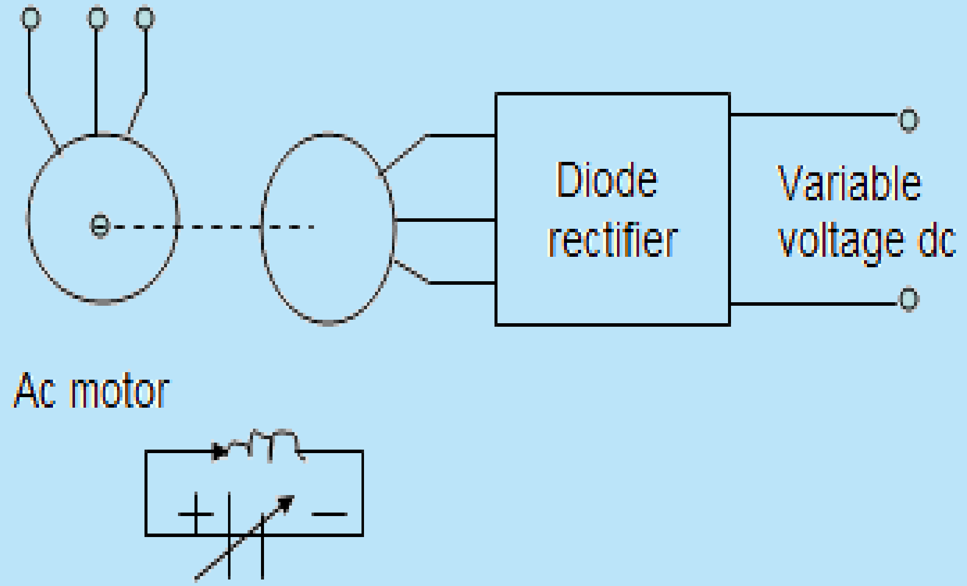
- The power modulator performs the following functions:
- (i) It modulates the flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.
- (ii) It restricts source and motor currents to permissible limits during transient operations, such as starting, braking and speed reversal.
- (iii) It converts the electrical energy of the source in the form suitable to the motor. Example, if the source is dc and an induction motor is to be employed, then the power modulator is required to convert dc in to a variable frequency ac.
- (iv) It selects the mode of operation of the motor i.e., motoring and braking.
- When power modulator is employed mainly to perform the third function, it is more appropriately called converter. While (iii) is the main function, depending on its circuit a converter may also perform other functions of the power modulator.

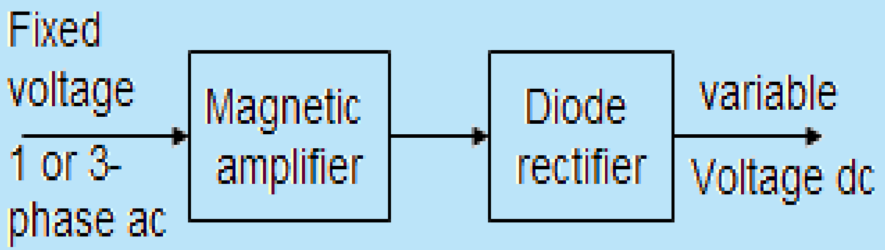
AC-DC Converters or Rectifiers



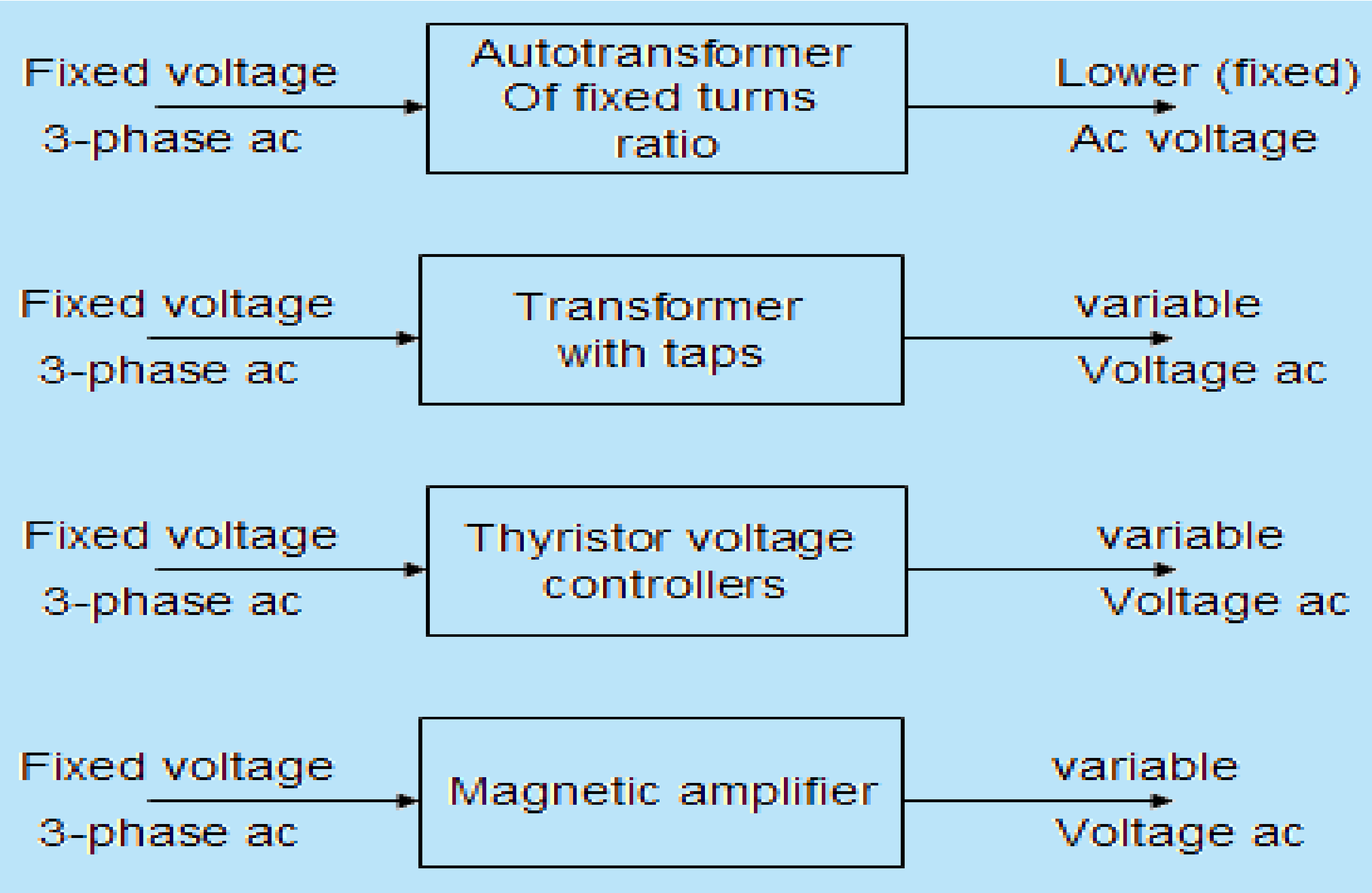
AC-DC Converters or Rectifiers (Cont.)



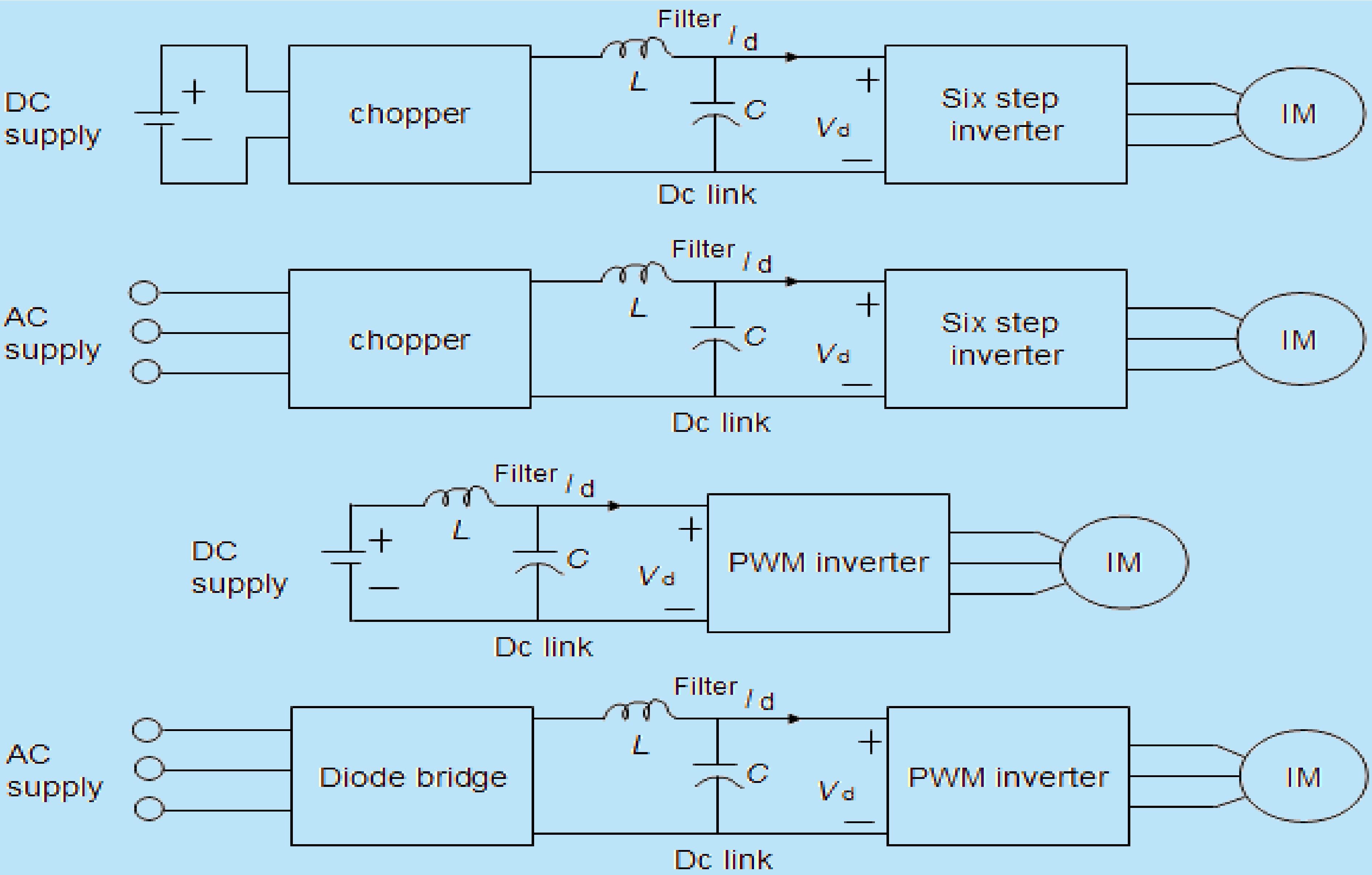




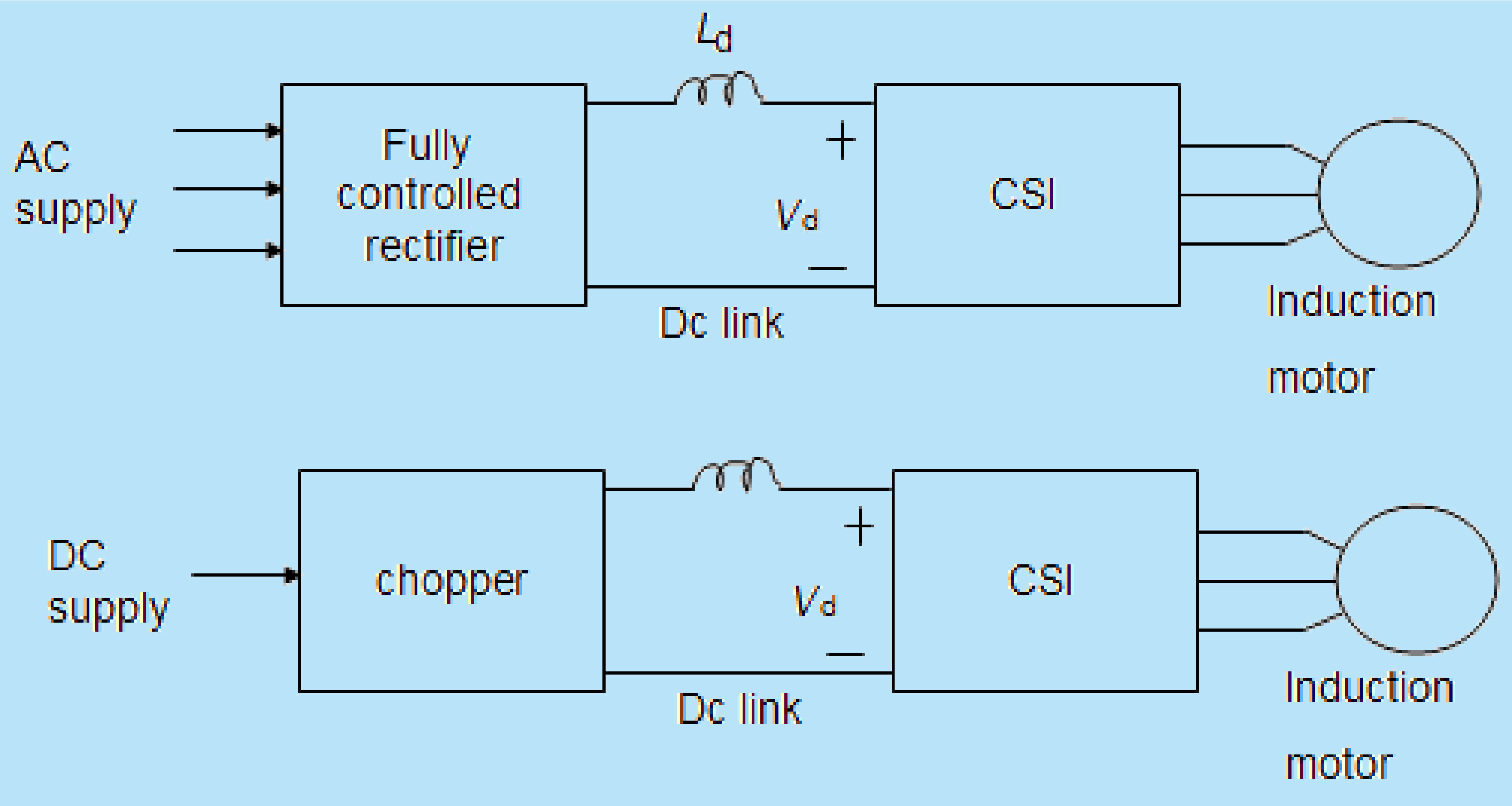
AC Voltage Controller



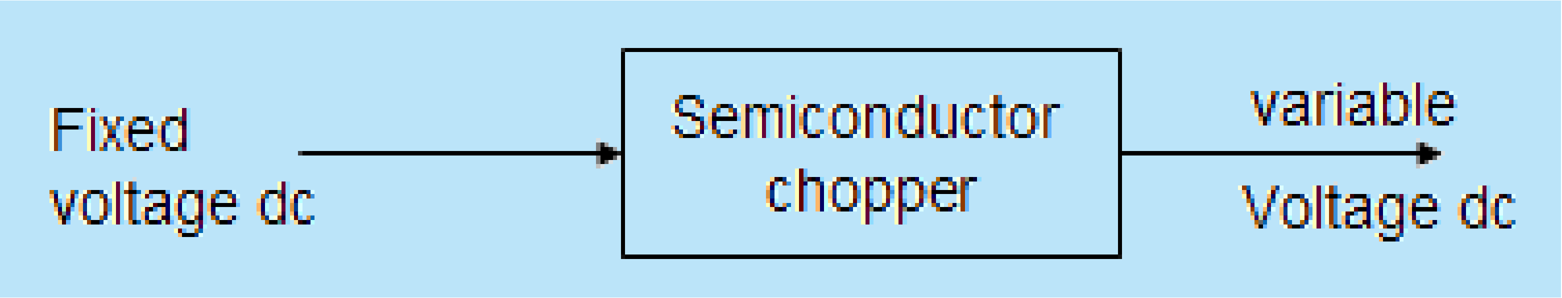
VSI Controlled Inverter for IM Drive



CSI Controlled Drives for IM



DC – DC Converter (Chopper)



Disadvantages of D.C Motors

- Requiring regular maintenance, they are not made readily available for replacement, as they are bulky in size.
- Sparking at the commutator is common.
- They are not suitable in chemical and petrochemical plants or in mines. Most of the variable speed drives installed at present in other industries are de drives.
- For ratings above 500 kW, manufacture of de motors itself poses problems. Due to this serious limitation, de motors are unsuitable for high capacity pumps or fans.

- Both series and separately excited de motors are normally used in variable speed drives, but series motors are traditionally employed for traction applications.
- At present, separately excited de motors controlled by thyristor converters are the most widely used motor drive systems in industry.
- The thyristor converter provides variable armature voltage for the drive motor.
- The three basic methods for obtaining a variable de output voltage from a fixed supply voltage (ac or de) are phase control, integral cycle control and chopper control.
- In all these methods, thyristors connect the supply to and disconnect it from the motor terminals. The frequency of switching is rapid; therefore, the motor responds to the average output voltage level and not to the individual voltage pulses.

Working Principle of dc Motor

- When the dc motor is connected to the supply mains, a direct current passes to the armature winding through the brushes and commutator.
- When the armature conductors become the current carrying conductors in a magnetic field generated by exciting field magnets, they experience a force tending to rotate the armature.
- The magnitude of the mechanical force experienced by the conductor is given by

$$F = BIl \quad \text{in newtons}$$

where

B = Flux density of magnetic field in Wb/m^2

I = Current in amperes

l = Length of conductor in metres.

- Now, by applying Fleming's left-hand rule, the direction of the force produced by each conductor can be determined.
- The conductors experience a force which tries to rotate the armature in the anti-clockwise direction.
- Then the machine acts as a motor. These motor forces collectively generate a driving torque, which is useful to rotate the armature

CLASSFICATION OF DC MOTORS AND THER SPEED CONTROL

- Depending upon the connection of the field winding with the armature terminals, the de motors can be classified into three types.
- They are:
- (i) Shunt mator or separately excited motor
- (ii) Series motor
- (iii) Compound motor.

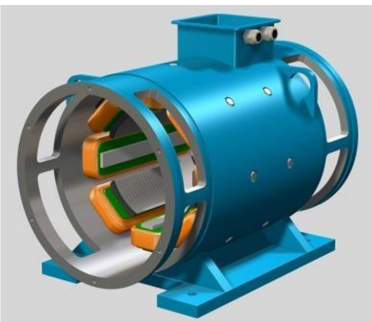
DC Shunt Motor or Separately Excited Motor

- It is loaded with a mechanical rotational system as shown in Fig.1. 1 with initial steady-state conditions.
- The load torque T_L, opposes the motor torque Tm.
- The motor is controlled by varying the armature voltage. The field voltage V_f, remains constant and is given by

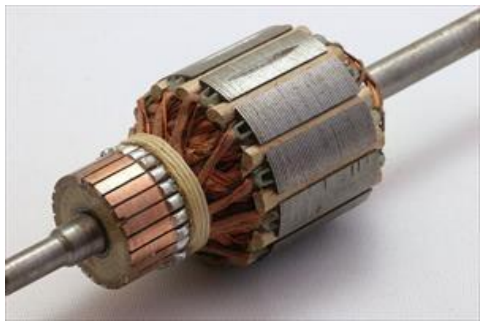
$$V_f = I_f R_f \text{---------------} 1$$

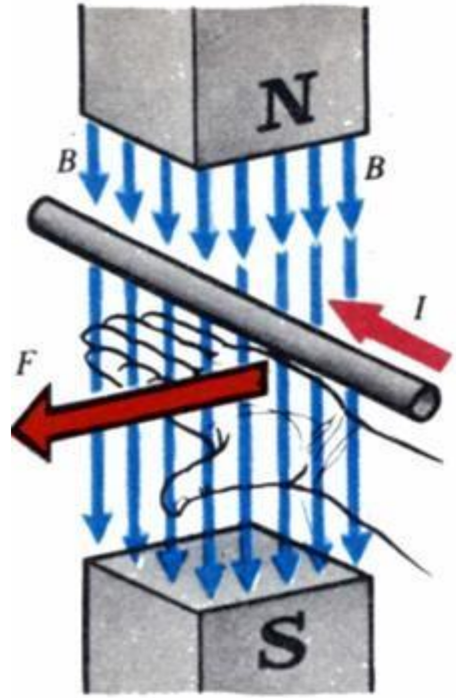
- where
  I_f = Field current in amperes
  R_f Field resistance in ohms.

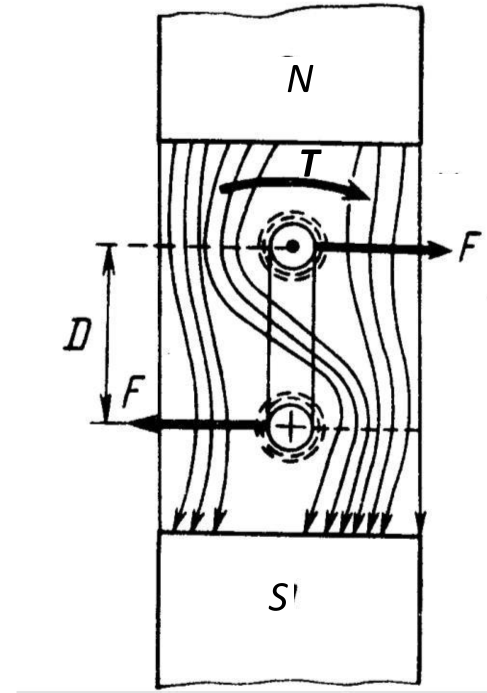
Stator

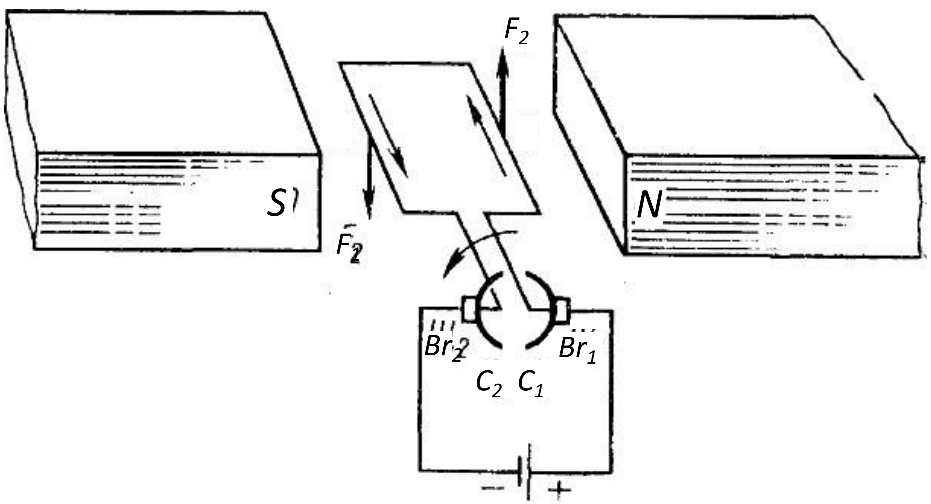


Armature









$$F = B \cdot I \cdot L$$

B - induction

I - current

L – length of the conductor

$$T = F \cdot D$$

F - force

T - torque

D - diameter

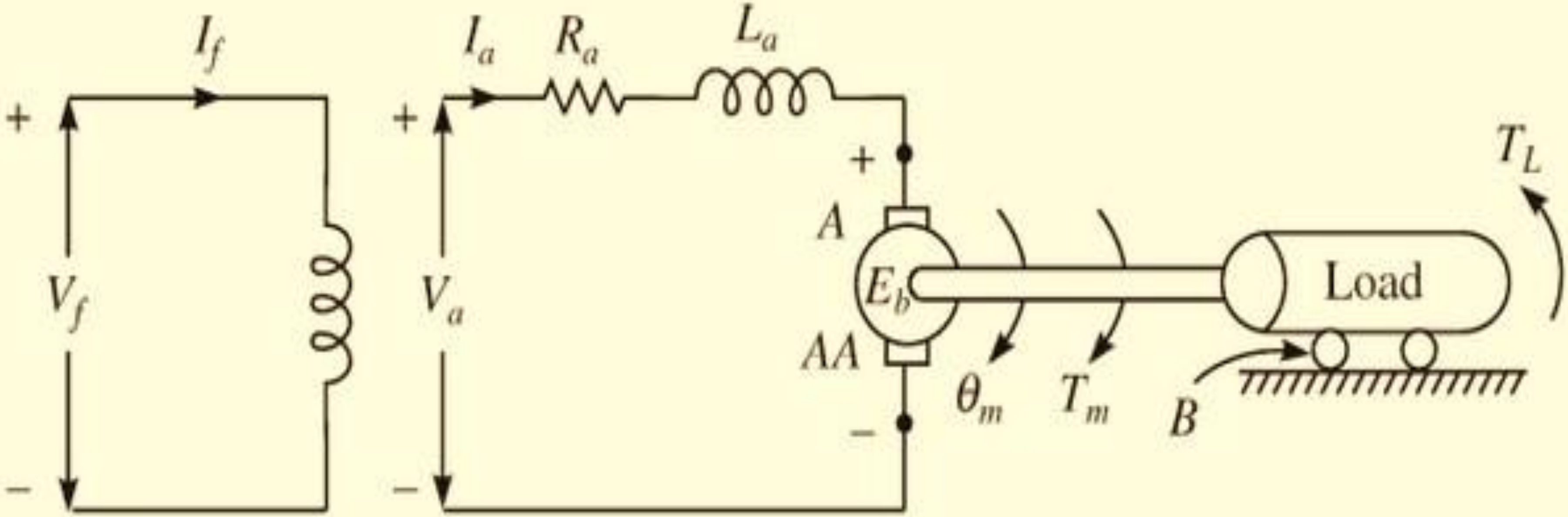


Fig. 1.1 Separately excited dc motor.

- From the armature-voltage control circuit, with its input excitation V, the potential in the armature circuit is

$$V_a = R_a I_a + L_a \frac{dI_a}{dt} + E_b$$

- ----------2

- When the armature leakage reactance is neglected, Eq. (2) reduces to

Va = RaIa + Eb------------ 3

where

V_a = Armature voltage in volts

I_a = Armature current in amperes

R_a = Armature resistance in ohms

E_b = Motor back emf in volts.

- In separately excited d.c motor, the back emf is directly proportional to speed

$$E_b \propto N$$

- $$E_b = K_t \phi_a N = K_m \omega_m \qquad \text{----4}$$

where

$K_m = K_t \phi_a$ = Torque constant in N-m/A

ω_m = Angular speed in rad/s

N = Speed in rpm.

- Now, from Fig. 1.1, the mechanical torque for the rotational system is given as where

$$T_m = B\omega_m + T_L$$

where

B = Ficticious friction constant in N-m-s/rad

T_L = Load torque in N-m.

- In a separately excited de motor, the torque is directly proportional to the armature current, i.e.,

$$T_m \propto I_a$$

$$T_m = K_t\phi_a I_a = K_m I_a$$

- From 3 and 4

$$E_b = V_a - I_a R_a = K_m \omega_m$$

$$\omega_m = \frac{V_a - I_a R_a}{K_m} = \frac{V_a - I_a R_a}{K_t \phi_a}$$

$$= \frac{V_a}{k_t \phi_a} - \frac{R_a}{(k_t \phi_a)^2} T_m \qquad \left(\text{since } I_a = \frac{T_m}{k_t f_\alpha}\right)$$

- From Eq. (6), the speed can be controlled with either the armature terminal Va (armature- voltage control) or with the field flux a (field-flux control).
-

Speed(N)-torque(T) and torque(T)-current(Ia) characteristics

- The speed-torque and torque-current characteristics of separately excited dc motor for rated terminal voltage and full field current are shown in Fig. 1.2.
- The speed-torque characteristic is a straight line.
- Speed decreases as torque increases and speed regulation depends upon the armature resistance.
- Separately excited dc motors are employed in applications requiring good speed regulation and adjustable speed.

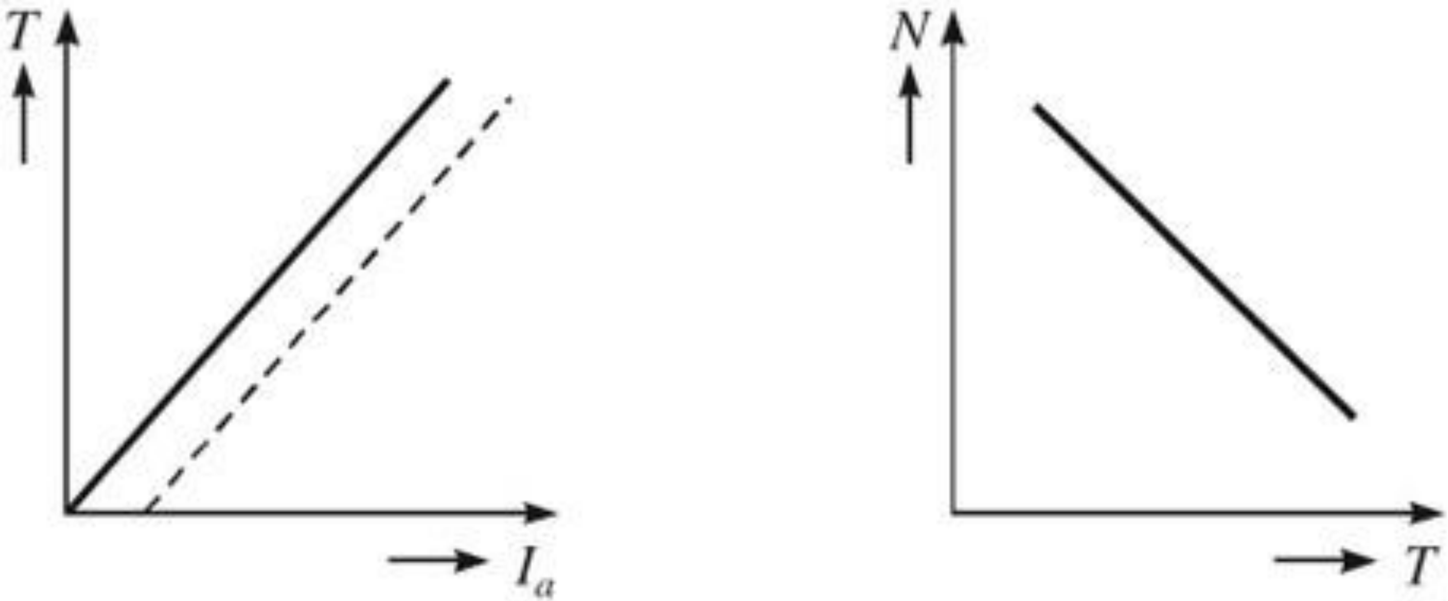


Fig. 1.2 Characteristics of separately excited dc motor.

D.C Series Motor

- A series excited dc motor is loaded with a mechanical rotational system as shown in Fig. 1.3 with initial steady-state conditions.
- The load torque (T) opposes the motor torque (Tm) with armature voltage as its input, where series field resistance and armature resistance are placed in series.
- From Fig. 1.3, the potential drop is given by

$$V_a = E_b + I_a (R_a + R_f)$$

- where Ra+Rf is the combined resistance of armature and field in ohm.
- Now from Fig. 1.3, the mechanical torque for the rotational system is given as

$$T_m = B\omega_m + T_L \qquad (1.8)$$

- In a series motor, the flux ϕ is a function of armature current in unsaturated magnetization characteristic, and can be assumed to be proportional to
- $\phi = K_f I_a \qquad (1.9)$

T-Ia and N-T characteristics

- The speed-torque and torque-current characteristics of series excited dc motor for rated terminal voltage and full field current are shown in Fig. 1.4.
- The speed-torque characteristic is a hyperbolic line since the torque is proportional to the square of the current.
- For the same increase in the torque, increase in the motor current is less compared to that in the separately exited motor, where the torque is proportional to the armature current.
- Hence a series motor should not be used in those drives where there is a possibility of torque being dropped to some extent.
- The speed may exceed twice the rated value. Series motor is suitable for applications requiring high starting torques.

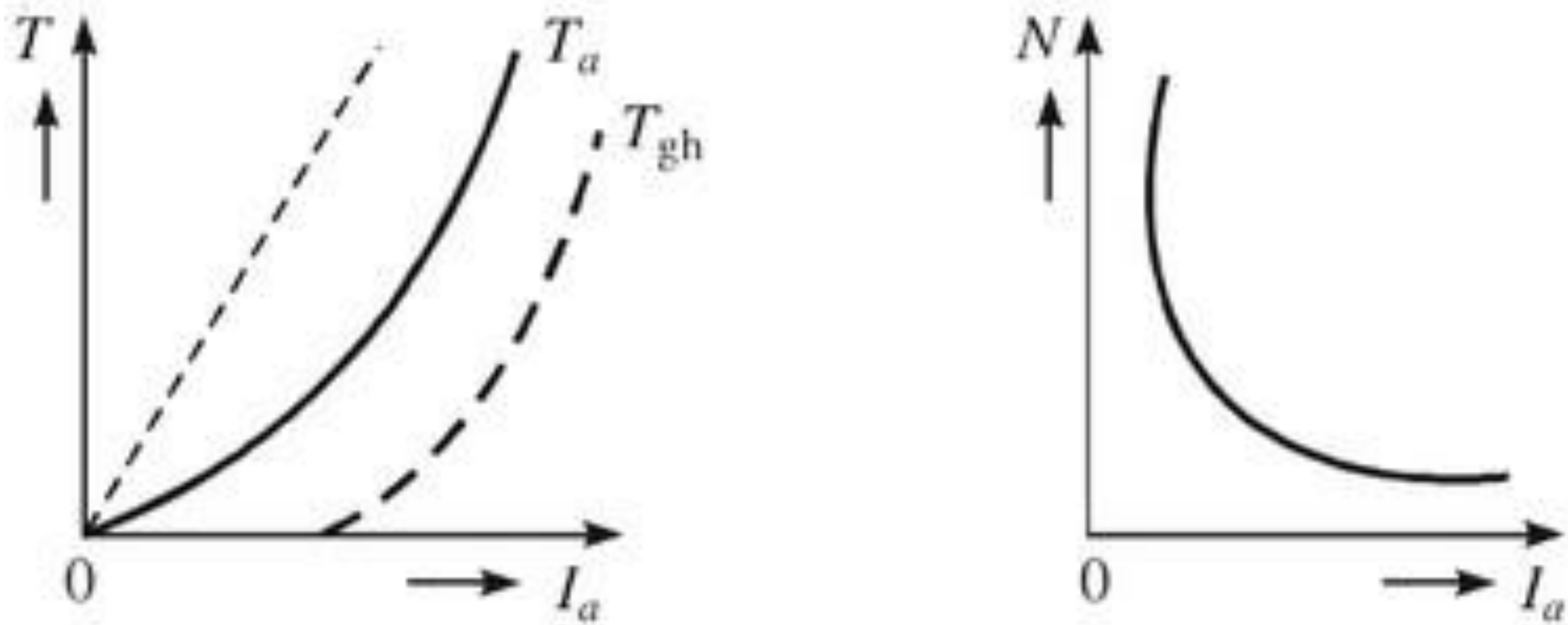


Fig. 1.4 Characteristics of dc series motor.

DC Compound Motor

- It is loaded with the mechanical rotational system with initial steady state conditions as shown in Fig. 1.5.
- The load torque T_L, opposes the motor torque T_m. In a cumulatively compound motor, the magnetomotive force (mmf) of the series field is a function of armature current and is in the same direction as the mmf of the shunt field.

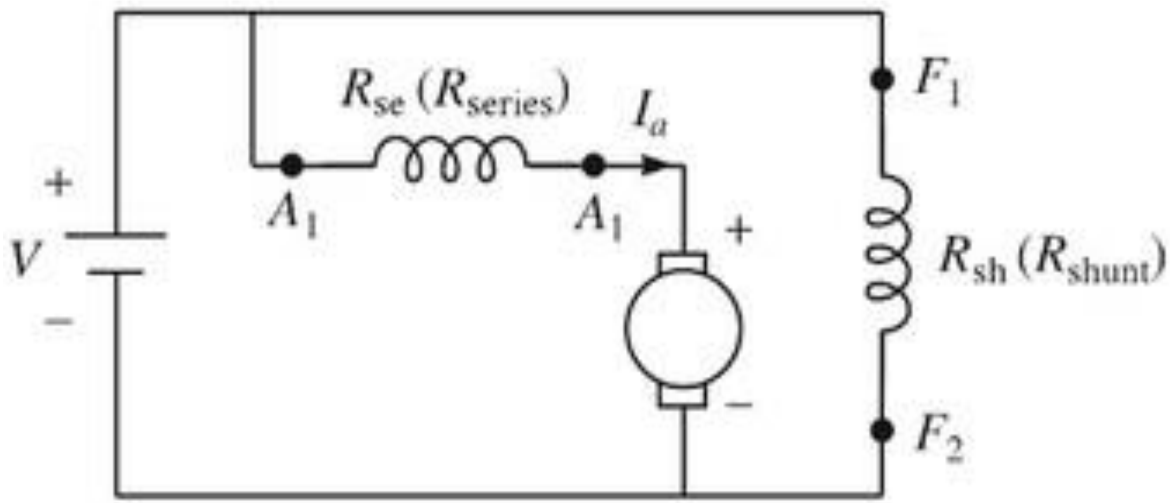


Fig. 1.5 DC compound motor.

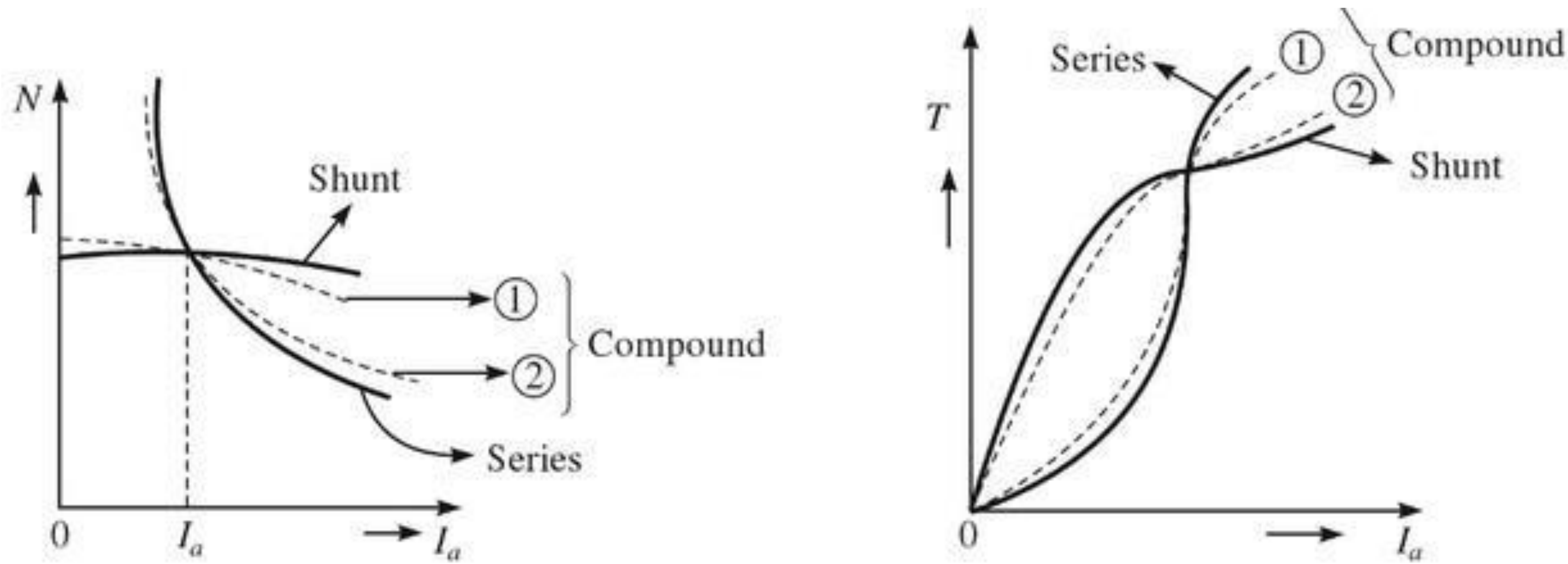


Fig. 1.6 Characteristics of dc compound motor.

SPEED CONTROL OF DC MOTORS

- The various methods for speed control of de motors are:
  - **1. Flux or field control method**
  - **2. Resistance of armature circuit (rheostat control) or armature voltage control method**
  - **3. Applied voltage control method.**

- **<u>1.Flux Control Method</u>**
- The flux control method is also called field control method.
- By decreasing the flux the speed can be increased and vice versa.
- The flux of a de motor can be changed by changing the field current with the help of a field rheostat.
- If the field resistance is increased, the field current decreases and there is a consequent decrease in field flux, due to which the speed increases.
- **<u>Shunt motor</u>**
  - In case of shunt motor, flux is controlled by using a shunt field rheostat.
  - Here IR loss is small, since Ish is very small.
  - So the rheostat is small in size.

- **Series motor**
- In case of series motor, the flux is controlled by using the following methods:
- **Field diverters:**
- In this method the series field winding is shunted by a variable resistance known as field diverter.
- Any desired amount of current can be passed through the diverter by adjusting its resistance.
- Hence the flux can be decreased and the speed of motor can be increased.
- **Armature diverter:**
- A diverter across the armature can also be used to control the speed.
- For a given constant load torque, if I, is reduced due to armature diverter, then flux must increase.
- This results in an increase in current taken from supply.
- **Tapped field control:**
- In this method, the number of series field turns in the circuit can be changed by tapping the number of turns in the series field.
- With full field, the motor runs at its minimum speed, which can be raised in steps by cutting out some of the series field turns.

- <u>Paralleling field coils:</u>
- In this method, several speeds can be obtained by regrouping field coils.
- When the field coils over the poles of the motor are connected in series, the normal full load current passes through them, and when the coils are connected across the parallel group the speed can be increased further.
- <u>Advantages of field control method</u>
- This method is economical and efficient, since very little power is wasted in external rheostat.
- <u>Disadvantages of field control method</u>
- This method can generate speeds only above normal speed because flux can only be decreased.
- Also, commutation becomes dissatisfactory because of the effect of armature reaction.

Armature Voltage Control

The back emf of a motor is given by

$$E=V-I_aR_a$$

As the supply voltage V is constant, the voltage across the armature is varied by inserting a variable rheostat or resistance called controller resistance in series with the armature circuit.

As the controller resistance is increased, the voltage drop across the armature is increased, thereby decreasing the back emf which in turn decreases the speed.

This method is usually employed when low speeds are required for a short period, only because the armature voltage can be decreased by the controller resistance.

Shunt motor

In case of shunt motor, an increase in armature circuit resistance will cause motor voltage drop in armature circuit and so the speed will be reduced.

The field current will remain unaffected as the shunt field is directly connected across the supply voltage.

The circuit for shunt motor is shown in Fig. 1.7.

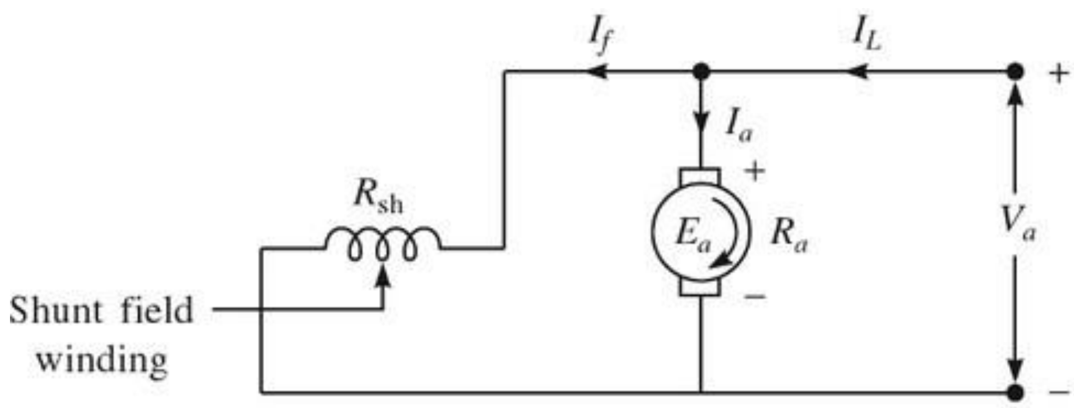


Fig. 1.7 DC shunt motor.

Series motor

In case of series motor, an increase in armature circuit resistance will cause more voltage drop in armature circuit and so speed will be reduced, as the torque is directly proportional to the flux and armature currents and hence the flux.

In order to obtain different speeds for constant load torque, the armature current is kept constant; so the flux remains constant.

- **Advantages of armature control method**
- The only advantage is that speed below normal speed can be achieved.
- **Disadvantages of armature control method**
- A large amount of power is wasted in controller resistance, which in turn decreases the efficiency.
- Also, it needs expensive arrangements for dissipation of heat produced in controller resistance.

Voltage Control Methods

- Multiple voltage controlling method the shunt field of the motor is permanently connected to a fixed exciting voltage.
- But the armature is supplied with different voltages by connecting it across one of the several different voltages by means of suitable switchgears.
- The armature speed will be approximately proportional to these different voltages.

Ward Leonard system

- This system is used where an unusually wide-ranging and very sensitive speed control method is required, as shown in Fig. 1.8.
- Here, M, is the main motor whose speed control is required.
- The field of this motor is of variable voltage across the armature, which is supplied by a motor generator set which consists of either dc or ac motor M2 directly coupled to generator G.
- 3- AC supplyM1Controlled rectifier Uncontrolled or controlled rectifier.
- The motor M2 runs at an approximately constant speed.
- The output voltage of G is directly fed to the main motor M.
- The voltage of the generator can be varied from zero up to its maximum value by means of its field regulator.
- By reversing the direction of field current of G by means of reversing switch (RS), the generated voltage can be reversed and hence the direction of rotation of M.
- The main advantage of this type is unlimited speed control in either direction of rotation, which can be achieved by field control of generator.

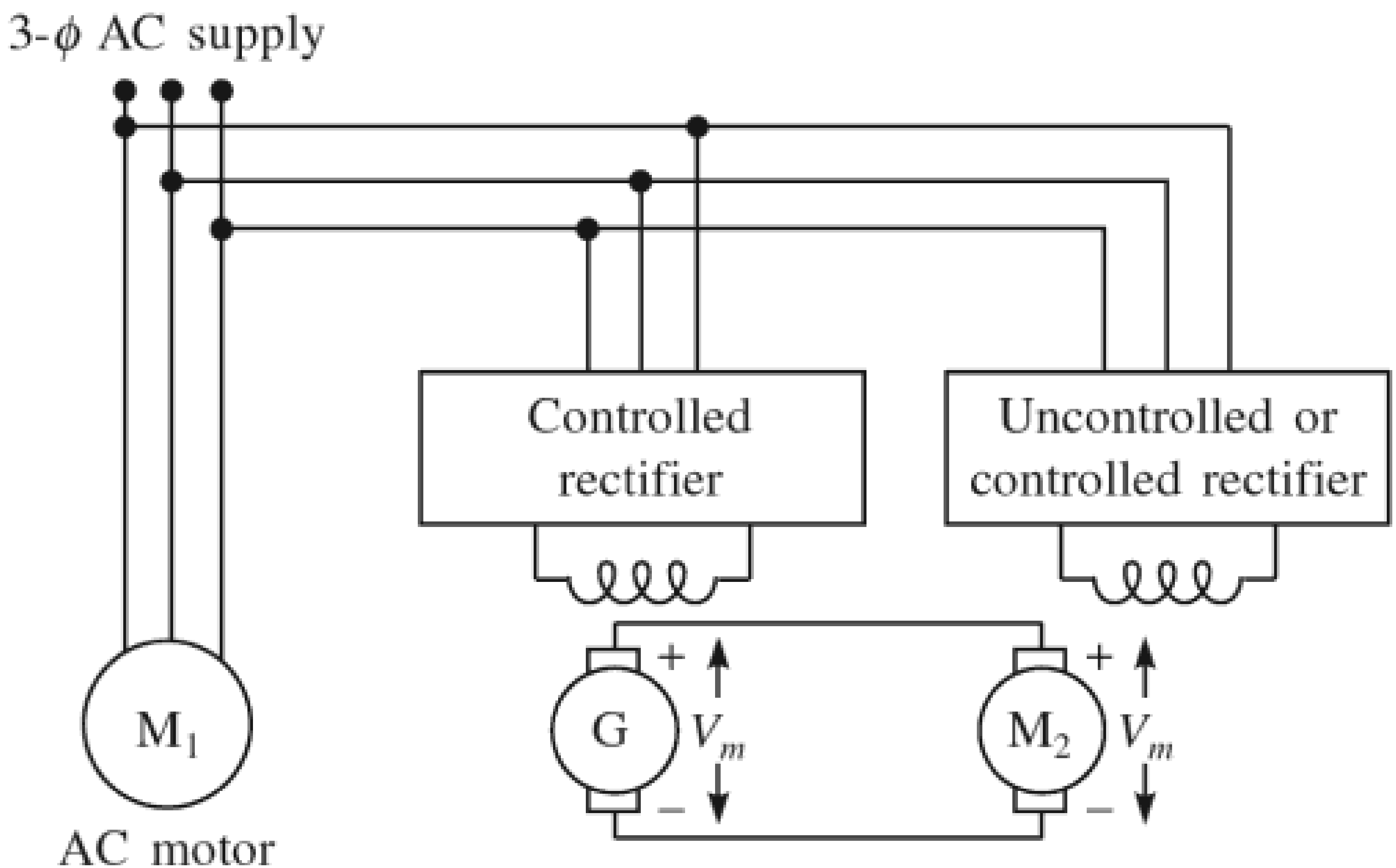


Fig. 1.8 Ward Leonard system.

Single-phase semi-controlled converter dc drives,

- Controlled converter fed dc drives are generally operated on the principle of operation of phase control, where the phase control depends upon either natural commutation or line commutation.
- In industrial applications, the drive circuits make use of more than one thyristor.
- In such circuits, when incoming thyristor is turned on by triggering, it immediately reverse biases the outgoing thyristor and turns it off.
- As phase control converters need no commutation circuitry, these are simple and less expensive, and therefore they are widely used in industrial applications such as steel rolling mills, paper mills, traction system working on dc, etc.
- Controlled converter dc drives can be categorized in two ways depending upon the supply systems, i.e., single-phase and three-phase systems. Controlled converter dc drives depend upon quadrant operations. They are classified as:
- (A) Single-phase semi-controlled converter dc drives, which are further divided into
- (i) Separately excited dc drive;
- (ii) Series dc motor drive;
- (B) Single-phase fully controlled converter dc drives, which are further divided into (i) Separately excited dc drive;
- (ii) Series de motor drive.

Single-phase semi-controlled converter dc drives- Separately excited dc drive

- A single-phase semi-controlled converter bridge with two thyristors and two diodes and its quadrant operation is shown in Fig. 1.10.
- The two thyristors are T1, and T2 and the two diodes are D1 and D2.
- The load is a separately excited drive, where the load current is assumed to be continuous over the working range.
- The drive is shown in Fig. 1.1, the motor is shown by its

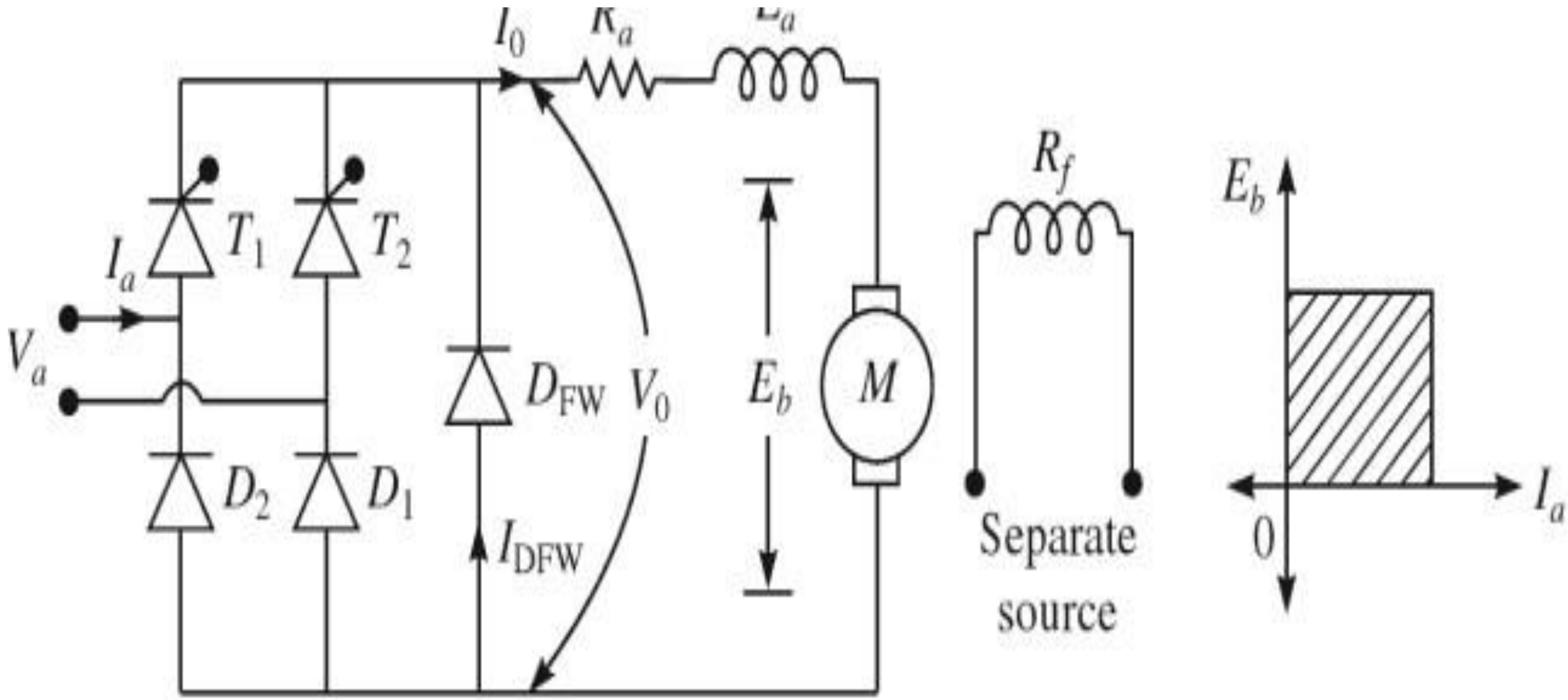


Fig. 1.10 Single-phase semi-controlled converter of dc separately excited motor.

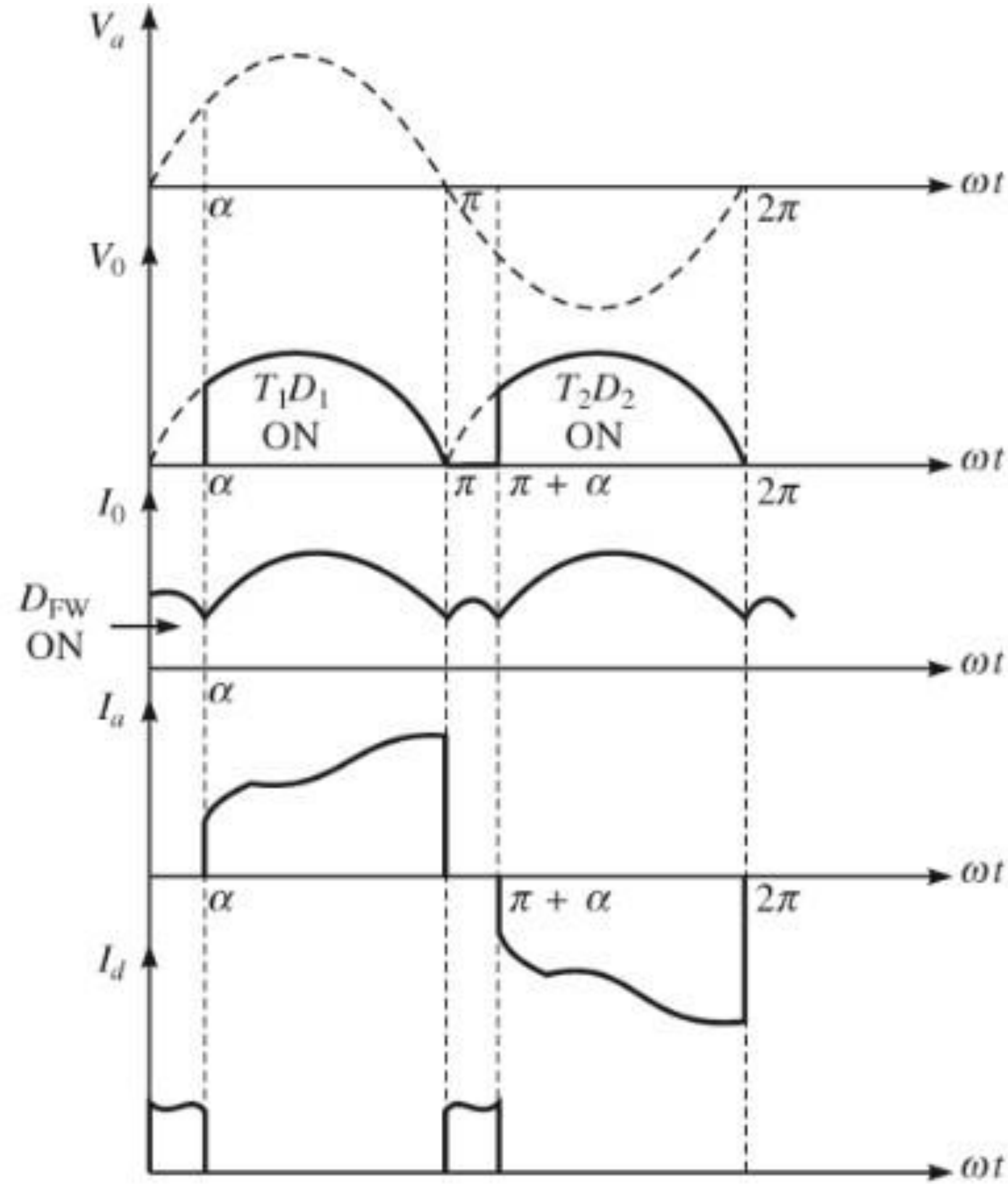


Fig. 1.11 Voltage and current waveforms in continuous conduction.

Continuous conduction

During the positive half cycle, the motor is connected to the supply voltage V_a through the thyristor T_1 triggered and diode D_1. The load terminal voltage V_0 is of the same wave shape as the ac source voltage V_a. Beyond period π, I_a tends to reverse as V_a changes polarity. This forward biases the freewheeling diode D_{FW} and it starts conducting. The motor current i_o which was flowing from the supply through T_1 is transferred to D_{FW}. During period $\pi < \omega t < (\pi + \alpha)$, the motor terminals are shorted through D_{FW}, making V_0 zero.

During the period $\alpha < \omega t < \pi$, the armature loop equation is

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b \tag{1.13}$$

During the negative half cycle at $\omega t = (\pi + \alpha)$, the thyristor T_2 and diode D_2 conduct, and the load is connected to the source through T_2 and D_2. The output voltage is of the same wave shape as the ac source voltage. Beyond 2π the source voltage polarity reverses; this forward biases the freewheeling diode and it starts conducting. The motor current i_a which was flowing from the supply through T_2 is transferred to D_{FW}. During the period $2\pi < \omega t < (2\pi + \alpha)$, the motor terminals are shorted through D_{FW}, making V_0 zero. From $2\pi + \alpha$ onwards the cycle will repeat.

During the period $\pi < \omega t < (\pi + \alpha)$, from Fig. 1.10 the armature loop equation is found to be

$$V_a = 0 = R_a i_a + L_a \frac{di_a}{dt} + E_b \tag{1.14}$$

The average dc output voltage across the motor terminals is

The average dc output voltage across the motor terminals is

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d(\omega t)$$

$$= \frac{V_m}{\pi}\left[-\cos \omega t\right]_{\alpha}^{\pi} = \frac{V_m}{\pi}(1+\cos \alpha) \qquad (1.15)$$

The steady-state speed equation is

$$N = \frac{V_a - i_a R_a}{K\phi} = \frac{(V_m/\pi)(1+\cos \alpha) - i_a R_a}{K\phi}$$

We know that

$$T \propto \phi \cdot i_a$$

$$T = K\phi \cdot i_a$$

$$i_a = \frac{T}{K\phi}$$

∴ The average speed is $$N = \frac{(V_m/\pi)(1+\cos \alpha)}{K\phi} - \frac{R_a \cdot T}{(K\phi)^2} \qquad \left(\text{since } i_a = \frac{T}{K\phi}\right) \qquad (1.16)$$

In the above equation, the first term represents the theoretical no-load speed and the second term represents the speed drop produced by the armature current I_a and hence the torque T.

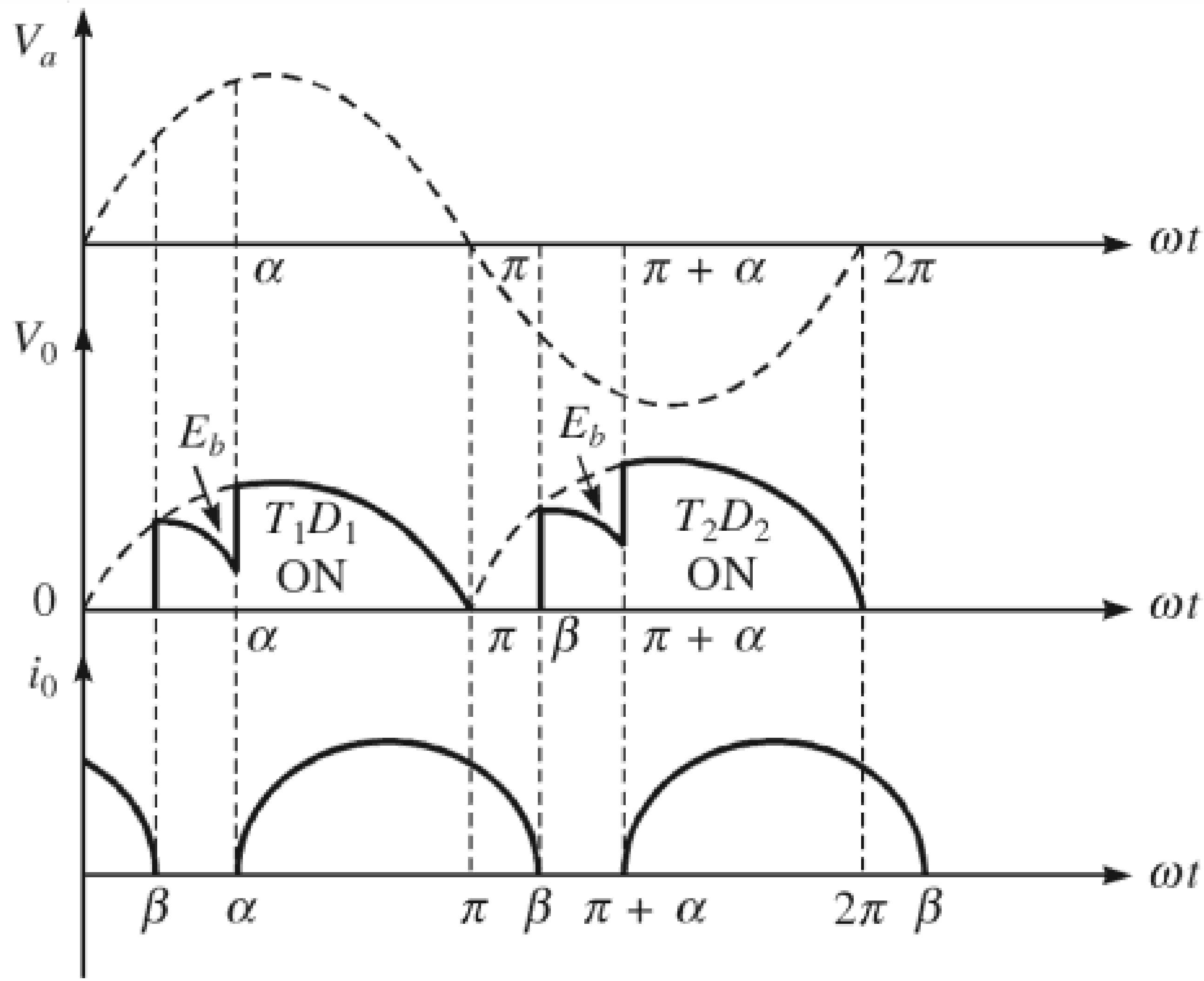


Fig. 1.12 Voltage and current waveforms in discontinuous condition.

General analysis of equations

A cycle of motor terminal voltage consists of the three following intervals:

Interval I $\alpha \le \omega t \le \pi$ (Duty interval): During this mode, the thyristor conducts and its governing equation is

$$R_a i_a + L_a \frac{di_a}{dt} + E_b = V_m \sin \omega t \tag{1.17}$$

or

$$\frac{di_a}{dt} + \frac{R_a}{L_a} i_a = \frac{V_m}{L_a} \sin \omega t - \frac{E_b}{L_a} \tag{1.18}$$

We solve the preceding equation using complex function (CF) and particular integral (PI). CF is

$$\frac{di_a}{dt} + \frac{R_a}{L_a} i_a = 0$$

$$\mathrm{R}\mathrm{i}_0 + \mathrm{L}\frac{\mathrm{d}\mathrm{i}_0}{\mathrm{dt}} = 0$$

$$\frac{\mathrm{R}}{\mathrm{L}}\mathrm{i}_0 + \frac{\mathrm{d}\mathrm{i}_0}{\mathrm{dt}} = 0$$

$$\left(\frac{\mathrm{R}}{\mathrm{L}} + \mathrm{p}\right)\mathrm{i}_0 = 0$$

$$\text{CF} = K_1 \cdot e^{-(R_a/L_a)t}$$

$$= K_1 \cdot e^{-(R_a/\omega L_a)\omega t} = K_1 \cdot e^{-\omega t \cot \phi}$$

$$\left[\because \quad \phi = \tan^{-1}\left(\frac{X}{R}\right) \quad X = \omega L \quad \phi = \tan^{-1}\left(\frac{\omega L_a}{R_a}\right)\right]$$

PI_1 is

$$\left(D + \frac{R_a}{L_a}\right) i_a = \frac{V_m}{L_a} \sin \omega t$$

$$PI_1 = \frac{V_m}{Z} \sin(\omega t - \phi)$$

where $Z = \sqrt{R_a^2 + (\omega L_a)^2}$ and $\phi = \tan^{-1}\left(\frac{\omega L_a}{R_a}\right)$

PI_2 is

$$\left(D + \frac{R_a}{L_a}\right) i_a = -\frac{E_b}{L_a}$$

$$i_a = -\frac{E_b}{L_a} \cdot \frac{1}{[D + (R_a/L_a)]}$$

$$= -\frac{E_b}{L_a \cdot (R_a/L_a)} \cdot \left[\frac{1}{1 + \{D(L_a/R_a)\}}\right]$$

$$= -\frac{E_b}{R_a}\left(1 - D\frac{L_a}{R_a} + \cdots\right)$$

$$\therefore \qquad PI_2 = -\frac{E_b}{R_a}$$

$$PI = PI_1 + PI_2 = \frac{V_m}{Z} \sin(\omega t - \phi) - \frac{E_b}{R_a} \tag{1.19}$$

The solution of Eq. (1.18) is

$$\therefore \qquad i_a = \frac{V_m}{Z} \sin(\omega t - \phi) - \frac{E_b}{R_a} + K_1 \cdot e^{-\omega t \cot \phi} \tag{1.20}$$

where K_1 = constant.

The first term of the preceding equation indicates the armature current due to the input supply voltage, the second term due to back emf and the third term due to the transient component of current. The constant K_1 can be evaluated by using the initial condition: when $\omega t = \alpha$, $i_a = 0$. Thus

$$0 = \frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a} + K_1 . e^{-\alpha \cot \phi}$$

$$K_1 . e^{-\alpha \cot \phi} = \frac{V_m}{Z} \cdot \sin(\alpha - \phi) + \frac{E_b}{R_a}$$

$$K_1 = -\left[\frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a}\right] . e^{\alpha \cot \phi} \tag{1.21}$$

Substituting K_1 from Eq. (1.21) in Eq. (1.20), we get

$$i_a = \left[\frac{V_m}{Z} \cdot \sin(\omega t - \phi) - \frac{E_b}{R_a}\right] - \left[\frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a}\right] e^{\alpha \cot \phi} . e^{-\omega t \cot \phi} \; i_a$$

$$i_a = \left[\frac{V_m}{Z} \cdot \sin(\omega t - \phi) - \frac{E_b}{R_a}\right] - \left[\frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a}\right] e^{-(\omega t - \alpha) \cot \phi} \tag{1.22}$$

Substituting $\omega t = \pi$ in Eq. (1.22), we get

$$\therefore \qquad i_a(\pi) = \left[\frac{V_m}{Z} \cdot \sin(\pi - \phi) - \frac{E_b}{R_a}\right] - \left[\frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a}\right] e^{-(\pi - \alpha) \cot \phi} \tag{1.23}$$

Interval II $\pi \le \omega t \le \beta$ (Freewheeling): During this period, the freewheeling diode acting takes place.

$$R_a i_a + L_a \frac{di_a}{dt} + E_b = 0 \tag{1.24}$$

or

$$\frac{di_a}{dt} + \frac{R_a}{L_a} i_a = -\frac{E_b}{L_a}$$

$$i_a = K_2 \cdot e^{-(R_a/L_a)t} = K_2 \cdot e^{-\omega t \cot \phi}$$

PI is

$$i_a = -\frac{E_b}{L_a}\left[\frac{1}{D + (R_a/L_a)}\right]$$

$$= -\frac{E_b}{R_a}\left(1 - D \cdot \frac{L_a}{R_a} + \cdots\right)$$

$$= -\frac{E_b}{R_a}$$

$\therefore$ $$i_a = K_2 \cdot e^{-\omega t \cot \phi} - \frac{E_b}{R_a} \tag{1.25}$$

For initial condition $\omega t = \pi$,

$$i_a(\pi) = K_2 \cdot e^{-\pi \cot \phi} - \frac{E_b}{R_a} \tag{1.26}$$

or $$K_2 \cdot e^{-\pi \cot \phi} = \frac{E_b}{R_a} + i_a(\pi)$$

Substituting $i_a(\pi)$ from Eq. (1.23) in the preceding equation, we get

$$K_2 \cdot e^{-\pi \cot \phi} = \frac{E_b}{R_a} + \left[\frac{V_m}{Z} \cdot \sin(\pi - \phi) - \frac{E_b}{R_a}\right] - \left[\frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a}\right] e^{-(\pi - \alpha)\cot \phi}$$

$$K_2 \cdot e^{-\pi \cot \phi} = \frac{E_b}{R_a} + \frac{V_m}{Z}\left[\sin \phi - \sin(\alpha - \phi) \cdot e^{-(\pi - \alpha)\cot \phi}\right] - \frac{E_b}{R_a} + \frac{E_b}{R_a} \cdot e^{-(\pi - \alpha)\cot \phi}$$

$$K_2 \cdot e^{-\pi \cot \phi} = \frac{V_m}{Z}\left[\sin \phi - \sin(\alpha - \phi) \cdot e^{-(\pi - \alpha)\cot \phi}\right] + \frac{E_b}{R_a} \cdot e^{-(\pi - \alpha)\cot \phi}$$

$$\therefore \quad K_2 = \frac{V_m}{Z}\left[e^{\pi \cot \phi} \cdot \sin \phi - e^{\alpha \cot \phi} \sin(\alpha - \phi)\right] + \frac{E_b}{R_a} \cdot e^{\alpha \cot \phi} \tag{1.27}$$

Substituting K_2 from Eq. (1.27) in Eq. (1.26), we get

$$i_a = \frac{V_m}{Z}\left[e^{\pi \cot \phi} \cdot \sin \phi - e^{\alpha \cot \phi} \sin(\alpha - \phi)\right] \cdot e^{-\omega t \cot \phi} + \frac{E_b}{R_a} \cdot e^{\alpha \cot \phi} \cdot e^{-\omega t \cot \phi} - \frac{E_b}{R_a}$$

$$i_a = \frac{V_m}{Z}\left[e^{-(\omega t - \pi)\cot \phi} \cdot \sin \phi - e^{-(\omega t - \alpha)\cot \phi} \sin(\alpha - \phi)\right] - \frac{E_b}{R_a}[1 - e^{-(\omega t - \alpha)\cot \phi}]$$

For $\pi \le \omega t \le \beta$, when $\omega t = \beta$ and $i_a = 0$,

$$0 = \frac{V_m}{Z}[e^{-(\beta - \pi)\cot\phi} \cdot \sin\phi - e^{-(\beta-\alpha)\cot\phi} \sin(\alpha - \phi)] - \frac{E_b}{R_a}[1 - e^{-(\beta-\alpha)\cot\phi}] \quad (1.28)$$

By solving non-linear Eq. (1.28), the value for angle β can be obtained (by using iterative methods).

Interval III $\beta \le \omega t \le \pi + \alpha$ (Zero current interval): None of the devices are in conducting mode, i.e.,

$$i_a = 0 \qquad V_a = E_b$$

since

$$V_a = E_b + I_a \cdot R_a \quad (1.29)$$

From the discontinuous waveform,

$$\begin{aligned} V_a = V_m \sin\omega t \qquad & \text{for } \alpha \le \omega t \le \pi \\ = 0 \qquad & \text{for } \pi \le \omega t \le \beta \\ = E_b \qquad & \text{for } \beta \le \omega t \le \pi + \alpha \end{aligned}$$

$$V_a = \frac{1}{\pi}\left(\int_\alpha^\pi V_m \cdot \sin\omega t \cdot d\omega t + \int_\beta^{\pi+\alpha} E_b \cdot d\omega t\right)$$

$$= \frac{V_m}{\pi}[-\cos\omega t]_\alpha^\pi + \frac{E_b}{\pi}[\omega t]_\beta^{\pi+\alpha}$$

$$V_a = \frac{V_m}{\pi}(1 + \cos\alpha) + \left(\frac{(\pi + \alpha - \beta)\cdot E_b}{\pi}\right) \quad (1.30)$$

From Eqs. (1.29) and (1.30), we have

$$\frac{V_m}{\pi}(1+\cos\alpha)+\frac{E_b}{\pi}(\pi+\alpha-\beta)=E_b+I_a\cdot R_a$$

$$\frac{E_b}{\pi}(\pi+\alpha-\beta)=-\frac{V_m}{\pi}(1+\cos\alpha)+I_a\cdot R_a$$

$$\frac{E_b}{\pi}(\pi+\alpha-\beta-\pi)=-\frac{V_m}{\pi}(1+\cos\alpha)+I_a\cdot R_a$$

$$\frac{E_b}{\pi}(\alpha-\beta)=-\frac{V_m}{\pi}(1+\cos\alpha)+I_a\cdot R_a$$

$$E_b=\frac{V_m}{\beta-\alpha}(1+\cos\alpha)-\frac{I_a\cdot R_a\cdot\pi}{\beta-\alpha}$$

$\therefore$

$$K\cdot\omega_m=\frac{V_m}{\beta-\alpha}(1+\cos\alpha)-\frac{I_a\cdot R_a\cdot\pi}{\beta-\alpha}$$

$$\omega_m = \frac{V_m}{K \cdot (\beta - \alpha)}(1 + \cos \alpha) - \frac{T \cdot R_a \cdot \pi}{K^2(\beta - \alpha)} \tag{1.31}$$

The boundary between continuous and discontinuous conduction is reached when $\beta = \pi + \alpha$. Substituting $\beta = \pi + \alpha$ in Eq. (1.28) gives the critical speed ω_{mc}, which separates continuous conduction from discontinuous conduction for a given α.

$$\therefore \qquad 0 = \frac{V_m}{Z}[e^{-(\beta - \pi)\cot \phi} \cdot \sin \phi - e^{-(\beta - \alpha)\cot \phi} \sin (\alpha - \phi)] - \frac{E_b}{R_a}[1 - e^{-(\beta - \alpha)\cot \phi}]$$

$$\frac{E_b}{R_a}[1 - e^{-(\beta - \alpha)\cot \phi}] = \frac{V_m}{Z}[e^{-(\beta - \pi)\cot \phi} \cdot \sin \phi - e^{-(\beta - \alpha)\cot \phi} \sin (\alpha - \phi)]$$

$$E_b = \frac{R_a}{Z} \cdot \frac{V_m[e^{-(\beta - \pi)\cot \phi} \cdot \sin \phi - e^{-(\beta - \alpha)\cot \phi} \cdot \sin (\alpha - \phi)]}{[1 - e^{-(\beta - \alpha)\cot \phi}]}$$

Substituting $\beta = \pi + \alpha$, we get

Substituting $\beta = \pi + \alpha$, we get

$$K \cdot \omega_{\text{mc}} = \frac{R_a}{Z} \cdot \frac{V_m[e^{-(\pi + \alpha - \pi)\cot\phi} \cdot \sin\phi - e^{-(\pi + \alpha - \alpha)\cot\phi} \cdot \sin(\alpha - \phi)]}{[1 - e^{-(\pi + \alpha - \alpha)\cot\phi}]}$$

$$\omega_{\text{mc}} = \frac{R_a}{Z} \cdot \frac{V_m[e^{-\alpha\cot\phi} \cdot \sin\phi - e^{-\pi\cot\phi} \cdot \sin(\alpha - \phi)]}{[1 - e^{-\pi\cot\phi}] \cdot K} \tag{1.32}$$

Speed–torque characteristics

Speed–torque curves are shown in Fig. 1.14. The no-load speed is given by the equation $\omega_m = V_m/K$ for $0 \le \alpha \le \pi/2$ and V_m/K (sin α) for $\pi/2 \le \alpha \le \pi$. The operation of the drive, which operates in quadrant-I only, is represented by the equivalent circuit of Fig. 1.10. Figure 1.13

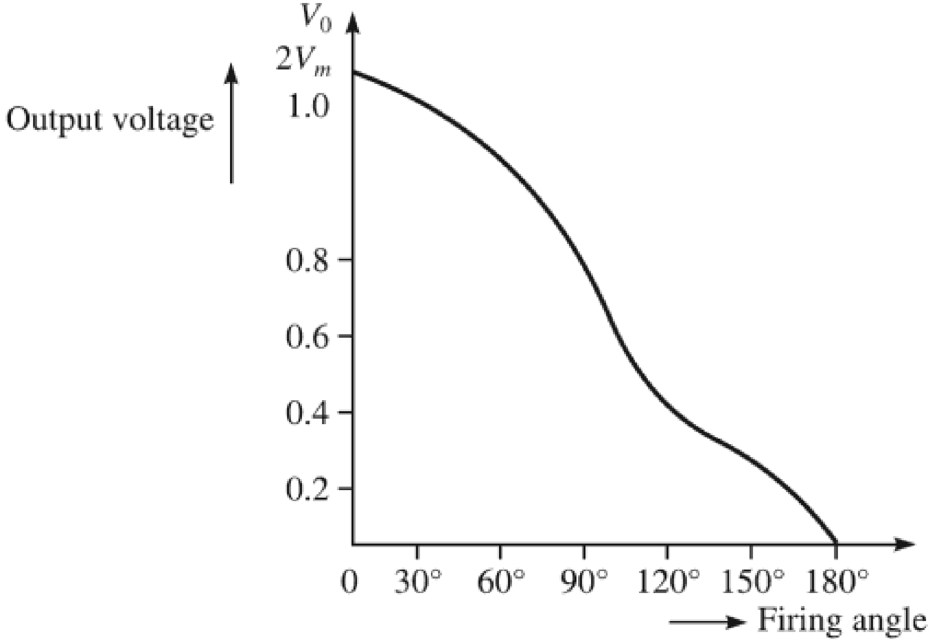


Fig. 1.13 Armature voltage versus firing angle.

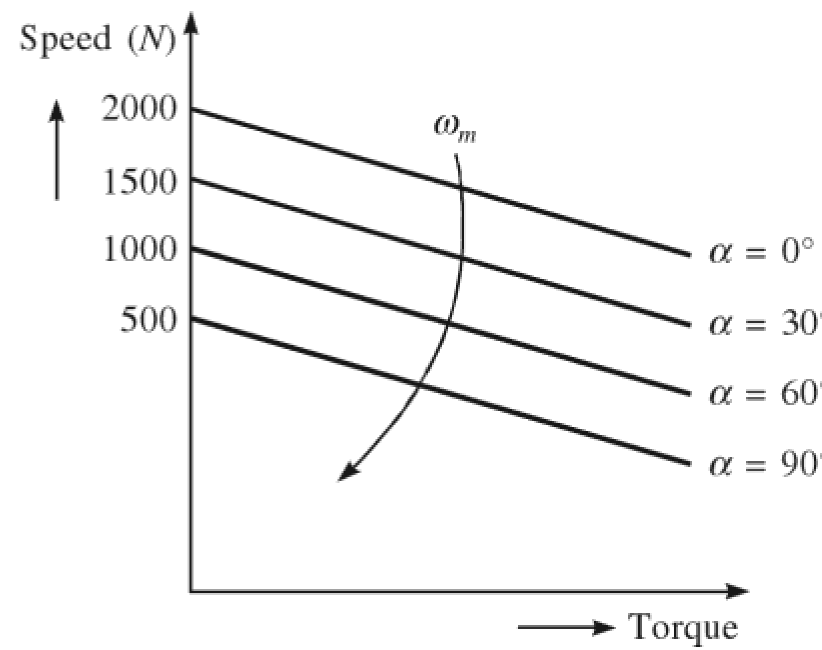


Fig. 1.14 Speed-torque characteristics.

Problem 1

A single-phase, 230 V, 50 Hz supply feeds a separately excited dc motor through two single-phase semi-converters, one for the field and the other for the armature. The firing angle for the semiconverter in field circuit is zero, the field resistance is 200 Ω and the armature resistance R_a is 0.3 Ω. The load torque is 50 N-m at 900 rpm, the voltage constant is 0.8 V/A-rad/s and the torque constant is 0.8 N-m/A^2. Assume that the armature and field currents are continuous and constant, and neglect the losses. Find the following:

(a) The field current

(b) The firing angle of semi-converters in the armature circuit

(c) The power factor of semi-converters in the armature circuit.

Since the firing angle of the converters in the field circuit is zero,

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

$$I_f = \frac{V_f}{R_f}$$

Torque $T = K_t I_f I_a$

$$I_a = \frac{T}{K_t \cdot I_f}$$

$$\omega = \frac{2\pi N}{60}$$

$$E_b = K_t I_f \omega$$

$$V_a = E_b + I_a R_a$$

$$V_a = \frac{V_m}{\pi}(1 + \cos\ \alpha_a)$$

Power output of converts in the armature circuit

$$V_a I_a$$

$$\text{Input current} = \left[\frac{2}{2\pi}\left(\int_{\alpha_a}^{\pi} I_a^2 \, d\omega t\right)\right]^{1/2}$$

$$= \frac{\sqrt{I_a^2}}{\pi}\left[\int_{\alpha_a}^{\pi} d\omega t\right]^{1/2} = \frac{I_a}{\pi}\left[[t]_{\alpha_a}^{\pi}\right]^{1/2}$$

$$= I_a\left(\frac{\pi - \alpha_a}{\pi}\right)^{1/2}$$

Input VA =

Input power factor, pf =

Problem-2

Two independent 1-ϕ semiconverters are supplying the armature and field circuits of a separately excited dc motor for controlling its speed. The firing angle of the converter supplying the field adjusted such that maximum field current flows. The machine parameters are: armature resistance = 0.25 Ω, field circuit resistance = 147 Ω, motor voltage constant K_v = 0.7032 V/A-rad/s. The load torque is T = 45 N-m at 1000 rpm. The converters are fed from a 208 V, 50 Hz ac supply, and the friction and windage losses are neglected. The inductance of the field and armature circuits is sufficient to make the armature and field current continuous and ripple-free. Determine

(a) The field current

(b) The delay angle of the armature converters

(c) The input power factor of armature circuit converters.

Problem-3

A 1-ϕ half-controlled converter is fed from a 120 V, 60 Hz supply and provides a variable dc voltage at the terminals of a dc motor. The thyristor is triggered continuously by a dc signal. The resistance of armature circuit is 10 Ω. Because of fixed motor excitation and high inertia, the motor speed is considered constant, so that the back emf is 60 V. Find the average value of the armature current, neglecting armature inductance.

$$V_{\text{rms}} = 120 \text{ V}$$

$$V_{\max} = 120\sqrt{2} = 169.7 \text{ V}$$

$$R_a = 10\ \Omega \quad \text{and} \quad \alpha = 0^\circ$$

$$f = 60 \text{ Hz}$$

$$E_b = 60 \text{ V}$$

$$V_a = \frac{V_m}{\pi}(1 + \cos\alpha)$$

$$V_a = E_b + I_a R_a$$

Problem-4

A separately excited dc motor running at 1200 rpm is operated from a 1-ϕ, half-controlled bridge with input voltage 320 sin 310t, emf 100 V and armature resistance 5 ohms. SCRs are fired at $\alpha = 45°$ for every half cycle. Calculate

(i) The armature current

(ii) The motor torque.

$$V_a = \frac{V_m}{\pi}(1 + \cos \alpha) = E_b + I_a R_a$$

$$E_b = K_t \phi \omega$$

$$K_t \phi = \frac{E_b}{\omega}$$

$$T = K_t \phi I_a$$

Problem-5

A 200 V, 1000 rpm, 13 A separately excited dc motor has armature circuit resistance and inductance of 3 ohm and 100 mH respectively. It is fed from a 1-ϕ half-controlled rectifier with ac source voltage of 230 V, 50 Hz. Calculate

(i) The motor torque for $\alpha = 30^\circ$ and speed = 400 rpm

(ii) The motor speed for $\alpha = 30^\circ$ and $T = 70$ N-m.

$$\omega_{mc} = \frac{R_a V_m}{KZ}\left[\frac{\sin\phi\, e^{-\alpha\cot\phi} - \sin(\alpha-\phi)\, e^{-\pi\cot\phi}}{1-e^{-\pi\cot\phi}}\right]$$

$$\alpha = 30^\circ = \frac{30\pi}{180} = 0.524 \text{ rad/s}$$

$$\phi = \tan^{-1}\left(\frac{2\pi fL}{R}\right)$$

$$e^{-\pi\cot\phi}$$

$$e^{-\alpha\cot\phi}$$

$$Z = \sqrt{R^2 + (2\pi fL)^2}$$

$$E_b = V_a - I_a R_a$$

$$K = \frac{E_b}{\omega_m}$$

$$V_a = \frac{V_m}{\pi}(1 + \cos \alpha)$$

$$T = KI_a = K\left(\frac{V_a - E_b}{R_a}\right)$$

(ii) Motor back emf for critical speed equal to 1149.67 rpm

$$E_c = \frac{1149.67}{1000} \times 161$$

Critical torque, $$T_c = K\left(\frac{V_a - E_b}{R_a}\right) = 1.537\left(\frac{193.2 - 185.1}{3}\right)$$

Since the motor torque of 70 N-m is greater than the critical torque T_c, the drive is operating in continuous conduction.

$$I_a = \frac{T}{K} = \frac{70}{1.53} \quad ;$$

$$E_b = V_a - I_a R_a$$

$$N = \frac{55.95}{162} \times 1000 = 345.37$$

Problem 6

A 230 V, 650 rpm, 100 A separately excited dc motor has armature circuit resistance and inductance of 0.08 Ω and 8 mH respectively. The motor is controlled by 1-ϕ half-controlled rectifier with source voltage of 230 V, 50 Hz. Identify the modes and calculate the speeds for

(a) $\alpha = 60°$ and torque 1000 N-m

(b) $\alpha = 120°$ and torque 1000 N-m.

Single phase Fully controlled Converter of Separately Excited dc Motor

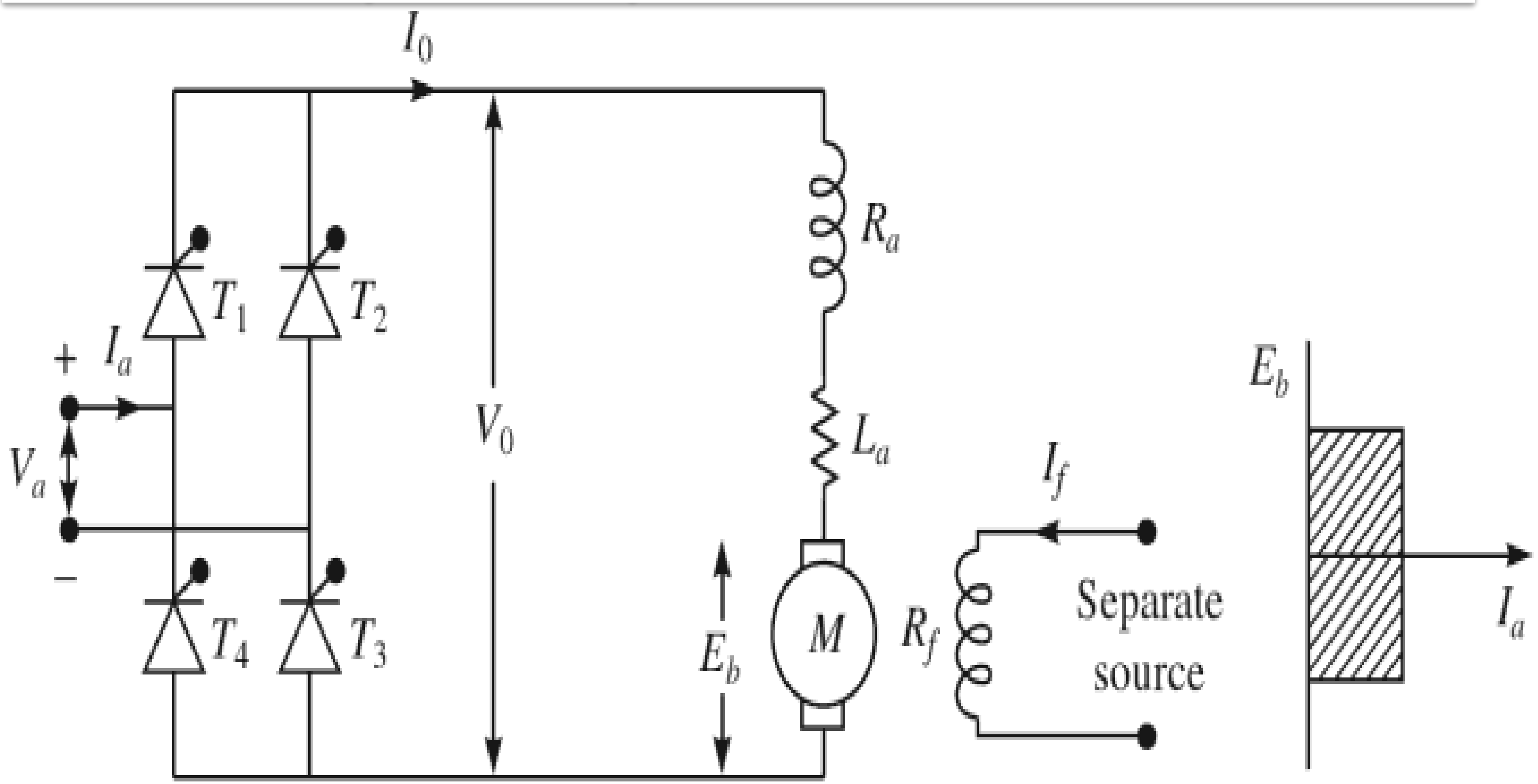


Fig. 1.15 Single-phase fully controlled converter of separately excited dc motor.

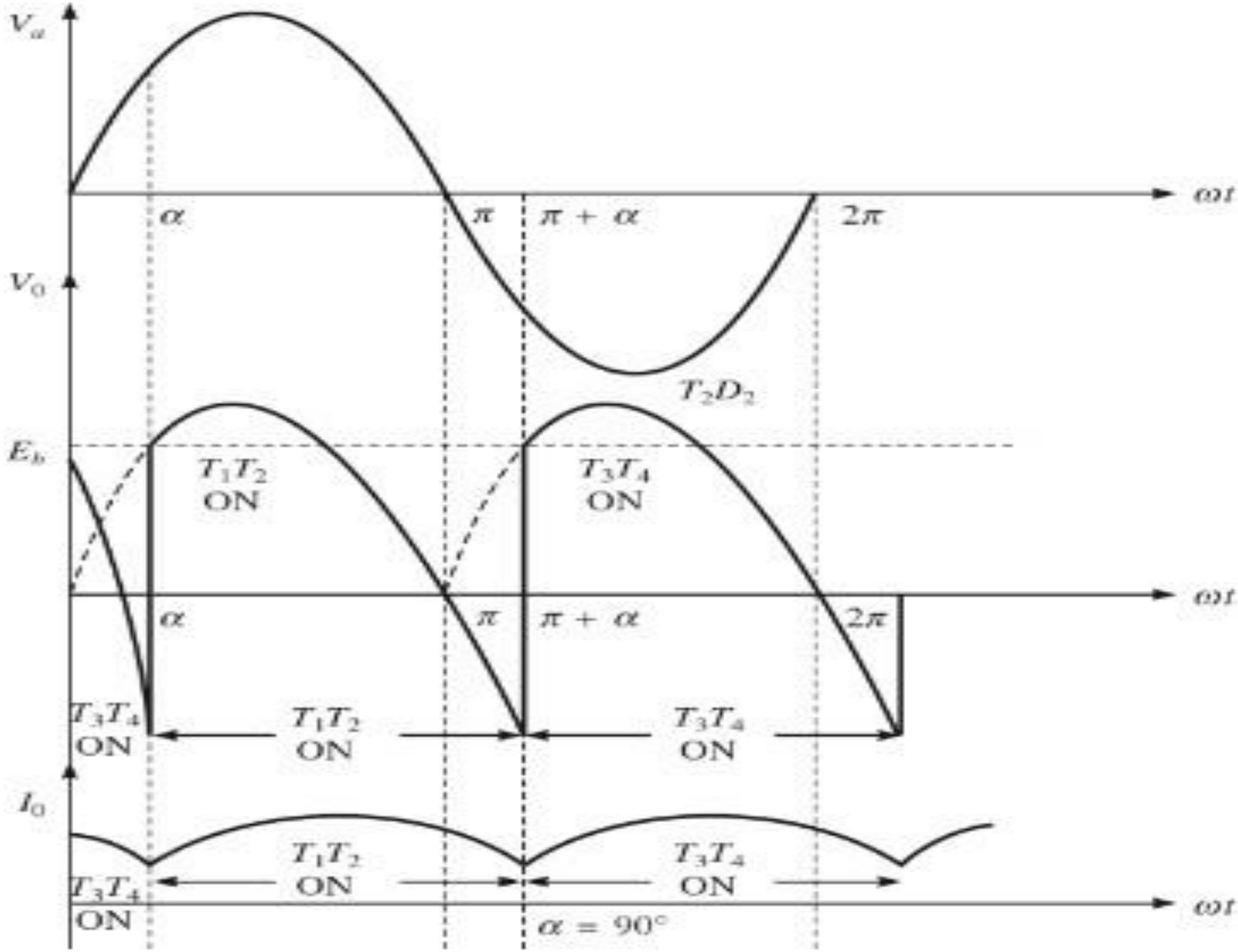


Fig. 1.16 Voltage and current waveforms in continuous conduction.

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b \qquad \text{for } \alpha \leq \omega t \leq (\pi + \alpha)$$

$$V_a = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d\omega t$$

$$= \frac{V_m}{\pi} (-\cos \omega t)_{\alpha}^{\pi+\alpha} = \frac{2V_m}{\pi} \cos \alpha$$

$$N = \frac{V_a - I_a R_a}{K\phi} = \frac{(2V_m / \pi)\cos\alpha - I_a R_a}{K\phi}$$

$$T \propto \phi \cdot i_a$$

$$T = K\phi \cdot i_a$$

$$i_a = \frac{T}{K\phi}$$

$$N = \frac{(2V_m / \pi)\cos\alpha}{K\phi} - \frac{R_a \cdot T}{(K\phi)^2}$$

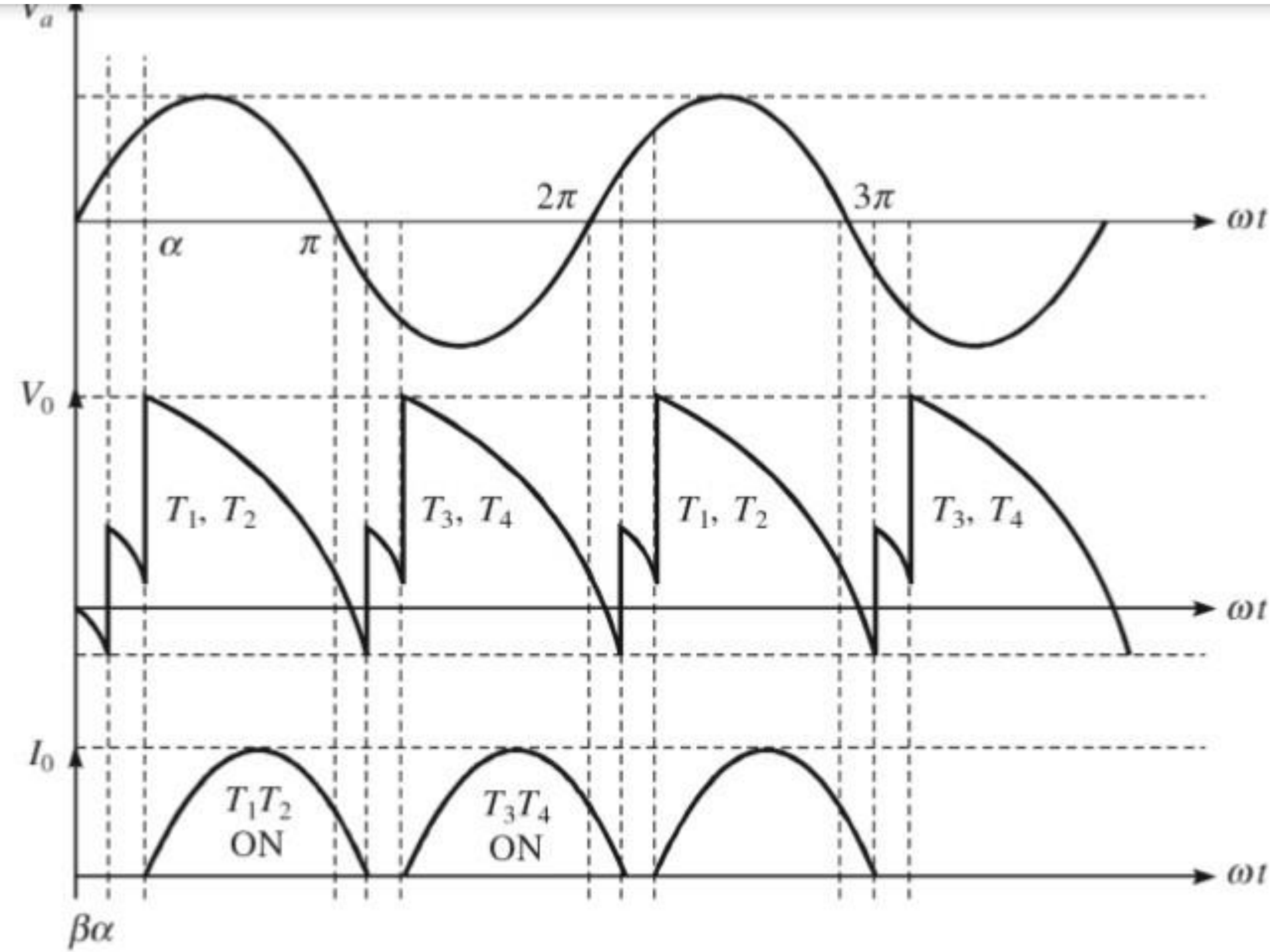


Fig. 1.17 Voltage and current waveforms for discontinuous conduction.

(i) Duty interval ($\alpha \le \omega t \le \beta$): The motor is connected to source voltage V_a.

(ii) Zero current interval ($\beta \le \omega t \le (\pi + \alpha)$): When $i_a = 0$, $V_a = E_b$.

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b = V_m \sin \omega t \qquad \text{for } \alpha \le \omega t \le \beta$$

$$V_a = E_b \text{ and } i_a = 0 \qquad \text{for } \beta \le \omega t \le (\pi + \alpha)$$

$$i_a = \frac{V_m}{Z} \sin(\omega t - \phi) - \frac{E_b}{R_a} + K_1 \cdot e^{-\omega t \cot \phi}$$

$$\text{where } Z_a = \sqrt{R_a^2 + (\omega L_a)^2}\ ;\ \text{and } \phi = \tan^{-1} \frac{\omega L_a}{R_a}.$$

Now, the constant K_1 can be evaluated by applying initial conditions $\omega t = \alpha$ and $i_a = 0$.

$$0 = \frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a} + K_1 \cdot e^{-\alpha \cot \phi}$$

$$K_1 \cdot e^{-\alpha \cot \phi} = -\frac{V_m}{Z} \sin(\alpha - \phi) + \frac{E_b}{R_a}$$

$$K_1 = -\left[\frac{V_m}{Z} \cdot \sin(\alpha - \phi) - \frac{E_b}{R_a}\right] \cdot e^{\alpha \cot \phi}$$

Substitute K_1 in the i_a equation, we get

$$i_a = \left[\frac{V_m}{Z}\cdot\sin(\omega t-\phi)-\frac{E_b}{R_a}\right]-\left[\frac{V_m}{Z}\cdot\sin(\alpha-\phi)-\frac{E_b}{R_a}\right]e^{\alpha\cot\phi}\cdot e^{-\omega t\cot\phi}$$

$$i_a = \left[\frac{V_m}{Z}\cdot\sin(\omega t-\phi)-\frac{E_b}{R_a}\right]-\left[\frac{V_m}{Z}\cdot\sin(\alpha-\phi)-\frac{E_b}{R_a}\right]e^{-(\omega t-\alpha)\cot\phi}\ i_a$$

$$i_a = \frac{V_m}{Z}\left[\sin(\omega t-\phi)-\sin(\alpha-\phi)\cdot e^{-(\omega t-\alpha)\cot\phi}\right]-\frac{E_b}{R_a}\left[1-e^{-(\omega t-\alpha)\cot\phi}\right]$$

for $\alpha \leq \omega t \leq \beta$

Since $i_a(\beta) = 0$, i.e., $\omega t = \beta$, we substitute $i_a = 0$

$$0 = \left[\frac{V_m}{Z}\cdot\sin(\beta-\phi)-\frac{E_b}{R_a}\right]-\left[\frac{V_m}{Z}\cdot\sin(\alpha-\phi)-\frac{E_b}{R_a}\right]e^{-(\beta-\alpha)\cot\phi}$$

$$\frac{V_m}{Z}\cdot\sin(\beta-\phi)-\frac{E_b}{R_a}=\left[\frac{E_b}{R_a}-\frac{V_m}{Z}\cdot\sin(\alpha-\phi)\right]e^{-(\beta-\alpha)\cot\phi}=0$$

$$V_a = \frac{1}{\pi}\left[\int_{\alpha}^{\beta} V_m \sin \omega t \, d\omega t + \int_{\beta}^{\pi+\alpha} E_b \cdot d\omega t\right]$$

$$= \frac{V_m}{\pi}[-\cos(\omega t)]_{\alpha}^{\beta} + \frac{E_b}{\pi}[\omega t]_{\beta}^{\pi+\alpha}$$

$$V_a = \frac{V_m(\cos\alpha - \cos\beta) + (\pi + \alpha - \beta)E_b}{\pi}$$

$$V_a = E_b + I_a R_a$$

$$\frac{V_m(\cos\alpha - \cos\beta) + (\pi + \alpha - \beta)E_b}{\pi} = E_b + I_a \cdot R_a$$

Substituting $E_b = K \cdot \omega_m$ and $T = K \cdot I_a$

$$\omega_m = \frac{V_m(\cos\alpha - \cos\beta)}{K(\beta - \alpha)} - \frac{\pi \cdot R_a}{K^2 \cdot (\beta - \alpha)} \cdot T$$

- Boundary condition is $\beta = (\pi + \alpha)$.

- Then the Critical Speed is

$$\omega_{\text{mc}} = \frac{R_a \cdot V_m}{Z \cdot K} \sin(\alpha - \phi) \left[\frac{1 + e^{-\pi \cot\phi}}{e^{-\pi \cot\phi} - 1} \right]$$

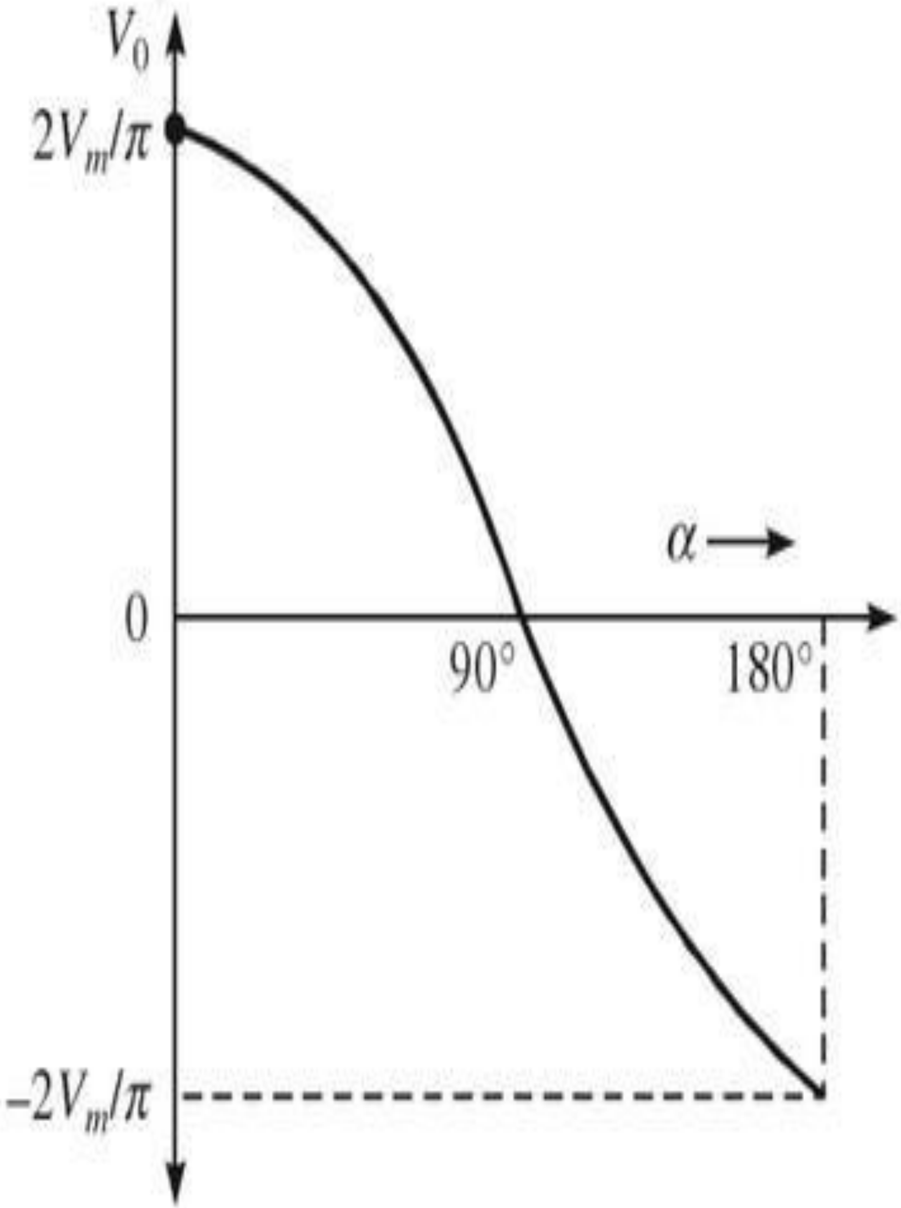


Fig. 1.18 Voltage versus firing angle waveform.

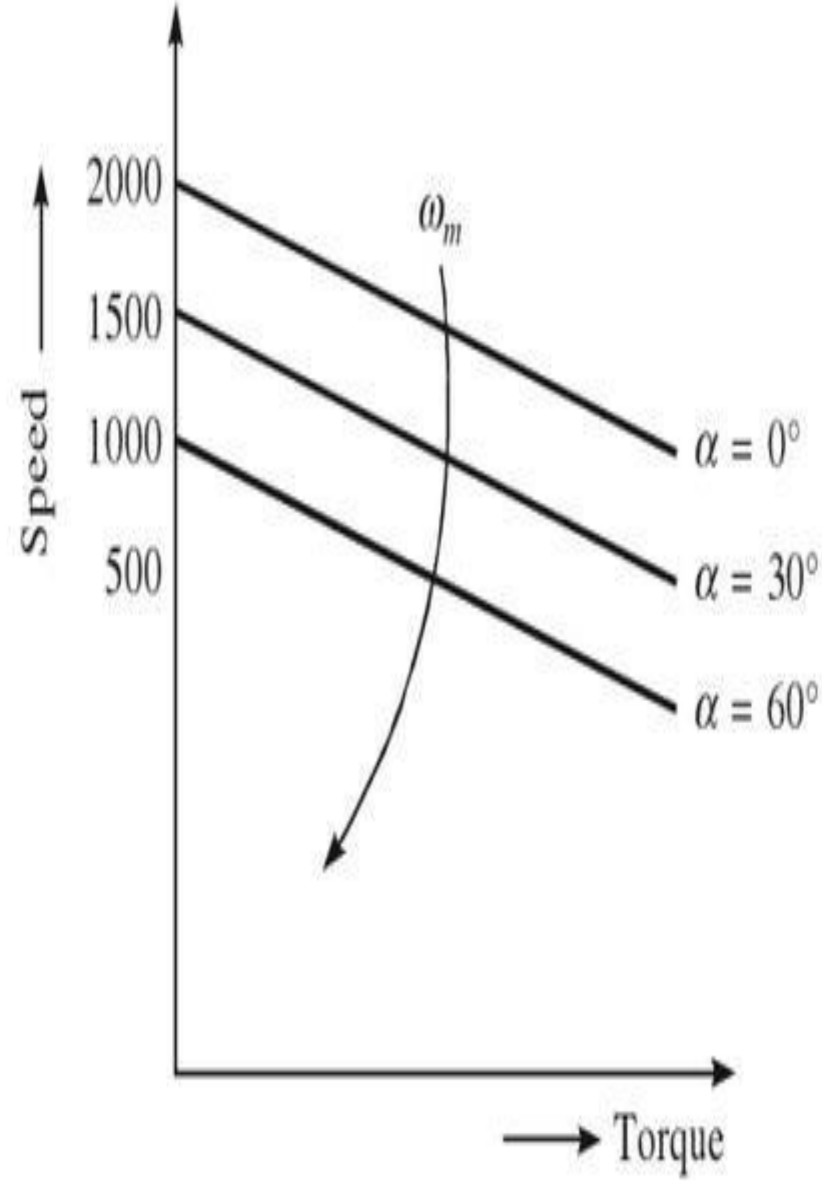


Fig. 1.19 Speed–torque characteristics.

Problem -7

A 230 V, 1-ϕ, 50 Hz supply feeds the armature and field circuits of a separately excited dc motor through two full converters. The firing angles of converters in the field circuit are zero. The armature and field resistances are 0.25 Ω and 200 Ω respectively. The torque and voltage constants are 1.1, the firing angle of converters in the armature circuit is 45° and the armature current is 50 A. Find the torque developed and the motor speed. Assume that the brush contact drop is 1 V/brush.

Problem -8

A 210 V, 1 HP separately excited dc motor running at 800 rpm is controlled by single-phase full converter. The motor rated armature current is 25 A, armature resistance $R_a = 0.5\ \Omega$. The ac supply voltage is 230 V, motor voltage constant $K_a\phi = 0.172$ V/rpm. To make the motor current continuous and ripple-free, assume that sufficient inductance is present in the armature circuit.

(a) For motoring action, determine motor torque, speed of motor, supply power factor for $\alpha = 60°$ and rated motor armature current.

(b) For regeneration action, motor back emf polarity is reversed by severing field excitation. Find the firing angle to keep motor current as valid value for power fed back to supply.

Problem -9

A 220 V, 750 rpm, 175 A separately excited dc motor has an armature resistance of 0.05 Ω and inductance of 0.85 mH and is controlled by a single-phase fully controlled rectifier with an ac source of 230 V, 50 Hz. (i) Calculate the motor torque for $\alpha = 60°$ and speed = 600 rpm.

Now, an external inductance of 5 mH is added to the armature circuit to reduce the region of discontinuous conduction. Calculate the torque for

(ii) $\alpha = 150°$ and speed = –400 rpm

(iii) $\alpha = 120°$ and speed = –600 rpm.

Problem-10

A 220 V, 1200 rpm, 15 A separately excited dc motor has armature resistance and inductance of 1.8 Ω and 32 mH respectively. The motor is controlled by a 1-ϕ fully controlled rectifier with an ac source voltage of 230V, 50Hz with rectified nodes. Calculate developed torques for

(i) $\alpha = 60°$ and speed = 450 rpm

(ii) $\alpha = 60$ and speed = 1500 rpm.

DC Series Motor

- In a series-connected dc motor drive, the field circuit is connected in series with the armature terminals, which provides for high speed and high starting torque.
- Some of the devices in which they are used are cranes, hoists, elevators and traction work.
- Speed control is very difficult with the series motor because any changes in the load current will immediately be reflected in a speed change, and hence all speed control systems will use separately excited motors. I
- n separately excited motors, a large back emf E, is always present even when the motor armature current is absent.
- The back emf tends to oppose the motor current and decays rapidly. This leads to discontinuity in motor current over a wide range of operations.
- In series motor, the back emf is proportional to the motor current.

- Therefore, back emf decreases with armature current and so the motor current tends to be continuous over a wide range of operations.
- In dc series motor drives, only at high speed and low current is the motor current likely to become discontinuous.
- The armature circuit resistance R and inductance La includes the resistance of the series field winding.
- Its back emf voltage is $E_b = K_a \phi N$
- In series motor, the flux has two components; one component, say ϕa, is produced by the armature current flowing through the series field winding, and the other component, say ϕres, is due to residual magnetism. The latter is small and can be assumed constant.

$$\phi = \phi_a + \phi_{res}$$

$$\phi_a = K_f i_a$$

$$E_b = K_a (K_f i_a + \phi_{rcs}) N$$

$$= K_a K_f i_a N + K_a \phi_{res} N$$

$$E_b = K_{af} i_a N + K_{rcs} N$$

If the flux ϕ_{rcs} is neglected, than its average torque is given by

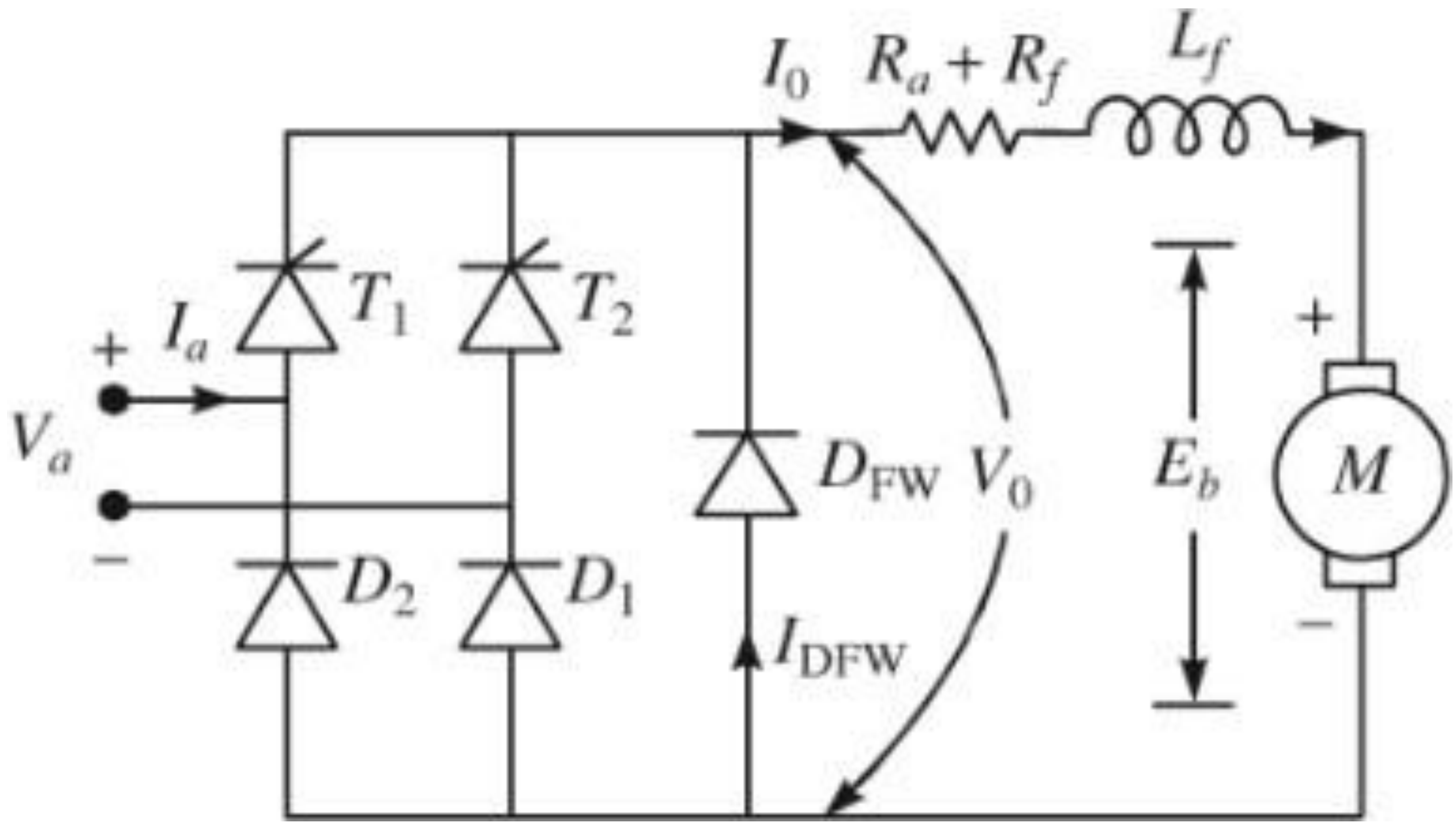
$$T = K_{af} I_{af}^2$$

The armature circuit voltage is

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b$$

$$V_a = R_a i_a + E_b$$

Single Phase Semi Controlled Converter of DC Series Motor



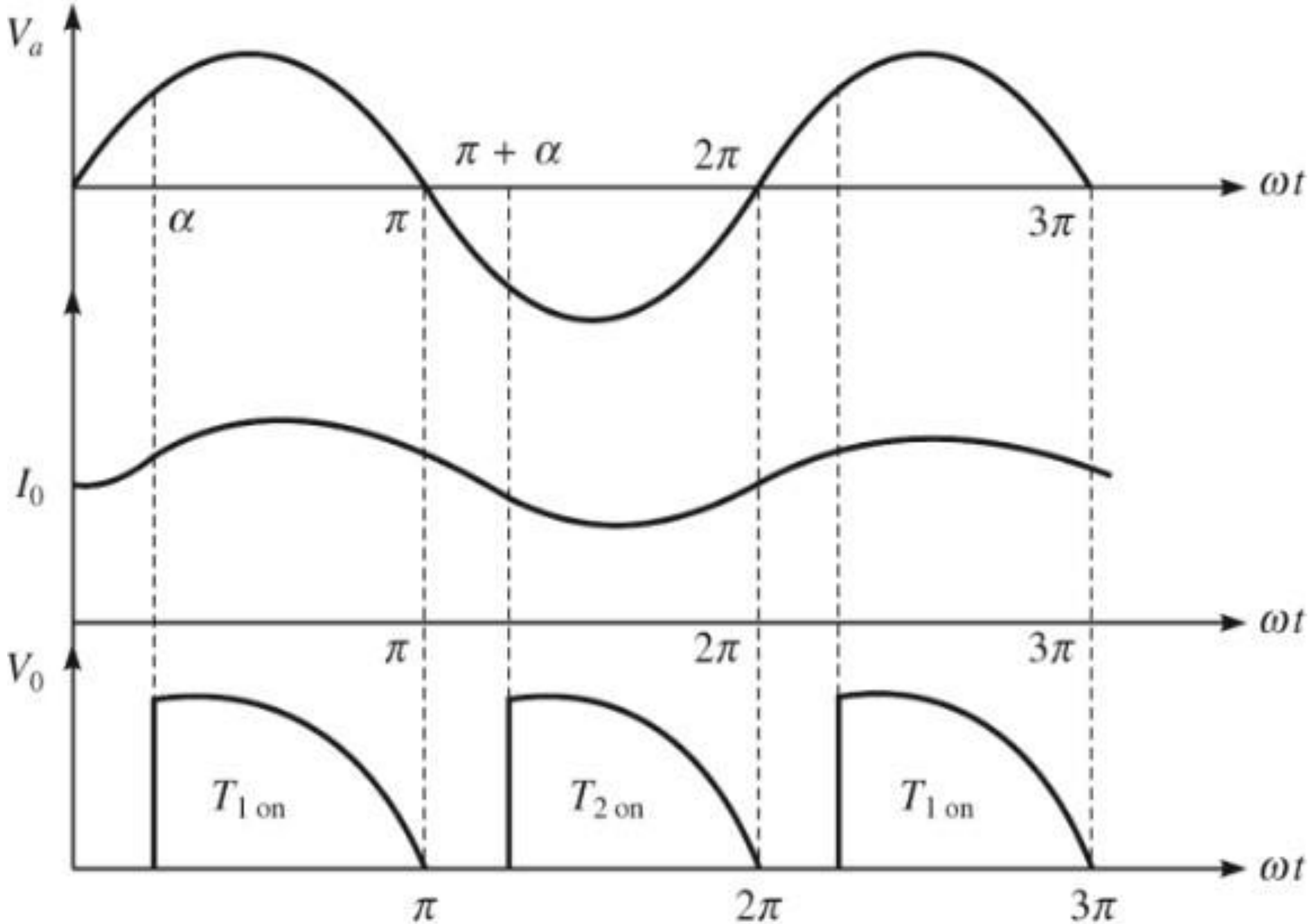


Fig. 1.21 Waveforms for continuous conduction.

$\alpha < \omega t < \pi.$

The armature loop equation is

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + E_b$$

$\pi < \omega t < (\pi + \propto)$

$$V_a = 0 = R_a i_a + L_a \frac{di_a}{dt} + E_b$$

The average dc output voltage across the motor terminals is given by

$$V_a = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin \omega t \, d\omega t = \frac{V_m}{\pi}(1 + \cos \alpha)$$

$$R_a I_a + K_{af} I_a N + K_{res} N = V_a = \frac{V_m}{\pi}(1 + \cos \alpha)$$

$$N = \frac{(V_m/\pi)(1 + \cos\alpha) - R_a I_a}{K_{\text{af}} I_a + K_{\text{res}}}$$

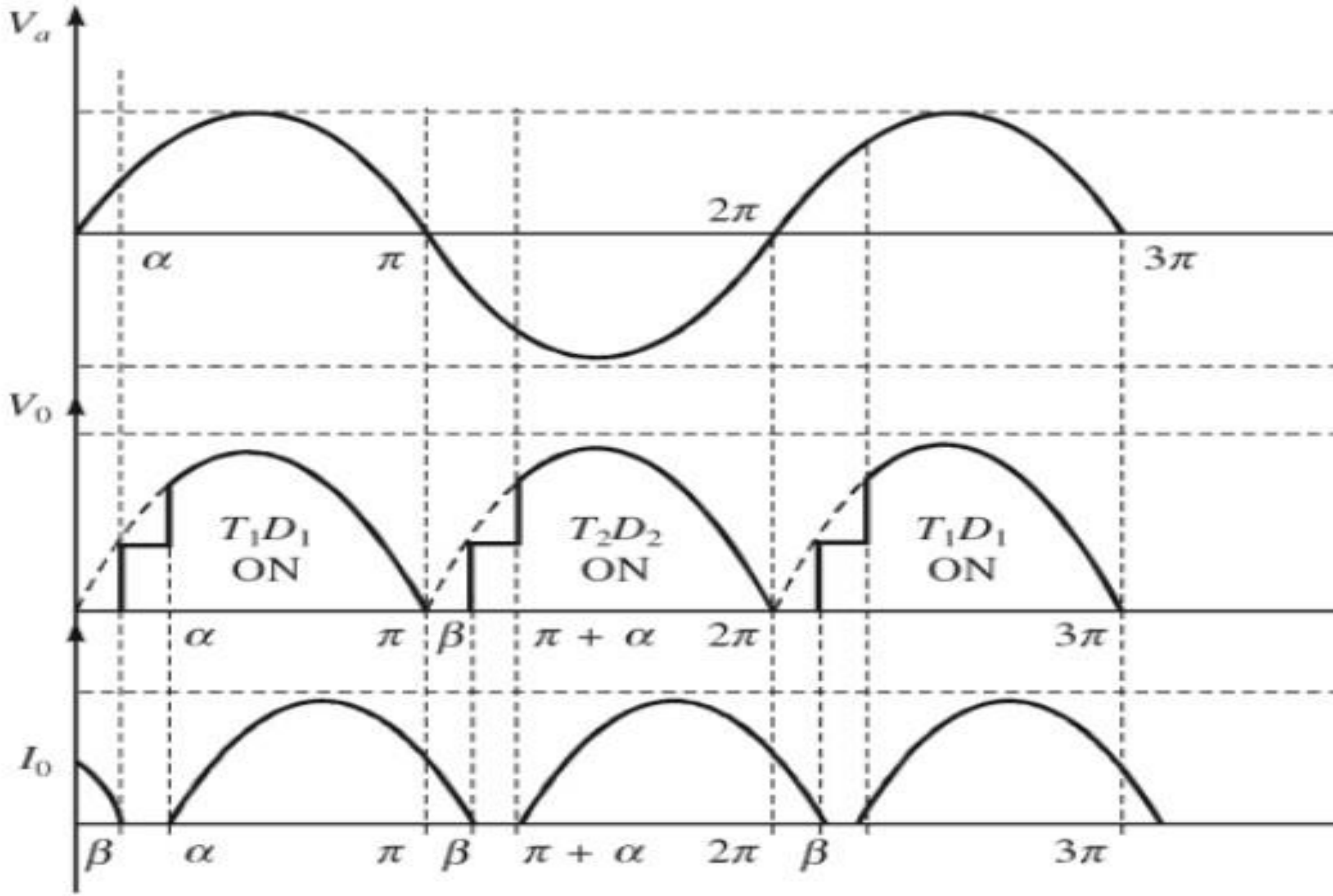
Since in series motor the torque developed is proportional to the square of the motor RMS current,

$$T \propto I_a^2$$

$$T \simeq K_{\text{af}} I_a^2$$

$$T \simeq K_{\text{af}} \left[\frac{(V_m/\pi)(1 + \cos\alpha) - K_{\text{res}} N}{R_a + K_{\text{af}} N} \right]^2$$

Discontinuous mode



Mode 1: During the interval $\alpha < \omega t < \pi$,

$$V_a = V_m \sin \omega t = R_a i_a + L_a \frac{di_a}{dt} + K_{af} i_a N + K_{res} N$$

The electrodynamic equation is

$$T = K_{af} I_{af}^2 = J \frac{d\omega}{dt} + B\omega + T_L$$

Mode 2: During the interval $\pi < \omega t < \beta$,

The freewheeling diode action will be absent if $\beta < \pi$, i.e.,

$$V_a = 0 = R_a i_a + L_a \frac{di_a}{dt} + K_{af} i_a N + K_{res} N$$

and its governing mechanical rotational system,

$$T = K_{af}\, i_a^2 + J\frac{d\omega}{dt} + B\omega + T_L$$

Mode 3: The motor coasts during the interval $\beta < \omega t < (\pi < \alpha)$.

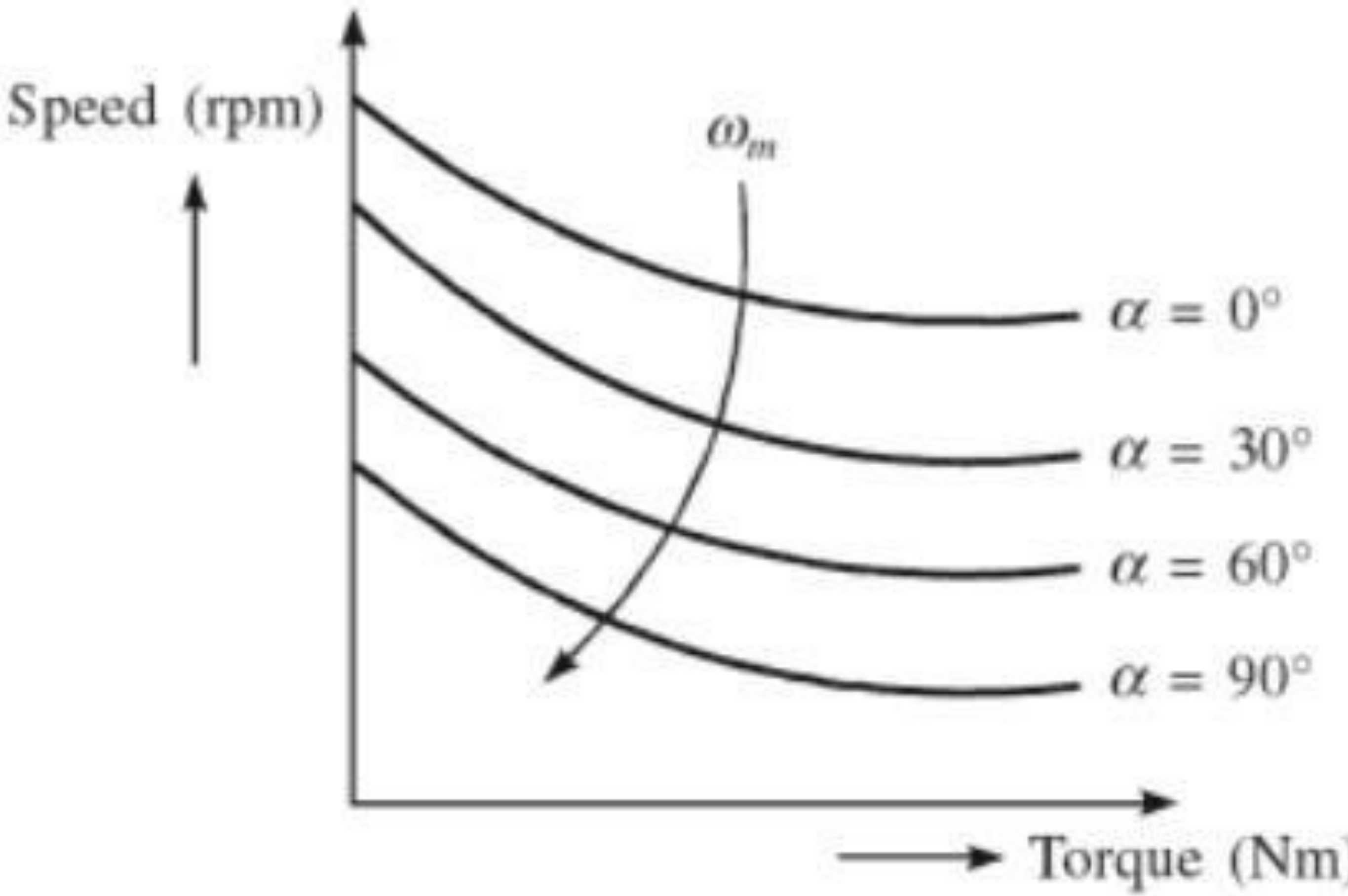
$$i_a = 0$$

$$T = 0 = J\frac{d\omega}{dt} + B\omega + T_L$$

The following sequence of steps are used to calculate the speed-torque characteristics for the firing angle taking into account:

(i) Nonlinearity of the magnetic circuit: A value is chosen for armature current. The corresponding value K is obtained from the magnetization characteristics of the motor.

(ii) For the known value of firing, calculate the output voltage from Eq. (1.15), depending upon the circuit used. Now N and T are obtained from Eqs. (1.58) and (1.59) respectively.



Speed (rpm)
ω_m
$\alpha = 0°$
$\alpha = 30°$
$\alpha = 60°$
$\alpha = 90°$
Torque (Nm)

Problem-11

The speed of a 20 HP, 210 V, 1000 rpm series dc motor is controlled by a semi-converter, the combined field and armature circuit resistance is 0.25 Ω, $K_{af} = 0.03$ N-m/A^2 and $K_{res} = 0.075$ V-s/rad. The supply voltage is 230 V. Assuming continuous and ripple-free motor current, determine the following for a firing angle $\alpha = 30°$ and speed $N = 1000$ rpm:

(i) The motor torque

(ii) The motor current

(iii) The supply power-factor.

Problem-12

A 18 HP, 210 V series dc motor running at 1300 rpm is controlled by 1-ϕ semi-converter, combined field and armature resistance is 0.75 Ω. The following are the motor constants: $K_{af} = 0.03$ N-m/A^2 and $K_{res} = 0.075$ V-s/rad. The supply voltage is 230 V. Determine

(i) motor torque
(ii) motor current
(iii) supply power factor

for $\alpha = 45°$ and speed 1500 rpm, assuming continuous and ripple-free motor current.

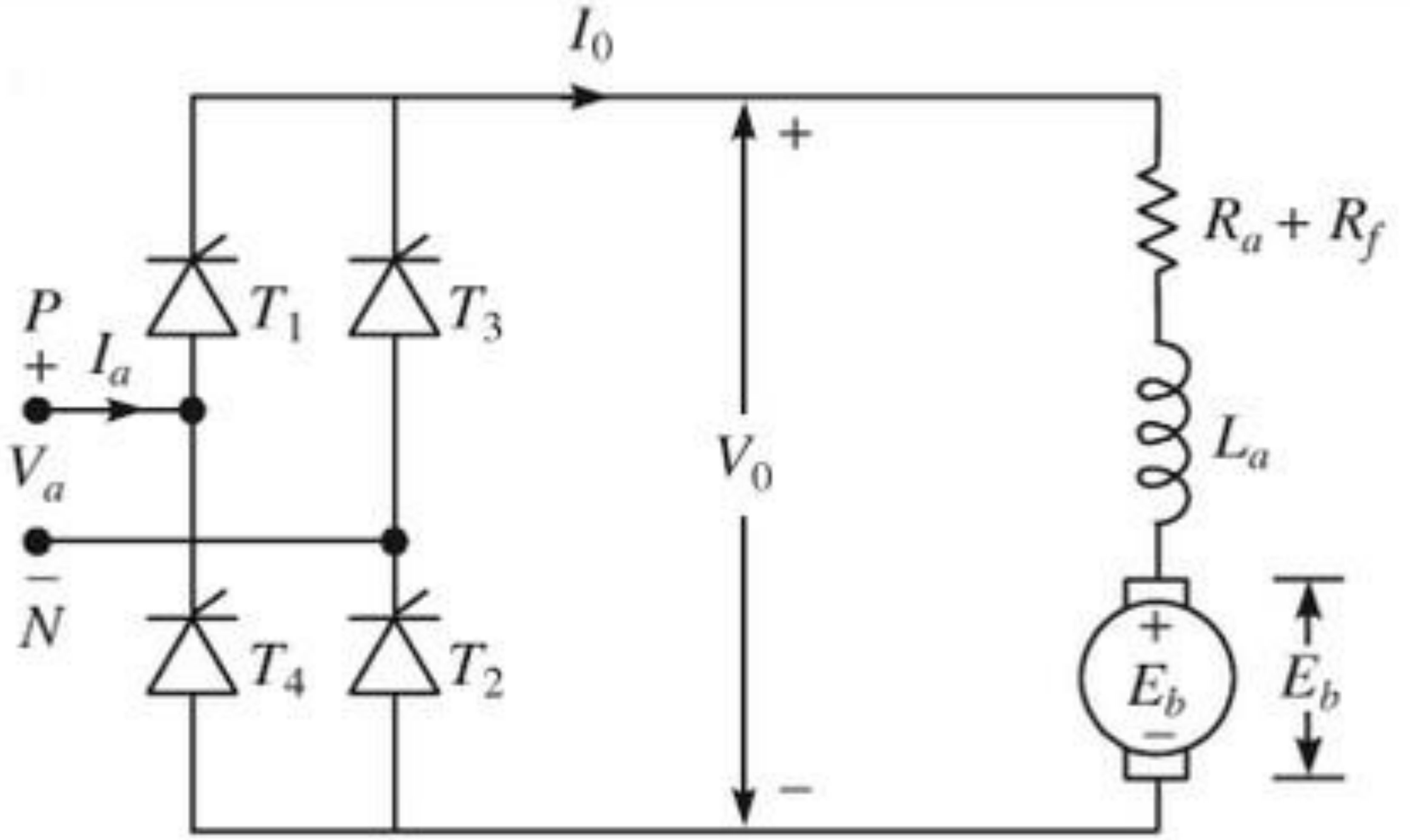
Problem-13

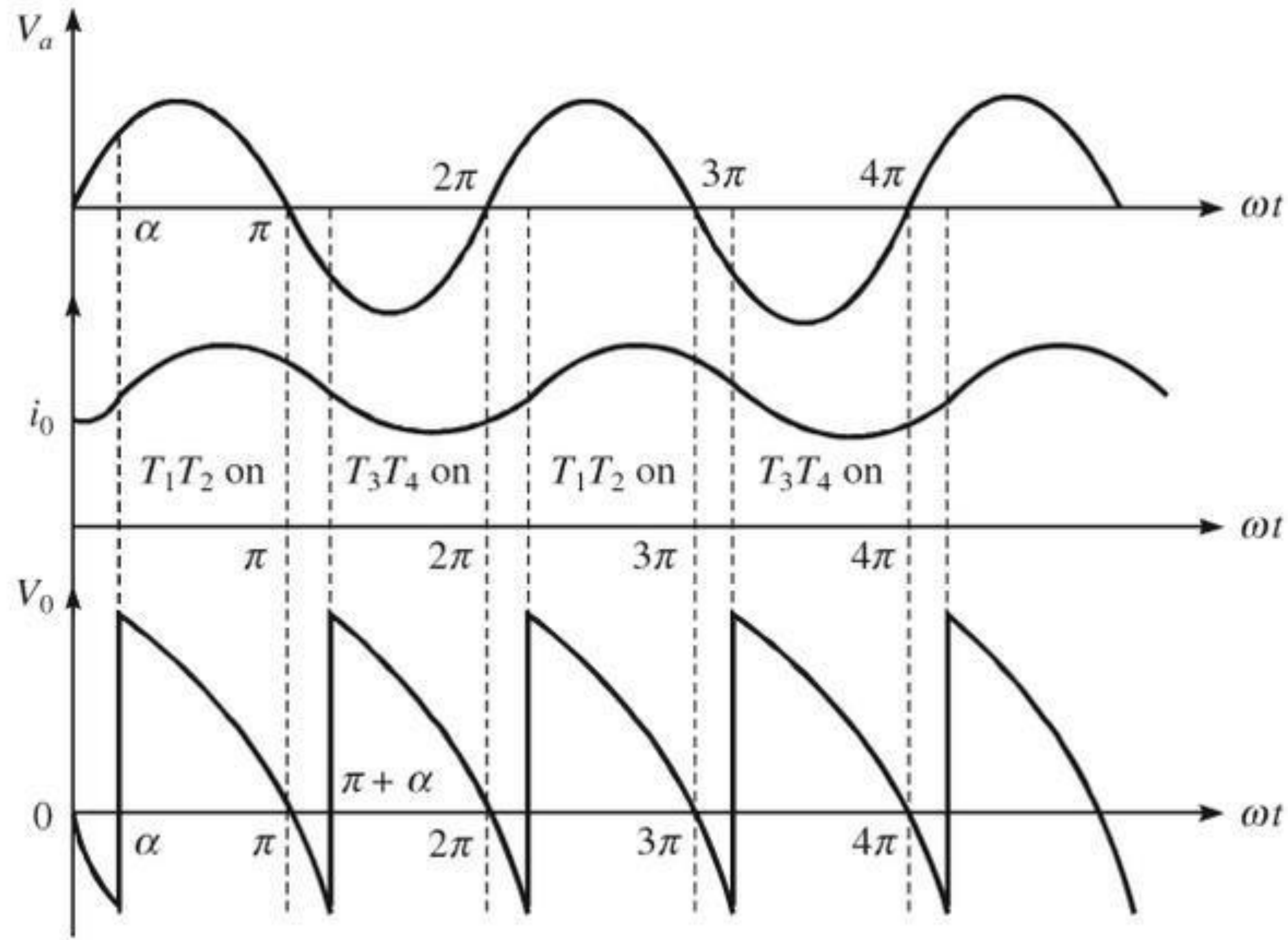
A single-phase semi-converter is used for controlling the speed of a 10 HP, 220 V, 900 rpm dc series motor. The total resistance of the field and armature circuit is 0.9 Ω. Assuming continuous current and speed of 900 rpm, obtain for an input voltage of 240 V the motor current and motor torque for a firing angle of 45°. Assume motor constant = 0.035 N-m/A^2.

(iii) supply power factor

for $\alpha = 45°$ and speed 1500 rpm, assuming continuous and ripple-free motor current.

Single Phase Fully Controlled Converter fed DC series Motor





Voltage and current waveforms for continuous conduction.

armature circuit equation for a full converter is as follows:

$$V_a = R_a I_a + L_a \frac{di_a}{dt} + E_b \qquad \alpha < \omega t < \pi + \alpha$$

The average motor terminal voltage is

$$V_0 = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_m \sin \omega t \, d\omega t$$

$$V_0 = \frac{2V_m}{\pi} \cos \alpha$$

$$R_a I_a + K_{\text{af}} I_a N + K_{\text{res}} N = \frac{2\sqrt{2} V_a}{\pi} \cos \alpha$$

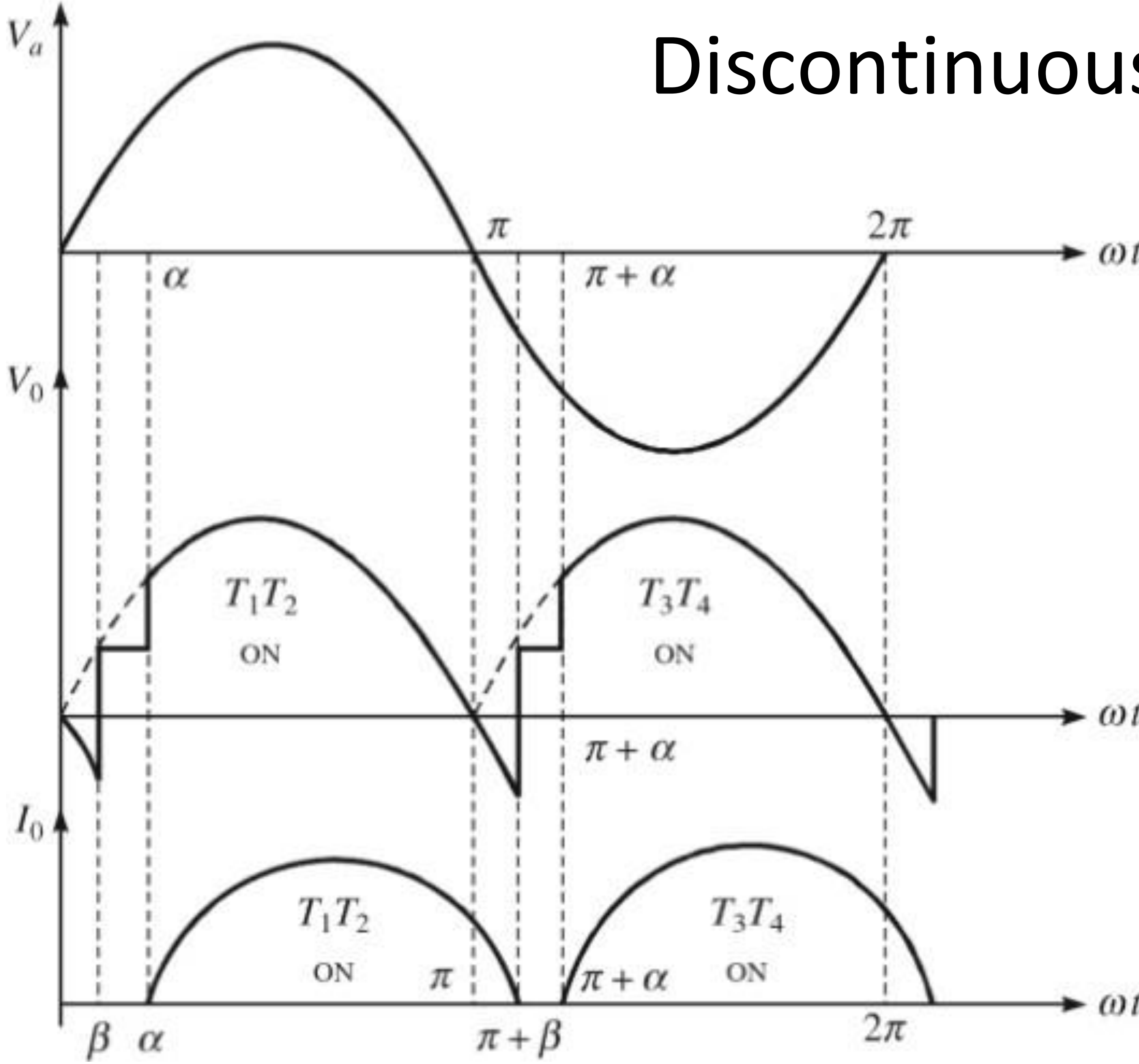
the average speed is

$$N = \frac{(2\sqrt{2}V_a/\pi)\cos\alpha - R_a I_a}{K_{af} I_a + K_{res}}$$

the torque developed is proportional to the square of the motor RMS current.

$$T \simeq K_{af}\left[\frac{(2\sqrt{2}V_s \cos\alpha/\pi) - K_{res}N}{R_a + K_{af}N}\right]^2$$

Discontinuous Mode



Mode 1: The thyristor conducts during the internal $\alpha < \omega t < \beta$. The voltage equation is

$$V_0 = \sqrt{2}\, V_s \sin \omega t = R_a i_a + L_a \frac{di_a}{dt} + K_{af} i_a N + K_{res} N$$

The electrodynamic equation is

$$T = K_{af} I_a^2 = J \frac{d\omega}{dt} + B\omega + T$$

Mode 2: During the interval $\pi < \omega t < \beta$, $V_0 = E_b$

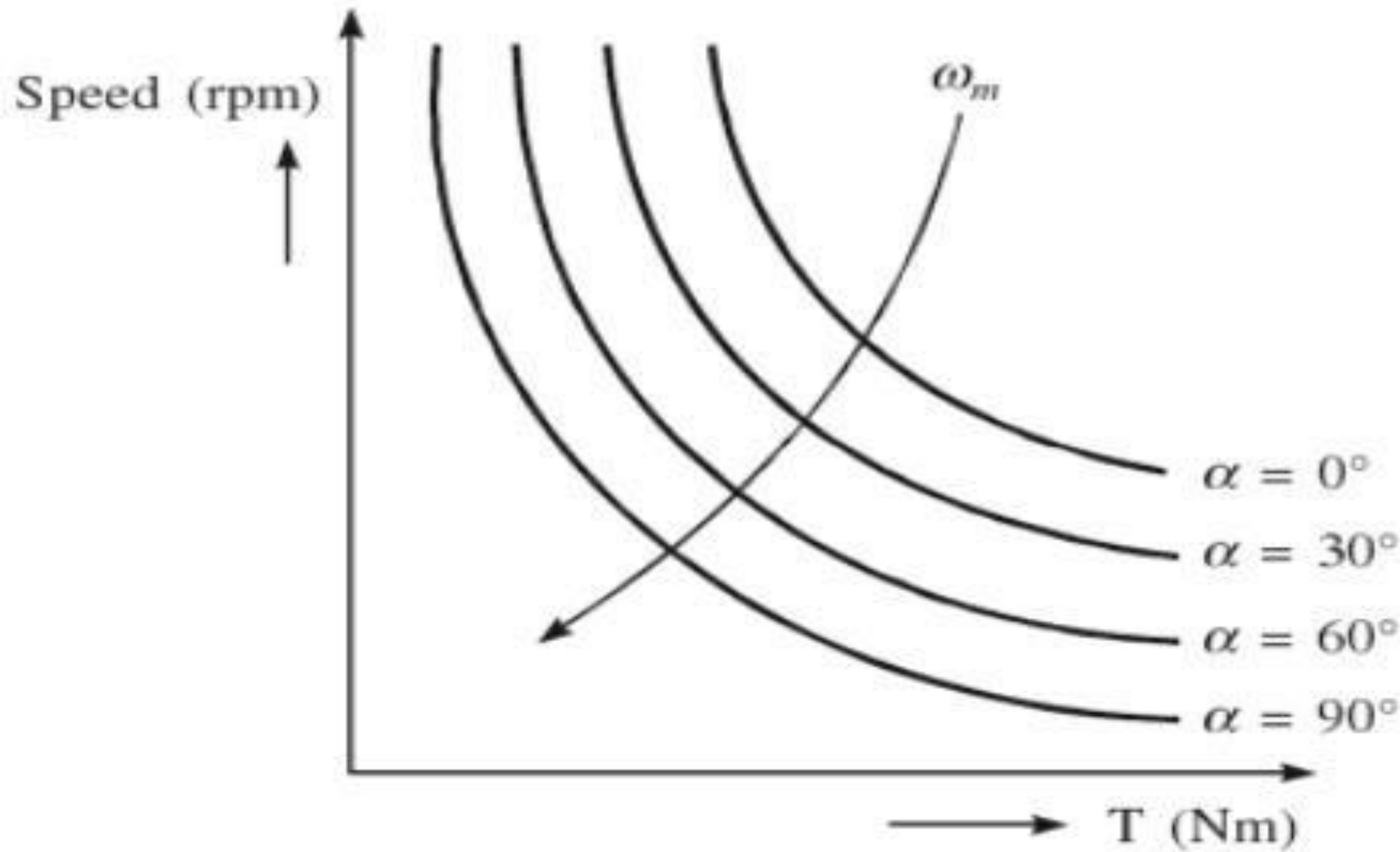
$$V_0 = 0 = R_a I_a + L_a \frac{di_a}{dt} + K_{af} I_a N + K_{res} N$$

$$T = K_{af} I_a^2 = J \frac{d\omega}{dt} + B\omega + T_L$$

Mode 3: The motor coasts during the interval $\beta < \omega t < (\pi + \propto)$.

$$I_a = 0$$

$$T = 0 = J\frac{d\omega}{dt} + B\omega + T_L$$



Problem-14

The speed of a 20 HP, 210 V, 1000 rpm series dc motor is controlled by a 1-ϕ full converter. The combined field and armature circuit resistance = 0.25 Ω, K_{af} = 0.03 N-M/A^2 and K_{res} = 0.075 V-s/rad. The supply voltage is 230 V. Assuming continuous and ripple-free motor current, determine the following for firing angle α = 30° and speed N = 1000 rpm:

(i) The motor current

(ii) The motor torque

(iii) The supply power factor.

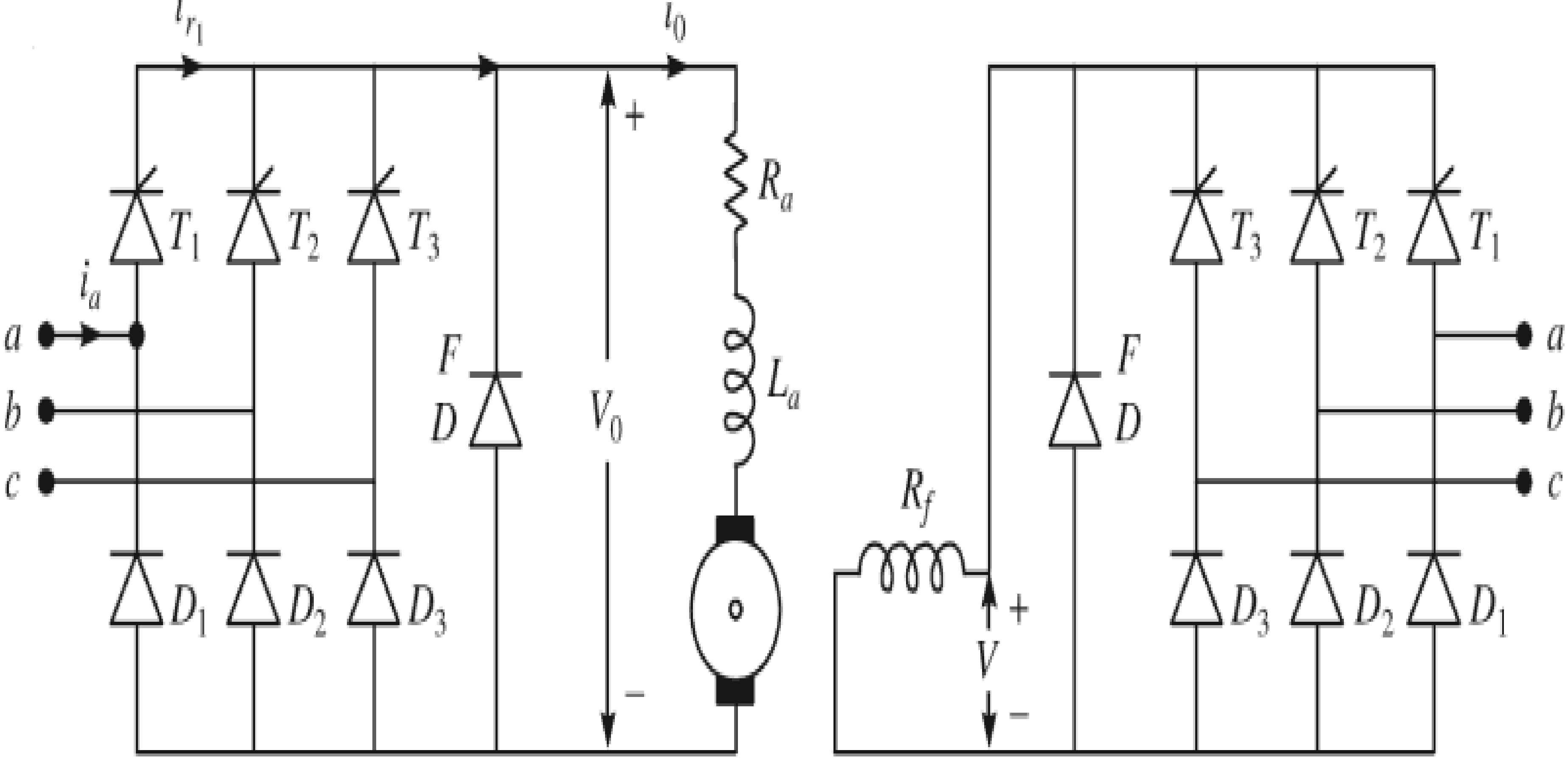
Problem-15

A dc series motor is supplied from a full converter whose $\alpha = 65°$. 1-ϕ supply is of 230 V rms and 50 Hz frequency. The armature and field resistance together equal 2 Ω. The torque constant $K_{af} = 0.23$ H and the load torque is 20 N-m. Neglecting damping, find the average armature current and speed.

Three Phase Converter fed DC drives

Three-phase controlled converter dc drives, depending upon the quadrant operations, hav
been classified as

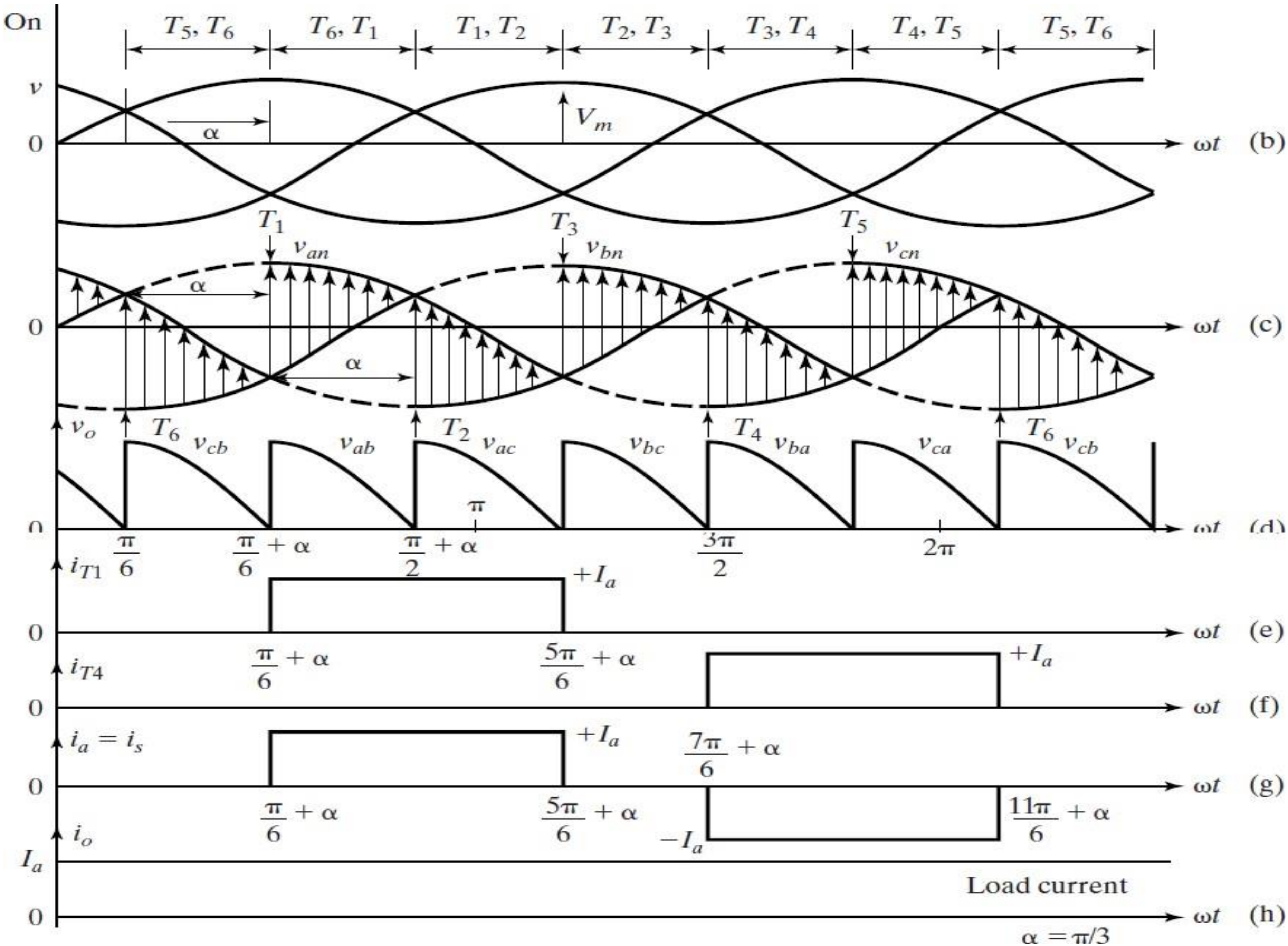
1. Three-phase semi-controlled converter dc drives, further divided into
   (i) Separately excited dc drive;
   (ii) Series dc motor drive;
2. Three-phase fully controlled converter dc drives, further divided into
   (i) Separately excited dc drive;
   (ii) Series dc motor drive.

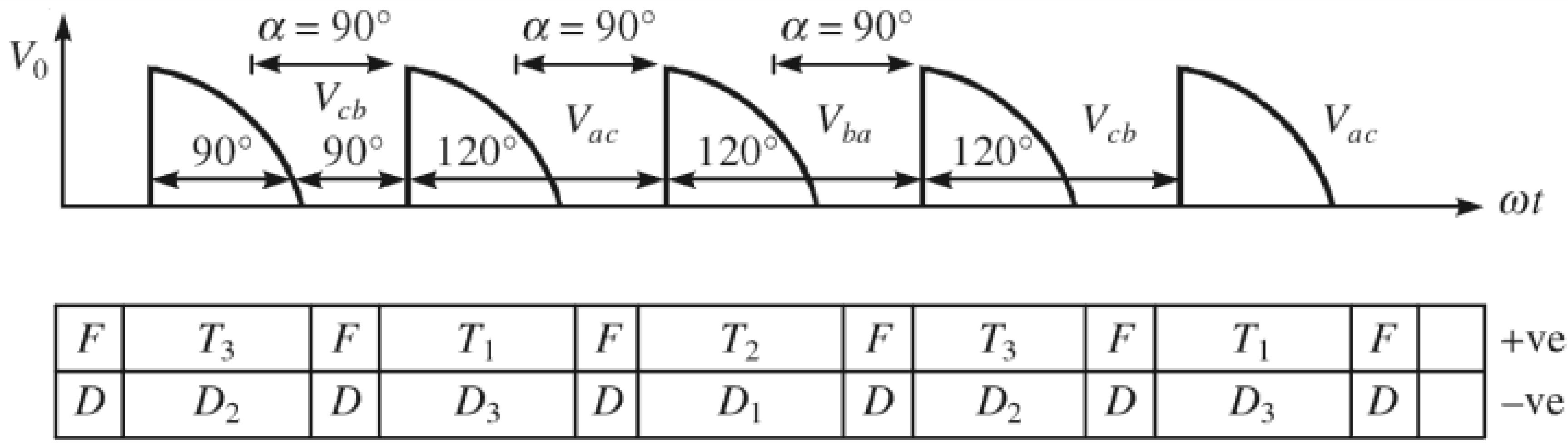


$$V_{an} = V_m \sin \omega t$$

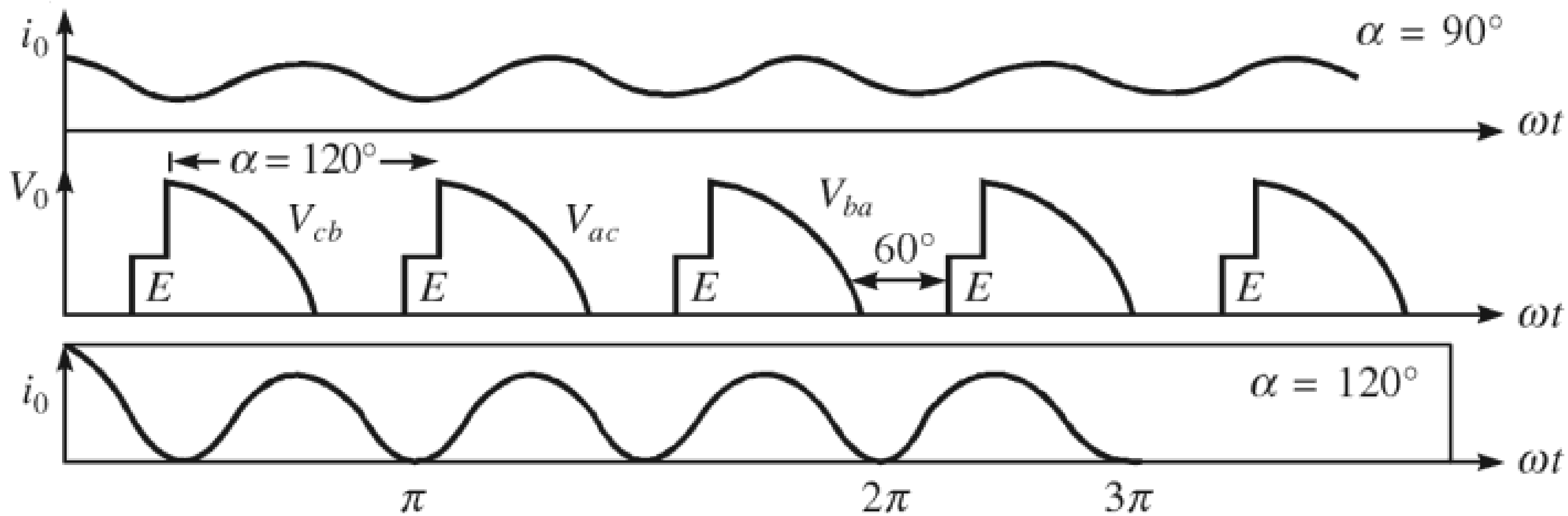
$$V_{bn} = V_m \sin (\omega t - 120)$$

$$V_{cn} = V_m \sin (\omega t + 120)$$


On
T5, T6
T6, T1
T1, T2
T2, T3
T3, T4
T4, T5
T5, T6
v
α
Vm
0
ωt
(b)
T1
T3
T5
van
vbn
vcn
α
α
0
ωt
(c)
vo
T6
vcb
vab
T2
vac
vbc
T4
vba
vca
T6
vcb
π
0
ωt
(d)
π/6
π/6 + α
π/2 + α
3π/2
2π
iT1
+Ia
0
ωt
(e)
iT4
π/6 + α
5π/6 + α
+Ia
0
ωt
(f)
ia = is
+Ia
7π/6 + α
0
ωt
(g)
π/6 + α
5π/6 + α
11π/6 + α
io
−Ia
Ia
Load current
0
ωt
(h)
α = π/3



(d)



(e)

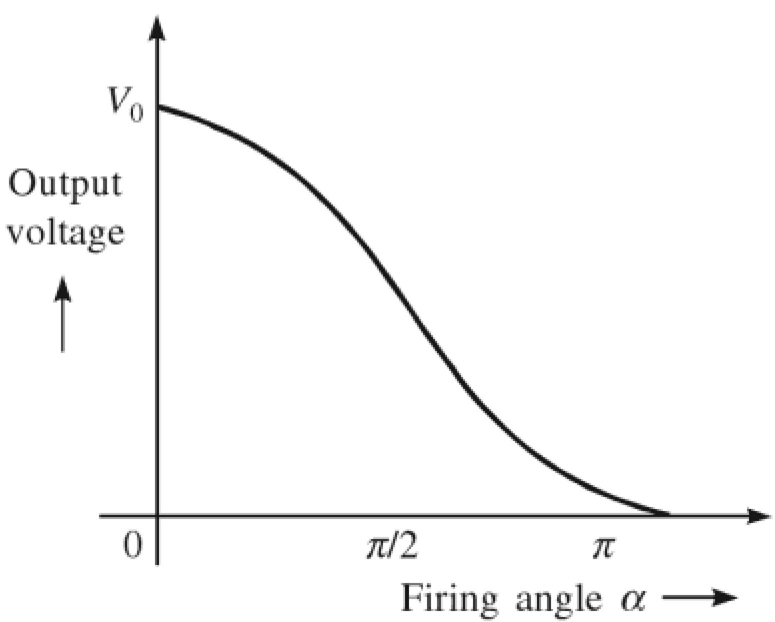
Fig. 2.2(a)–(e) Voltage and current waveforms for 3-phase semi-converters.

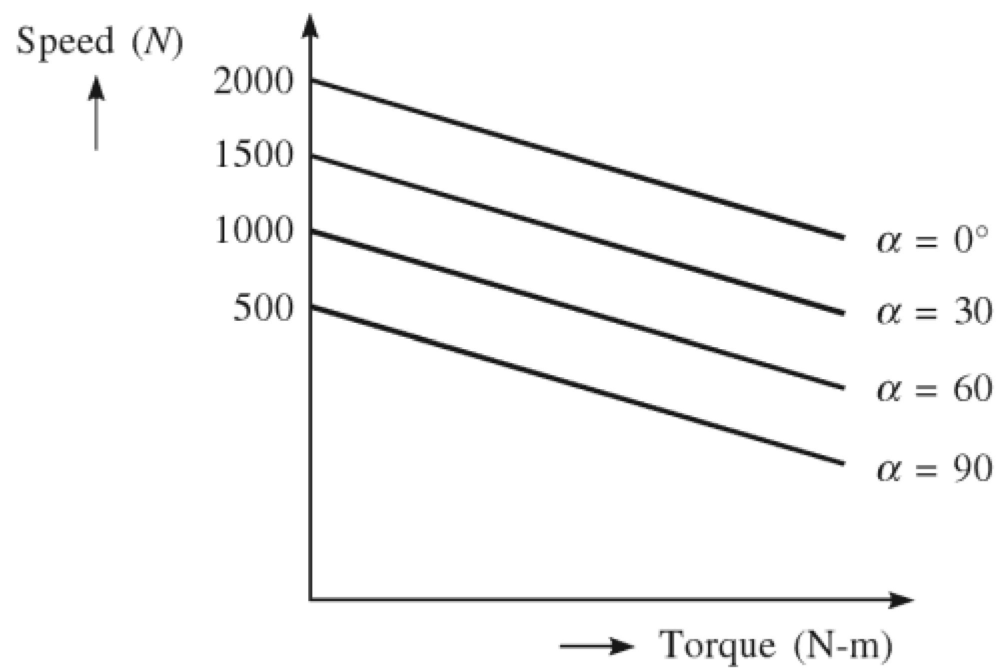
The average terminal output voltage can be expressed when armature current is continuous.

$$V_0(\alpha) = \frac{3}{2\pi} \int_{30^\circ+\alpha}^{150^\circ+\alpha} (V_A - V_C)\, d\omega t$$

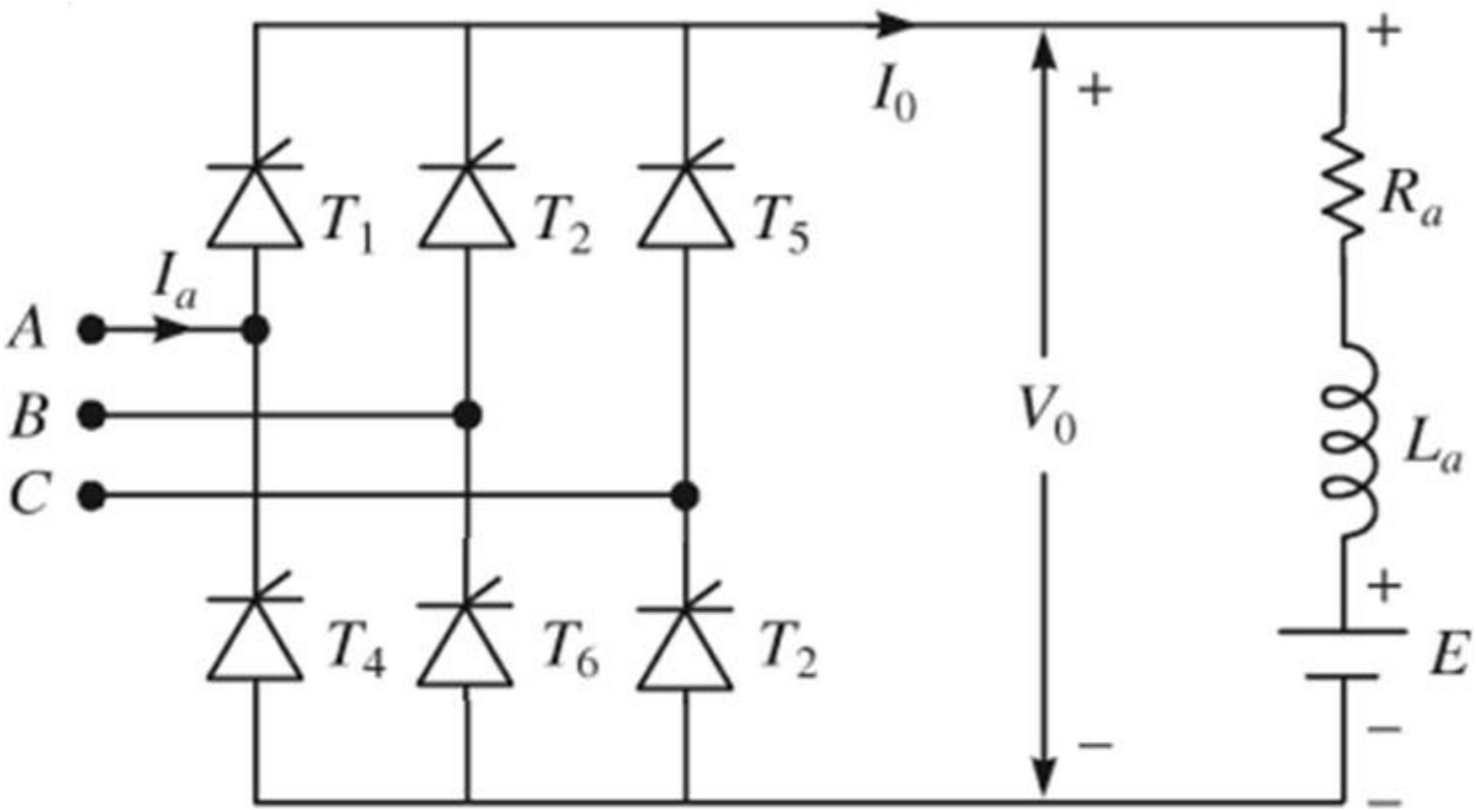
$$V_0(\alpha) = \frac{3\sqrt{6}V_L}{2\pi}(1+\cos\alpha)$$

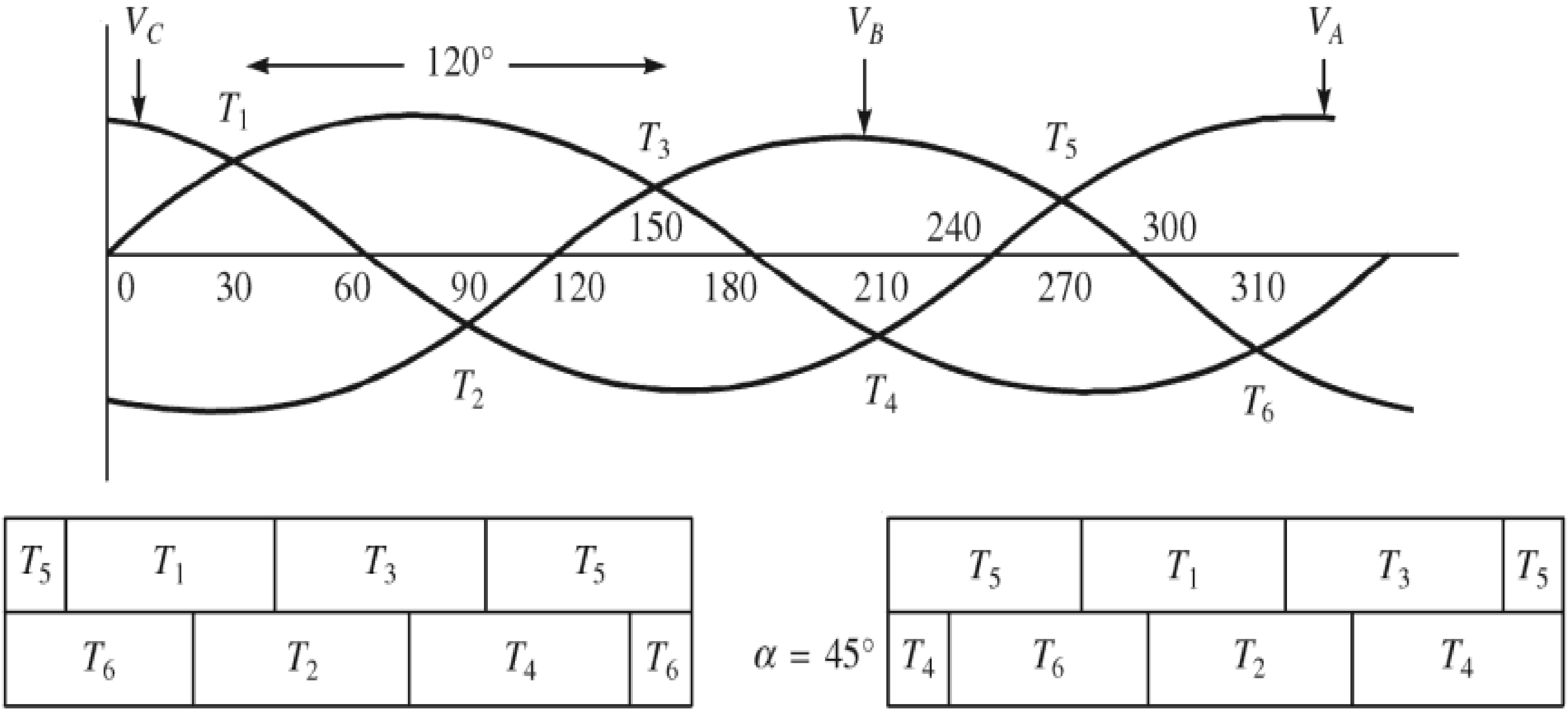
$$N = \frac{V_o(\alpha)}{K_a\,\phi} - \frac{R_a}{(K_a\,\phi)^2}T$$





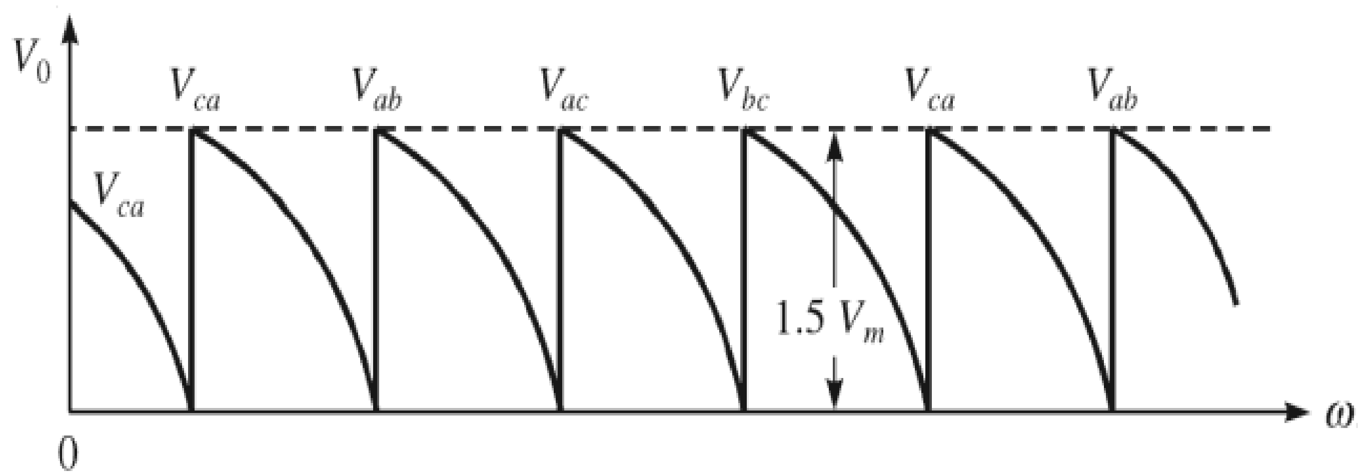
Three Phase full converter fed Separately Excited DC motor





V_C
120°
V_B
V_A
T_1
T_3
T_5
150
240
300
0
30
60
90
120
180
210
270
310
T_2
T_4
T_6
T_5 T_1 T_3 T_5
T_6 T_2 T_4 T_6
$\alpha = 45°$
T_5 T_1 T_3 T_5
T_4 T_6 T_2 T_4

(a) (b)



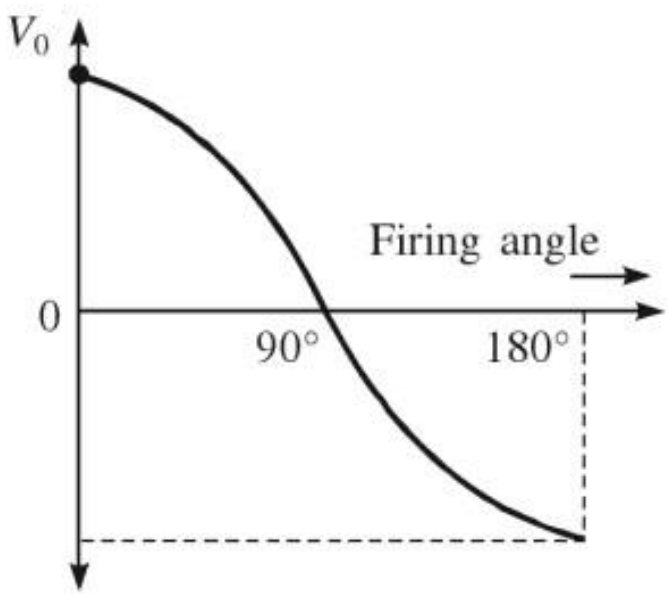
V_0
V_{ca}
V_{ab}
V_{ac}
V_{bc}
V_{ca}
V_{ab}
V_{ca}
1.5 V_m
0
ωt

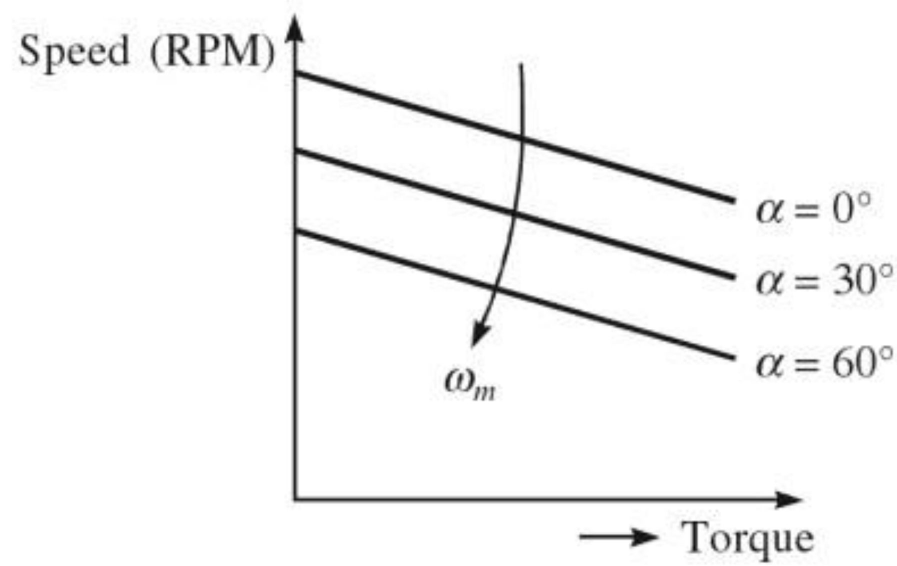
The average motor terminal voltage is given as

$$V_0(\alpha) = \frac{3}{\pi} \int_{30^\circ+\alpha}^{150^\circ+\alpha} (V_A - V_B)\, d\omega t$$

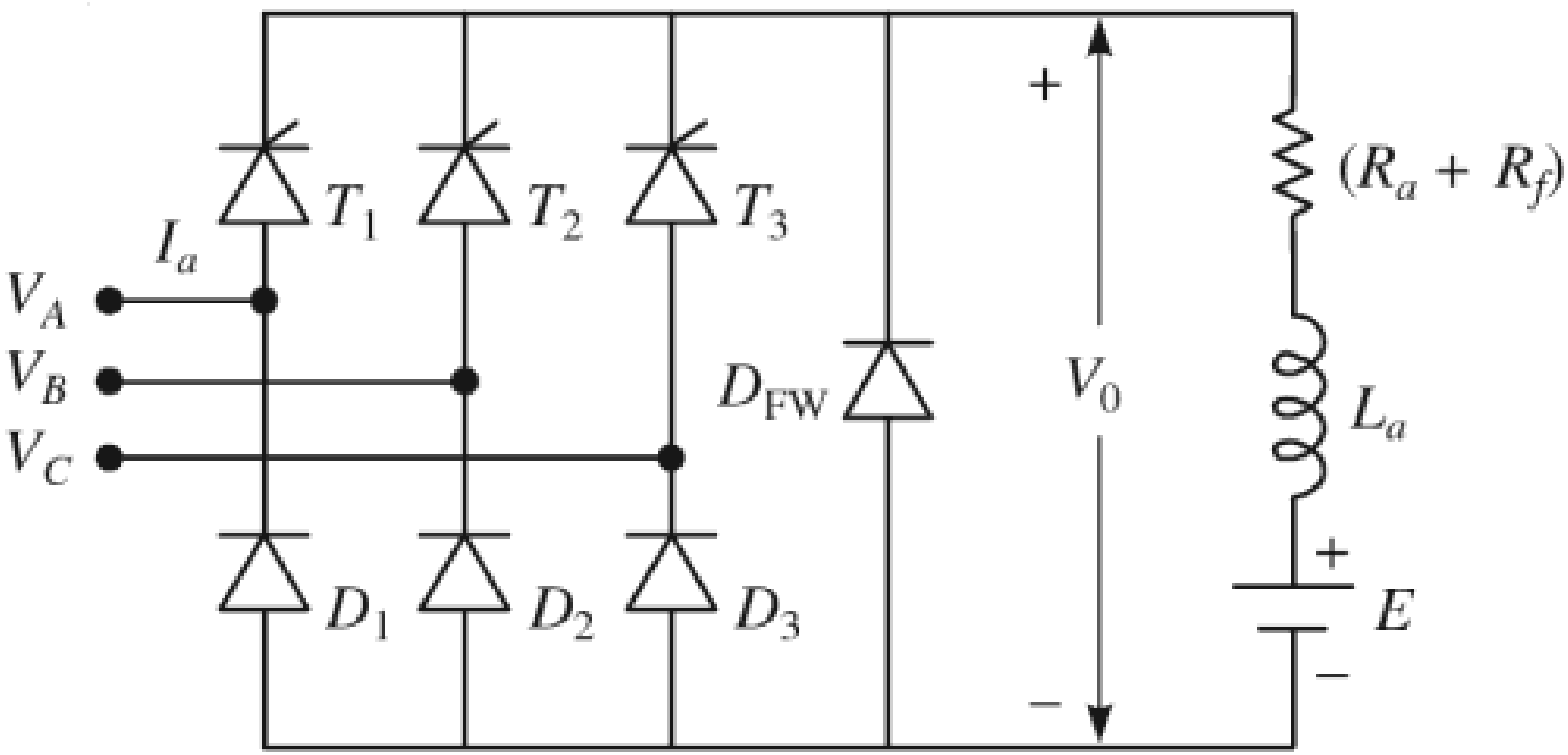
$$V_0(\alpha) = \frac{3\sqrt{6}V_s}{\pi} \cos\alpha = \frac{3\sqrt{(6/2)}\,V_m}{\pi} \cos\alpha = \frac{3\sqrt{3}}{\pi} V_m \cos\alpha$$

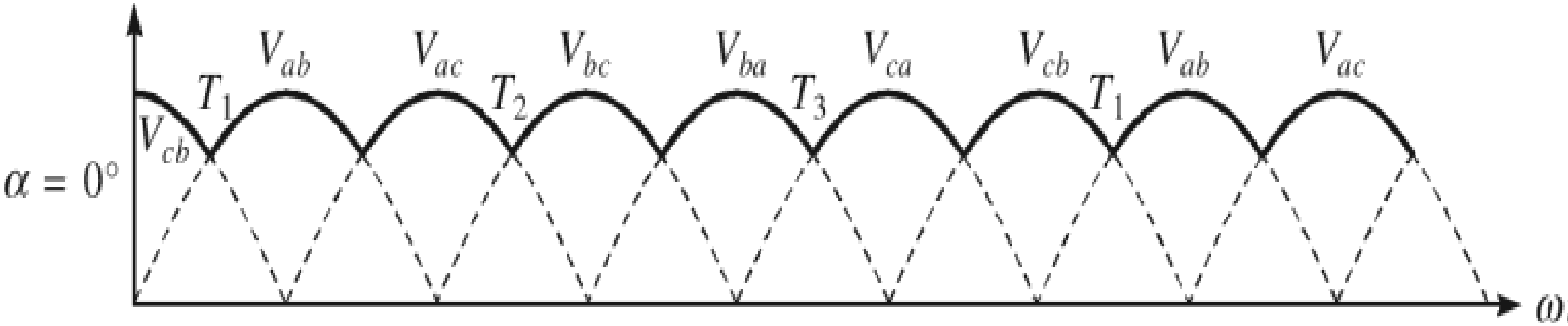
$$N = \frac{V_o(\alpha)}{K_a\phi} - \frac{R_a}{(K_a\phi)^2} T$$



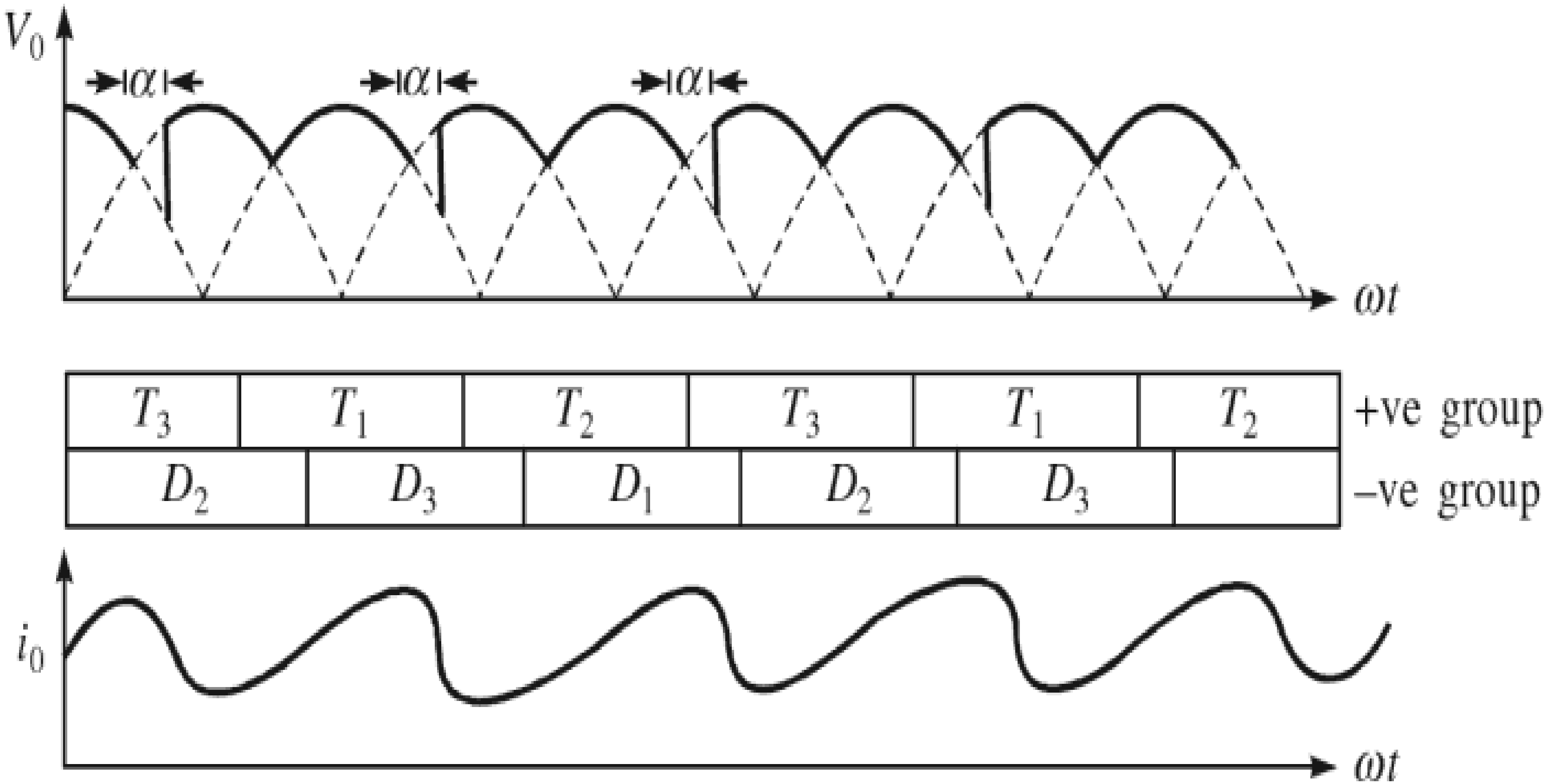


Three Phase SemiConverter Fed D.C Series Motor

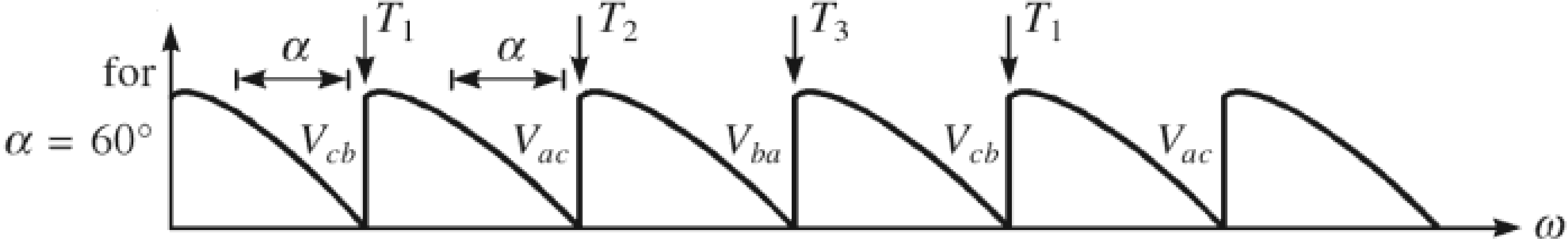



V_{ab}
V_{ac}
V_{bc}
V_{ba}
V_{ca}
V_{cb}
V_{ab}
V_{ac}
T_1
T_2
T_3
T_1
V_{cb}
$\alpha = 0°$
ωt

(a)

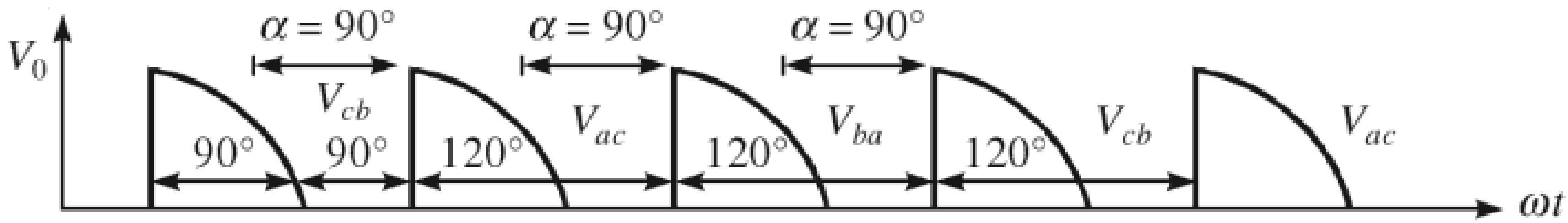

V_0
α
α
α
ωt
T_3 T_1 T_2 T_3 T_1 T_2
+ve group
D_2 D_3 D_1 D_2 D_3
–ve group
i_0
ωt

(b)



T_3	T_1	T_2	T_3	T_1	T_2	+ve
D_2	D_3	D_1	D_2	D_3	D_2	–ve

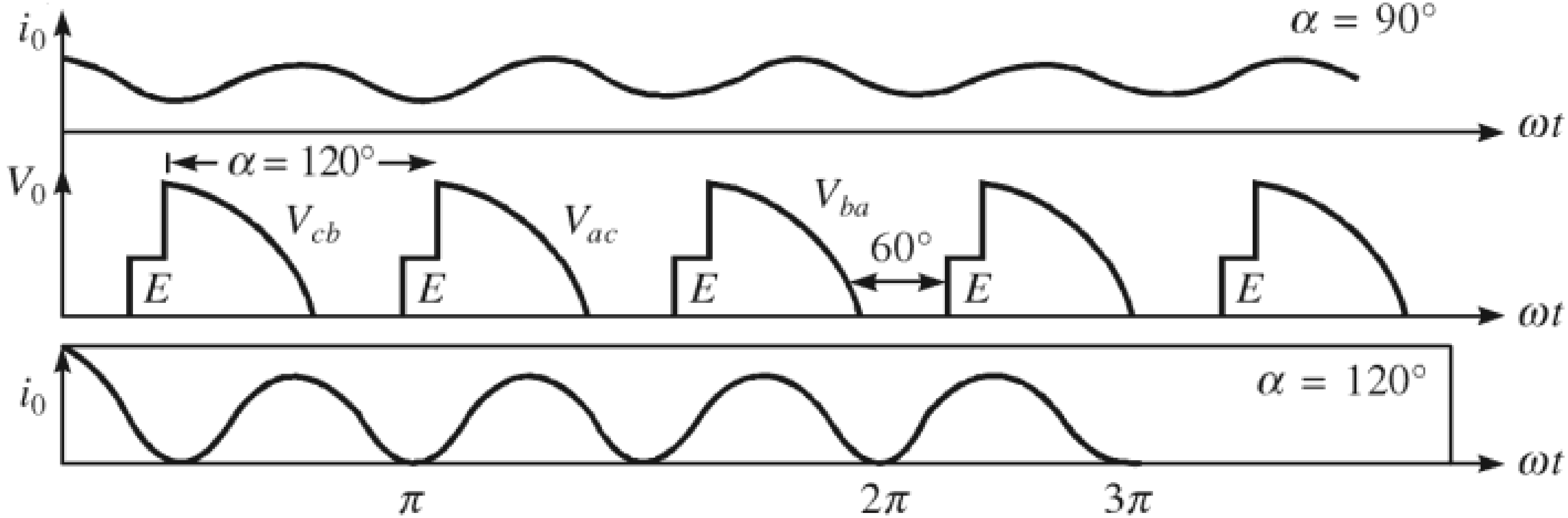
(c)



F	T_3	F	T_1	F	T_2	F	T_3	F	T_1	F		+ve
D	D_2	D	D_3	D	D_1	D	D_2	D	D_3	D		–ve

(d)

(d)

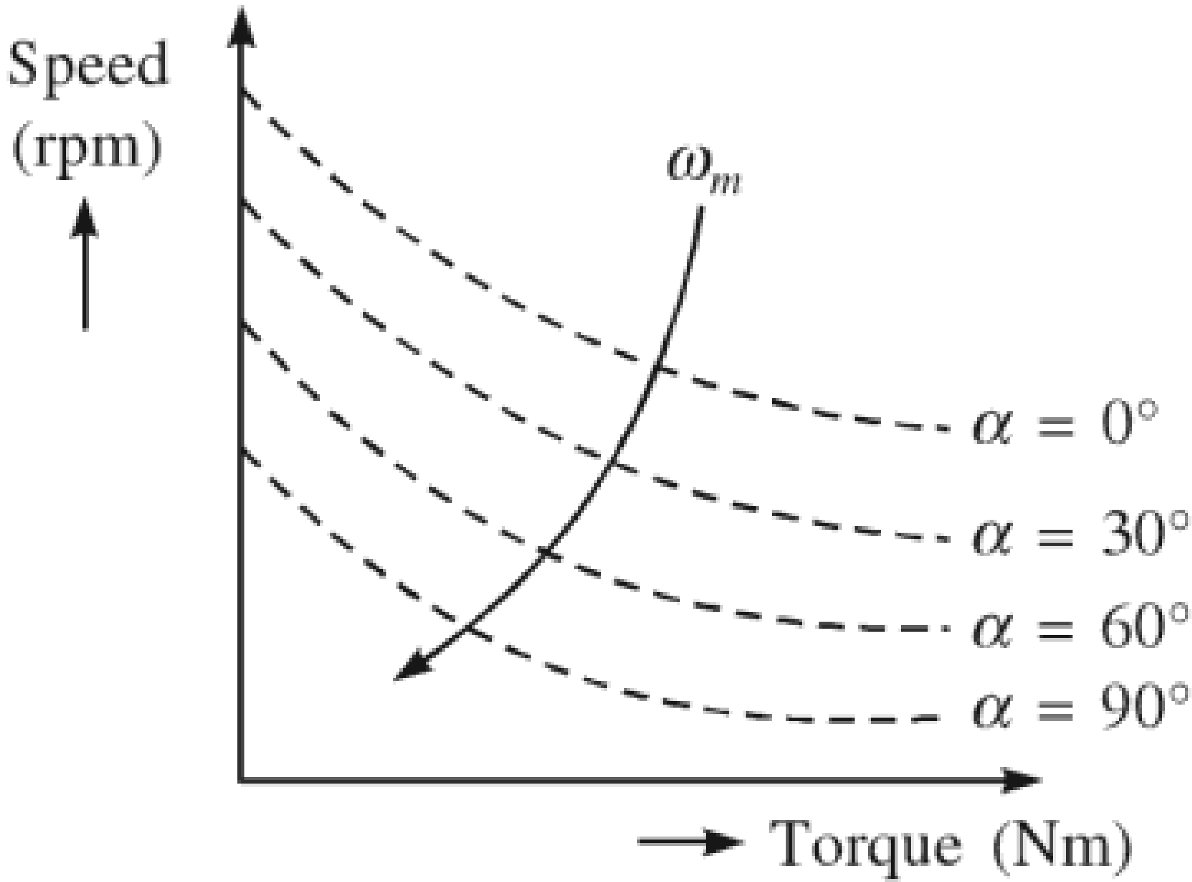


(e)

$$V_0(\alpha) = \frac{3}{2\pi} \int_{30^\circ+\alpha}^{150^\circ+\alpha} (V_A - V_C)\, d\omega t$$

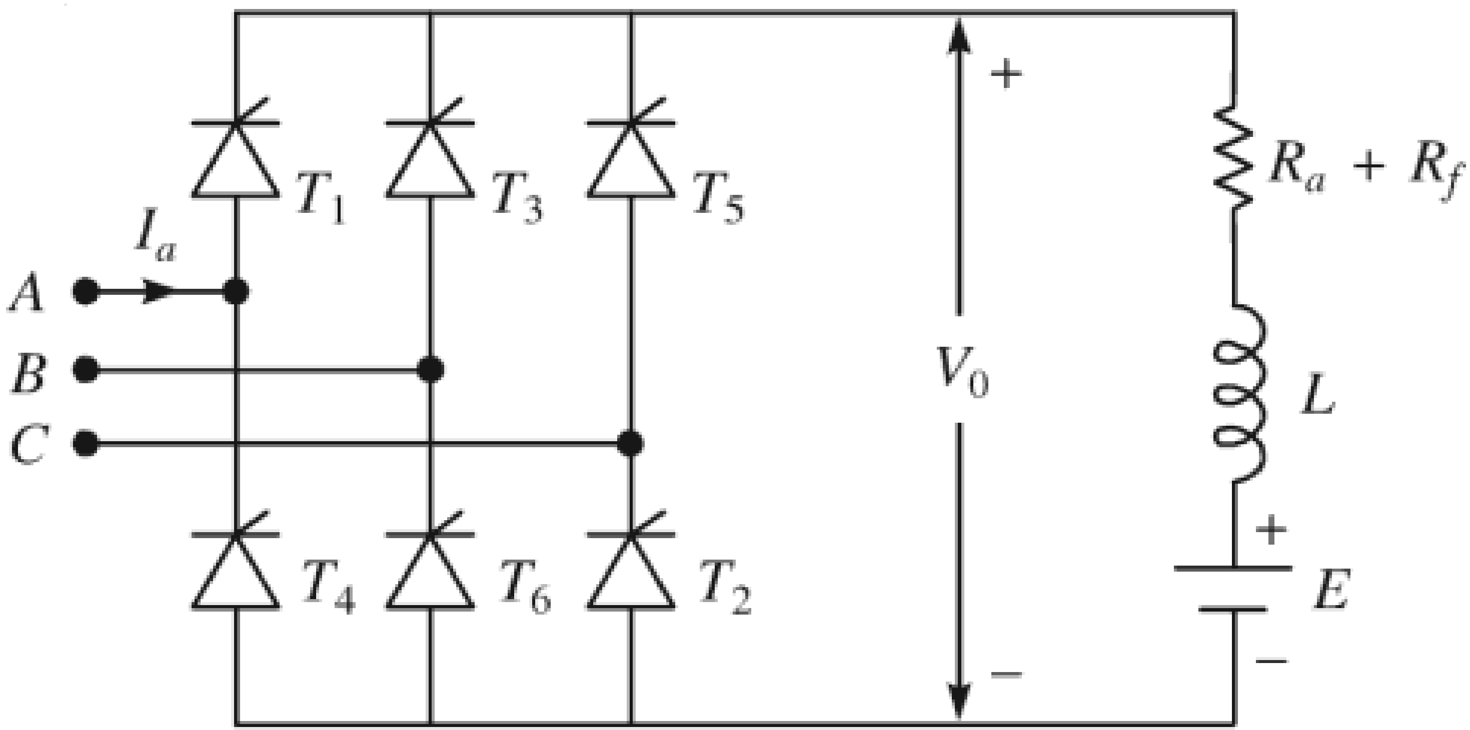
$$R_a I_a + K_{af} I_a N + K_{\text{res}} N = V_o(\alpha) = \frac{3\sqrt{6}\, V_s}{2\pi} (1 + \cos \alpha)$$

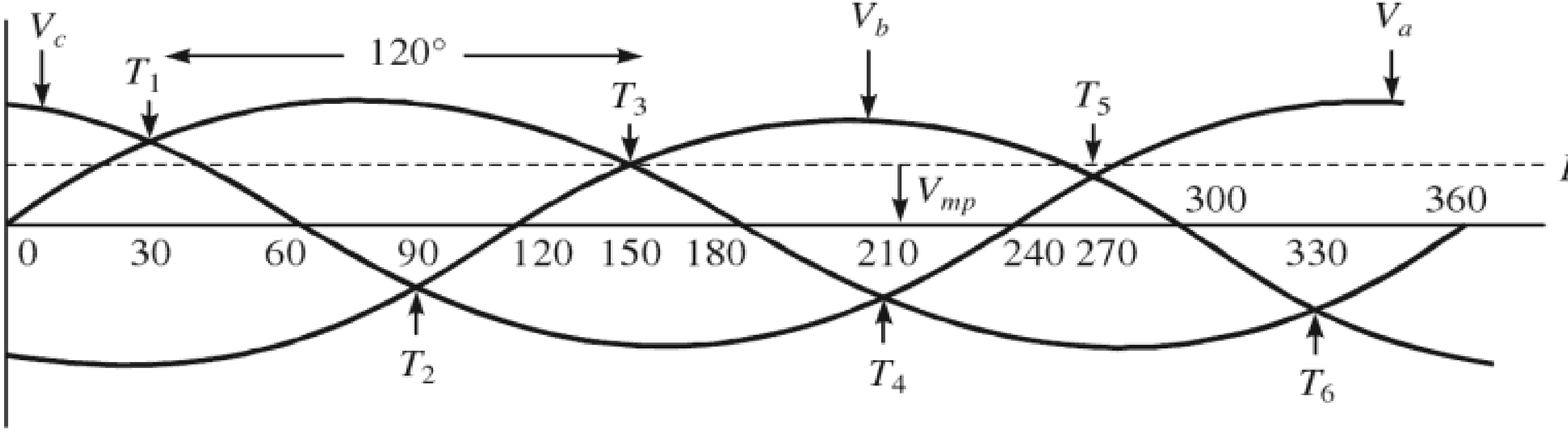
$$N = \frac{(\sqrt{3} V_s / 2\pi)(1 + \cos \alpha) - R_a I_a}{K_{af} I_a + K_{\text{res}}}$$



Speed
(rpm)
ω_m
$\alpha = 0°$
$\alpha = 30°$
$\alpha = 60°$
$\alpha = 90°$
Torque (Nm)

Three Phase Full Converter with DC Series Motor

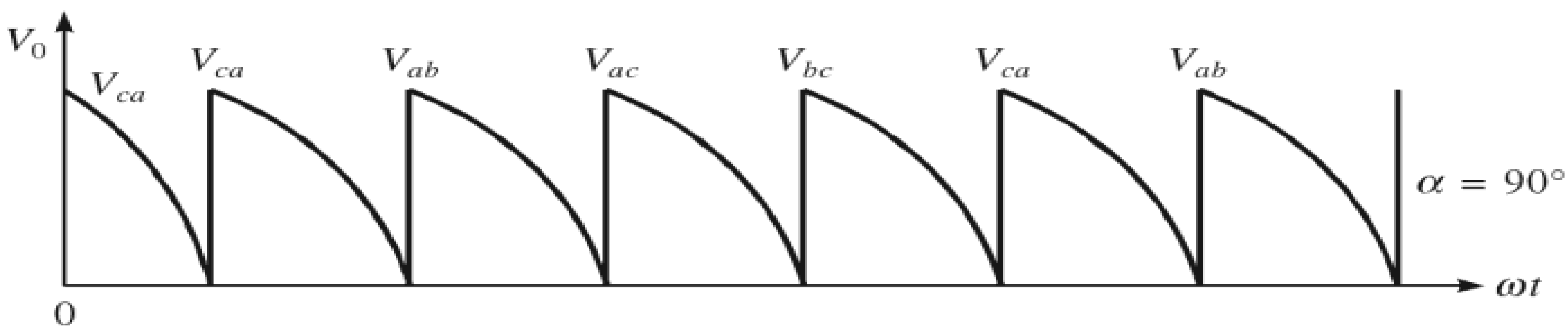




+ve group	T_5	T_1	T_3	T_5
–ve group	T_6	T_2	T_4	T_6

(b)

+ve group	T_5	T_1	T_3	T_5
$\alpha = 45°$, –ve group	T_4	T_6	T_2	T_4

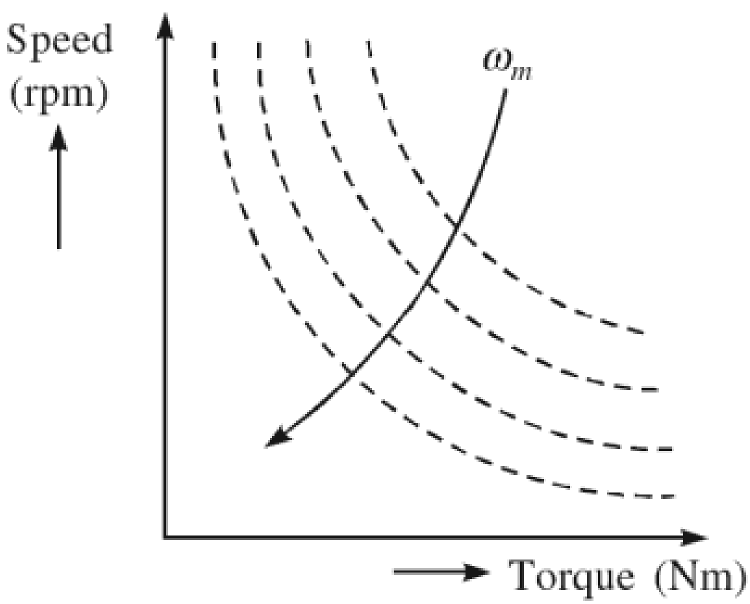


The average motor terminal voltage is given as

$$V_0(\alpha) = \frac{3}{\pi} \int_{30^\circ+\alpha}^{150^\circ+\alpha} (V_A - V_B)\, d\omega t$$

$$V_0(\alpha) = \frac{3\sqrt{6}V_s}{\pi} \cos \alpha$$

$$N = \frac{(\sqrt{3}V_s/\pi) \cos \alpha - R_a I_a}{K_{af} I_a + K_{\text{res}}}$$



Problem -16

The speed of a 150 HP, 650 V, 1750 rpm separately excited dc motor is controlled by a 3-ϕ full converter. The converter is operating from a 3-ϕ, 460 V, 50 Hz supply. The rated armature current of the motor is 170 A. The motor parameters are $R_a = 0.099\ \Omega$; $L_a = 0.73$ mH and $K_a\phi = 0.33$ V/rpm. Neglect the losses in the converter system. Determine the following:

(a) No-load speeds at firing angles $\alpha = 0°$ and $\alpha = 30°$. Assume that at no-load, the armature current is 10% of the rated current and is continuous.

(b) The firing angle to obtain rated speed of 1750 rpm of rated motor current also computes the supply power factor.

(c) The speed regulation for the firing angle obtained in part (b).

$$V_a = \frac{3\sqrt{3}V_m}{\pi} \cos \alpha$$

$$= \frac{3\sqrt{3}}{\pi}\frac{\sqrt{2}}{\sqrt{3}} V_L \cos \alpha = \frac{3\sqrt{2}}{\pi} V_L \cos \alpha$$

$$E_b = V_a - I_a R_a$$

The no-load speed at $\alpha = 0$, $N_0 = \dfrac{E_b}{K_a \phi}$

For $\alpha = 30°$

$$E_b = K_a \phi N = 0.3$$

$$V_a = E_b + I_a R_a$$

Problem 17

A 150 HP, 500 V separately excited dc motor running at 1650 rpm is controlled by a 3ϕ full converter, which is operating from a 3ϕ, 460 V, 50 Hz supply. The rated armature current of the motor is 150 A. Given motor parameters are $R_a = 0.099\ \Omega$, $L_a = 0.63$ mH and $K_a\phi = 0.33$ V/rpm. The losses in the system are neglected. Find

(a) At $\alpha = 0°$ and $\alpha = 45°$, no-load speeds, assuming that at no load the armature current is 10% of the rated current and is continuous. Hence find

(b) Firing angle at 1650 rpm at rated motor current. Compute supply power and supply power factor.

(c) For firing angle obtained in (b), find speed regulation.

Problem-18

A three-phase, three-pulse thyristor converter controlling a 100 HP, 440 V, 1000 rpm dc shunt motor is operating at 500 rpm, developing 85% of the rated torque. Calculate the triggering angle of the converter if the back emf at rated speed is 430 V. Assume the ac input voltage to be 415 V.

Problem-19

A three-pulse converter controls the armature of a 230 V, 1400 rpm dc motor. The voltage drop in the loop wires along with the armature is 15 V. Find the firing angle for the speed of 600 rpm, if the speed of the motor at $\alpha = 0°$ is 1400 rpm at full load.

(a) Light duty excavators
(b) Medium duty excavator
(c) Heavy duty excavators
(d) All of these.

Which electromagnet is preferred for noiseless operation?
(a) dc-operated
(b) ac-operated
(c) Both (a) and (b)
(d) None of these.

What is the necessity of controlled rectifier for dc drives?
(a) To improve efficiency
(b) To improve reliability
(c) To control speed
(d) To improve performance

The no-load speed equation for single phase full converter-fed dcse
(a) $\frac{V_m \cos\alpha}{\pi K_a \phi}$
(b) $\frac{2V_m \cos\alpha}{\pi K_a \phi}$
(c) $\frac{2V_m (1+\cos\alpha)}{\prod K_a \phi}$
(d) $\frac{2V_m (1+\cos\alpha)}{(K_a \phi)^2}$

10. The speed of a separately excited dc motor depends upon ________.
    (a) Armature voltage
    (b) Flux
    (c) Both a and b
    (d) None of these

11. The torque of a separately excited dc motor is directly proportional to________.
    (a) I_a
    (b) I_a^2
    (c) $\sqrt{I_a}$
    (d) None of these

12. The back emf of a series dc motor is directly proportional to ________.
    (a) $I_a N$
    (b) I_a^2
    (c) N
    (d) None of these

13. For regenerative braking, the armature voltage should be ________ back emf.
    (a) Greater than
    (b) Less than
    (c) Equal to
    (d) None of these

14. For plugging, the armature voltage and back emf are in __________ direction.
    (a) Same
    (b) Opposite
    (c) Both same and opposite
    (d) None of these

15. For a torque of 50 Nm and a motor constant of 1.5 V-s/A-rad, the armature current is __________ A.
    (a) 33.4
    (b) 75
    (c) 66.8
    (d) 25

16. As the torque applied on a dc motor increases, the speed will ________.
   (a) Decrease (b) Increase
   (c) Not change (d) Slightly change

17. The average output voltage of a 1-ϕ half-controlled converter is maximum and minimum at delay angles of _____ and _____ respectively.
   (a) $0°$ and $90°$ (b) $90°$ and $0°$
   (c) $0°$ and $180°$ (d) $180°$ and $0°$

18. The delay angle at which the average output voltage is half of the maximum output voltage for a semi-converter is ________.
   (a) $90°$ (b) $60°$
   (c) $120°$ (d) $30°$

19. The delay angle at which the average output voltage is half of the maximum output voltage for a full converter is ________.
   (a) $90°$ (b) $60°$
   (c) $120°$ (d) $30°$

20. For regenerative braking (for constant flux motor), the armature voltage V_a = ________.
   (a) $E_b + I_aR_a$ (b) $E_b - I_aR_a$
   (c) $E_b + I_a(R_a + R_f)$ (d) $E_b - I_a(R_a + R_f)$

21. For plugging (for series motor), the armature voltage V_a = ________.
   (a) $-E_b + I_aR_a$ (b) $E_b + I_aR_a$
   (c) $-E_b + I_a(R_a + R_f)$ (d) $E_b - I_a(R_a + R_f)$

22. The no-load speed for a semi-converter-fed separately excited dc motor when the delay angle (α) is less than 90° is ________.

(a) $\frac{V_m}{K}$ (b) $\frac{V_m \sin \alpha}{K}$

(c) Rated speed (d) None of these

23. The conduction period for a thyristor in a 1-phase full converter connected to a high inductive load (continuous current) is ________.

(a) 120° (b) 180°

(c) 60° (d) 360°

24. In constant torque mode of operation for a separately excited dc motor, ___________ is kept constant.

(a) Armature voltage (b) Flux

(c) Both (d) None of these

25. In constant power mode of operation for a separately excited dc motor, ___________ is kept constant.

(a) Armature voltage (b) Flux

(c) Both (d) None of these

26. What is meant by electrical drives?

(a) Drives employed for electric motors

(b) Motion control

(c) Drives employed for engines
(d) None of these.

27. What are the advantages of an ac driver?
(a) No commutation effect
(b) More sparking effect
(c) High cost
(d) All of these.

28. What are the different parts of electrical drives?
(a) Source
(b) Power modulator
(c) Control unit
(d) Motor
(e) All of these.

29. The semi-converter operates in the ________________ quadrant.
(a) First
(b) Second
(c) Third
(d) Fourth

30. Full converter operates in the ______________ and ________________ quadrants.
(a) First and fourth
(b) First and second
(c) Third and fourth
(d) First and third

31. In an armature voltage control dc motor, the motor is operated ______________ control.
(a) Above rated speed
(b) Below rated speed
(c) Above as well as below rated speed
(d) None of these.

32. In a single-phase half-controlled rectifier operation with a dc motor in discontinuo
conduction mode, the critical speed W_{mc} which separates continuous conduction fro
discontinuous conduction for a given value of α will occur at $\beta =$ _______.

(a) $\pi + \alpha$
(b) $\pi + \alpha$
(c) π
(d) α

33. For a half-controlled rectifier for continuous conduction mode, the output voltage cann
be reversed because the motor is in _______.

(a) Motoring operation
(b) Generating operation
(c) Both a and b
(d) None of these

34. In a 1-ϕ fully controlled rectifier in continuous conduction mode in a cycle, the mot
terminal voltage is given by_______.

(a) $\frac{2V_m}{\pi}\cos\alpha$
(b) $\frac{2V_m}{\pi}\sin\alpha$
(c) $\frac{2V_m}{\pi}$
(d) $\frac{V_m}{\pi}$

35. When a rectifier operation at an angle $\alpha > 90°$, V_a is negative. It means that the rectifi
takes power from dc terminals and transfers it to ac mains. This operation of the rectifi
is called _______.

(a) Conversion
(b) Inversion

(c) Linear (d) Non-linear

36. In a single-phase fully controlled rectifier in discontinuous conduction in a cycle, the motor terminal voltage for the duty interval $\alpha \leq \omega t \leq \beta$ is __________.
   (a) $V_a < V_s$ (b) $V_a = V_s$
   (c) $V_a > V_s$ (d) $V_a \neq V_s$

37. What are the application of electrical drives?
   (a) Smooth control (b) High efficiency
   (c) Accurate speed control (d) All of these.

38. For large power dc motor drives, __________ controlled rectifiers are used.
   (a) Semi (b) Fully
   (c) Half-wave (d) None

39. When a converter acts as a line commutative inverter,
   (a) $\alpha < 90°$ (b) $\alpha > 90°$
   (c) $\alpha = 0°$ (d) $\alpha = 180°$.

40. Write the expression for the average output voltage of a full converter-fed dc driver.
   (a) $\frac{2V_m}{\pi}\cos\alpha$ (b) $\frac{2V_m}{\pi}(1+\cos\alpha)$
   (c) $\frac{V_m}{\pi}\cos\alpha$ (d) $\frac{V_m}{\pi}(1+\cos\alpha)$

41. What is meant by phase control rectifier?
   (a) ac – dc
   (b) dc – ac
   (c) ac – ac
   (d) None of these

42. In phase-controlled dc drives, which commutation takes place?
   (a) Forced commutation
   (b) Class E
   (c) Natural commutation
   (d) None of these

43. For natural commutation, additional circulatory is __________.
   (a) Required
   (b) Not required
   (c) Both (a) and (c)
   (d) None of these

44. In a dual converter the switch acts like a __________.
   (a) Forward switching
   (b) Reversing motoring
   (c) Both (a) and (c)
   (d) None of these

45. Calculate the motor torque when armature current I_a = 38 A, resistance R_a = 0.32, V_s = 260 V, and motor constant K_{arp} = 0.182 V/rpm.
   (a) 6.621 N-m
   (b) 66.12 N-m
   (c) 0.6612 μ-m
   (d) 661.2 N-m

46. Given the expression for rms value of current (i_{rms}), when it is operated in a semi-converter, __________.

(a) $I_{rms} = I_a$ (b) $I_{rms} = I_a + I_T$

(c) $I_{rms} = I_a \left[\frac{(1-\alpha)}{\pi}\right]^{1/2}$ (d) None of these

47. In an single-phase series dc motor drives, the flux ϕ = __________.

(a) $\phi = \phi + \phi_{res}$ (b) $\phi = \phi_a + \phi_{res}$

(c) $\phi = \phi_{res}$ (d) $\phi = \phi_a$

48. The back emf voltage due to residual magnetism is very small, and it is proportional to the __________.

(a) Torque (b) Current

(c) Supply voltage (d) Speed

49. When an armature current is discontinuous when it is connected to a semi-connecting separately excited dc motor drive, during the operation period π to P, the freewheeling diode __________.

(a) Does not conduct (b) Conducts

(c) Is short-circuited (d) None of these

50. For the same values of bit 45, calculate the motor back emf voltage when it is operated full-converter for a separately excited dc motor.

(a) 1.1942 V (b) 91.42 V

(c) 0.191 V (d) 1914.2 V

51. In phase-controlled controllers, the thyristors' firing angle can be varied from __________.

(a) 0° to 90°
(b) 0° to 180°
(c) 0° to 360°
(d) None of these

52. The semi-controlled converter is also called a __________ converter.

(a) Unidirectional
(b) Bidirectional
(c) Both (a) and (b)
(d) None of these

53. The dual converter can be operated in __________ quadrant operation.

(a) First
(b) Second
(c) Third
(d) Fourth

54. The speed–torque characteristic of a separately excited motor for terminal voltage and full field excited will be a __________ .

(a) Inclined line
(b) Straight line
(c) Both (a) and (b)
(d) None of these

1. How many diodes are required for a three-phase semi-converter SEDC motor?
   (a) 1 (b) 2
   (c) 3 (d) 4.

2. The dc motor back emf, E_b = ________.
   (a) $E_a + I_a R_a$ (b) $E_a - I_a R_a$
   (c) $-E_a + I_a R_a$ (d) $-E_a - I_a R_a$

3. If $\alpha = 0°$, what is the triggering angle for a three-phase full converter SEDC motor drive________.
   (a) 60° (b) 90°
   (c) 30° (d) 120°
   [**Ans:** 30°]

4. If $\alpha = 180°$, three-phase semi-converter output voltage equation V_a = ________ and ________ motor is suitable for traction drives.
   (a) 0 V, series (b) 0 V, parallel
   (c) V_s, series (d) V_s, parallel
   [**Ans:** 0 V, series]

5. Three-phase drives are used for ________ applications.
   (a) Low speed (b) High speed
   (c) Medium speed (d) None

6. A three-phase full converter is a ________ quadrant converter.

(a) First
(b) Second
(c) Third
(d) Four

7. Speeds above rated speed will be obtained by the ________ method.

(a) Armature voltage control
(b) Flux control
(c) Both of these
(d) None of these

8. Speeds below rated speed will be obtained by the ________ method.

(a) Armature voltage control
(b) Flux control
(c) Both of these
(d) None of these

9. The conduction period for a thyristor in a three-phase full converter connected to a high inductive load (continuous current) is ________.

(a) 120°
(b) 180°
(c) 60°
(d) 360°

10. For dynamic braking (for series motor), back emf is ________.

(a) $I_a(R_a + R_f)$
(b) $I_a(R_b + R_f)$
(c) $I_a(R_a + R_f + R_b)$
(d) $I_a(R_a + R_f - R_b)$

11. In a 3-ϕ fully controlled rectifier fed to a separately excited dc motor, drive thyristors are fired in the phase sequence of their numbers with a phase difference of ________.

(a) 120° (b) 200°

(c) 60° (d) 0°

12. The three-phase half-controlled rectifier connected to a separately excited dc motor drive operation is in continuous conduction mode in the ________ quadrant operation.

(a) First (b) Second

(c) Third (d) Fourth

13. When a rectifier operation at an angle $\alpha > 90°$, V_a is negative. It means the rectifier takes power from dc terminals and transfers it to ac mains. This operation of rectifier is called ________.

(a) Conversion (b) Inversion

(c) Linear (d) Non-linear

14. The average output voltage of 3-ϕ half converter with R-load is ________.

(a) $V_a = (3\sqrt{3}/\pi)V_m$ (b) $V_a = (3\sqrt{3}/\pi)\, V_m \cos\alpha$

(c) $V_a = (3\sqrt{3}/\pi)\, V_m (1 + \cos\alpha)$ (d) $V_a = 3\sqrt{3}/\pi$

[**Ans:** $V_a = (3\sqrt{3}/\pi)\, V_m (1 + \cos\alpha)$]

15. The average output voltage of a 3-ϕ full converter with R–L load is ________.

(a) $V_a = (3\sqrt{3}/\pi)V_m$

(b) $V_a = (3\sqrt{3}/\pi)\ V_m \cos\alpha$

(c) $V_a = 3\sqrt{3}/\pi$

(d) None

[**Ans:** $V_a = (3\sqrt{3}/\pi)\ V_m \cos\alpha$]

16. In a semi-converter operation, when armature current is continuous the back emf will be directly proportional to

(a) $K_a\phi N$

(b) $K_a\phi I_a$

(c) $K_a\phi V_s$

(d) None of these

17. In a series motor operation, when it is connected to a full-converter having armature current continuous, the developed torque T_d is

(a) $K_a\phi N$

(b) $K_a\phi I_a$

(c) $K_a\phi V_s$

(d) None of these

18. Write the expression for speed N, in terms of motor terminal voltage and armature current.

19. Write the expression for a three-phase average motor terminal voltage which is connected to

(a) A semi-converter: E_a = ________.
[**Ans:** $(V_m/\pi)(1 + \cos\alpha)$]

(b) A full-converter: E_a = ________.
[**Ans:** $(2V_m/\pi)\cos\alpha$]

1. Describe some advantages of electrical drives.
2. Explain briefly about the functions of different converters that are shown in block diagrams of electrical drives.
3. Explain the advantages of dc drives over ac drives.
4. Why is a dc series motor applicable with torque overloads rather than other dc motors?
5. When varying speed by field flux control, flux must be varied in small steps. Why?
6. Explain the importance of Ward Leonard system over other speed controls.
7. Explain the importance of various characteristic curves drawn while operating with dc motors.
8. Write down equations for a dc series motor. Sketch the characteristics of this motor, with regard to the constant-torque mode and the constant-power mode.
9. Explain the operation of a separately excited dc motor fed by a single-phase semi-converter. Discuss the continuous and discontinuous modes of operation with the help of their governing equations.
10. Explain the speed–torque characteristic and voltage versus firing angle curves at different firing angles for a single-phase semi-converter feeding with a separately excited dc motor.

11. Sketch the appropriate voltage and current waveforms of the working of a single-phase full-converted fed dc drive and also derive the expression for the input power factor.
12. What is the importance of freewheeling diodes in converters?
13. Sketch the appropriate voltage and current waveforms for firing angle $\alpha = 30°$ for the working of a single-phase semi-converter fed with dc series motor.
14. Derive the expression for average speed in discontinuous current mode with the help of modes of operation performed in a single-phase fully controlled converter fed with series-excited dc motor.
15. Write a short note on the speed reversal process of a thyristor that is performed in dc motor drive systems.
16. Describe the importance of speed control of a dc series motor. Illustrate your answer with appropriate waveforms.
17. Explain how the speed of a dc series motor is controlled by using converters.
18. What is the purpose of a freewheeling diode in converters when fed to dc motors?
19. Explain the concepts of constant torque control and constant power control.
20. Explain how the speed control of a dc motor is achieved by illustrating the triggering circuits of the thyristors.

1. How is a separately excited dc motor operation fed by a three-phase converter?
2. Explain the operation of a three-phase converter fed (with series motor) in three-phase semi-converters for firing angle $\alpha = 45°$. Sketch its input and output voltage waveforms.
3. For a three-phase full converter, explain how the output voltage wave for a firing angle of 30° is obtained by using (a) phase voltages and (b) line voltages fed with a separately excited DC motor.
4. Describe the importance of speed control of a dc series motor. Illustrate your answer with appropriate waveforms.
5. Derive the expressions for rms value of voltage and currents, and average values for firing angles $\alpha < 60°$ and $\alpha > 60°$, when it is bun-fed with a series-excited motor in three-phase full-converters.
6. Explain how the speed of a dc series motor is controlled using converters.
7. What is the purpose of a freewheeling diode in converters when fed to dc motors?
8. Explain the concept of constant torque control and constant power control.
9. Explain how the speed control of a dc motor is achieved, illustrating the triggering circuits of the thyristors.
10. Explain how a four-quadrant operation is achieved by dual converters, each of 3-ϕ full wave configuration, for a separately excited dc motor.

UNIT-II:
Four quadrant operation of DC Drives

Syllabus

- Introduction to Four quadrant operation – Motoring operations, Electric Braking – Plugging, Dynamic, and Regenerative Braking operations. Four quadrant operation of D.C motors by single phase and three phase dual converters – Closed loop operation of DC motor (Block Diagram Only)
- **Control of DC Motors By Choppers:** Single quadrant, Two quadrant and four quadrant chopper fed dc separately excited and series motors – Continuous current operation – Output voltage and current wave forms – Speed and torque expressions – speed-torque characteristics – Problems on Chopper fed D.C Motors – Closed Loop operation (Block Diagram Only)

Introduction

Generally the four-quadrant operation will depend upon the rotation of the rotor with respect to the load, or it may undergo translational motion. The equivalent motor–load system is shown in Fig. 3.1.

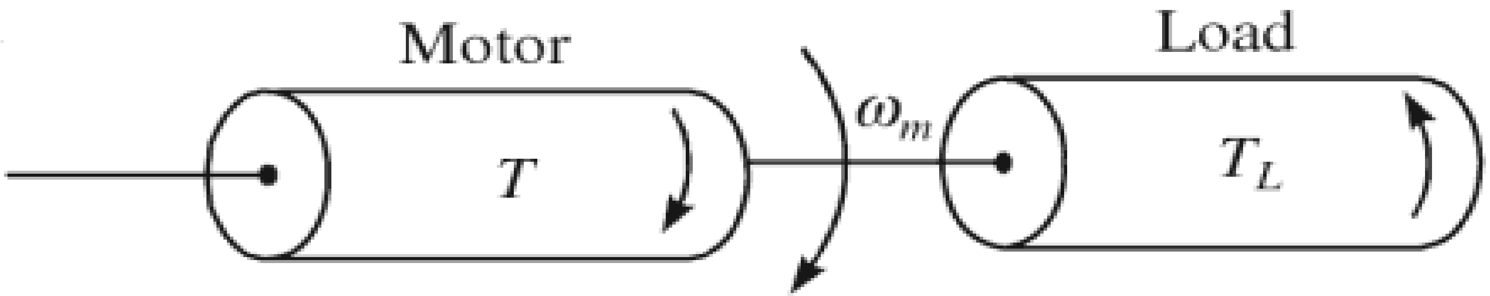


Fig. 3.1 Equivalent motor-load system.

From Fig. 3.1, the basic mechanical rotational equation is given as

$$T - T_L = \frac{d}{dt}(J\omega_m) = J\frac{d\omega_m}{dt} + \omega_m\frac{dJ}{dt}$$

For a constant inertia, $dJ/dt = 0$. Equation (3.1) becomes

$$\therefore \quad T = T_L + J\frac{d\omega_m}{dt}$$

Equation (3.2) shows the developed motor torque and load torque T_L, with dynamic torque $J(d\omega_m/dt)$, because it is present only during the transient operations.

Generally, in the multi-quadrant operation drives, where drive accelerates or decelerates depending on whether T is greater or lesser than T_L. When the motor accelerates, it should supply not only the load torque but an additional torque component $J(d\omega_m/dt)$ in order to overcome inertia. In motor deceleration, dynamic torque has a negative sign. Therefore, it assists the motor-developed torque T and maintains drive motion by extracting energy from stored energy.

In the four-quadrant operation of drives, the motor speed is positive when it is rotating in the forward direction. In loads involving up and down motions, the speed of the motor which causes upward motion is to be thought of as related to forward motion.

In quadrant operation, positive motor torque is defined as the torque which produces acceleration or positive rate of change of speed in forward direction. From Eq. (3.2), positive load torque is opposite in direction to the positive motor torque, and motor torque is considered negative if it produces deceleration.

A motor operates in two cases. They are motor action and braking action. Where the motoring action converts electrical energy to mechanical energy, it produces forward motoring motion, called motor and where braking action converts mechanical energy to electrical energy, it gives forward braking motion, called *generator*. The same action is performed in case of reverse motoring action and braking action.

Figure 3.2 shows the speed and torque coordinates for both forward (positive) and reverse (negative) motions. The power developed by a motor is given by the product of speed and torque.

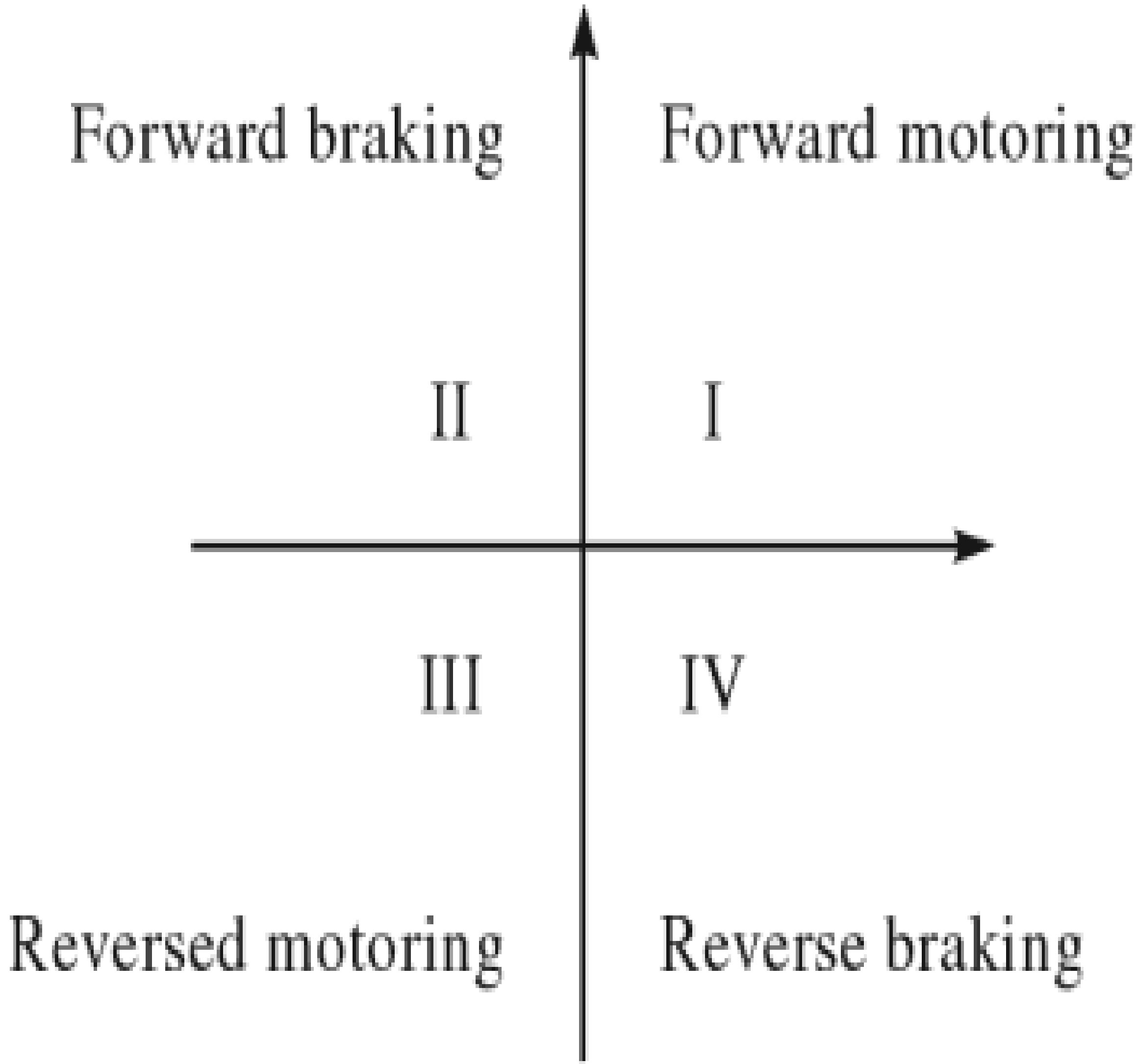


Fig. 3.2 Speed–torque characteristics of four-quadrant operations.

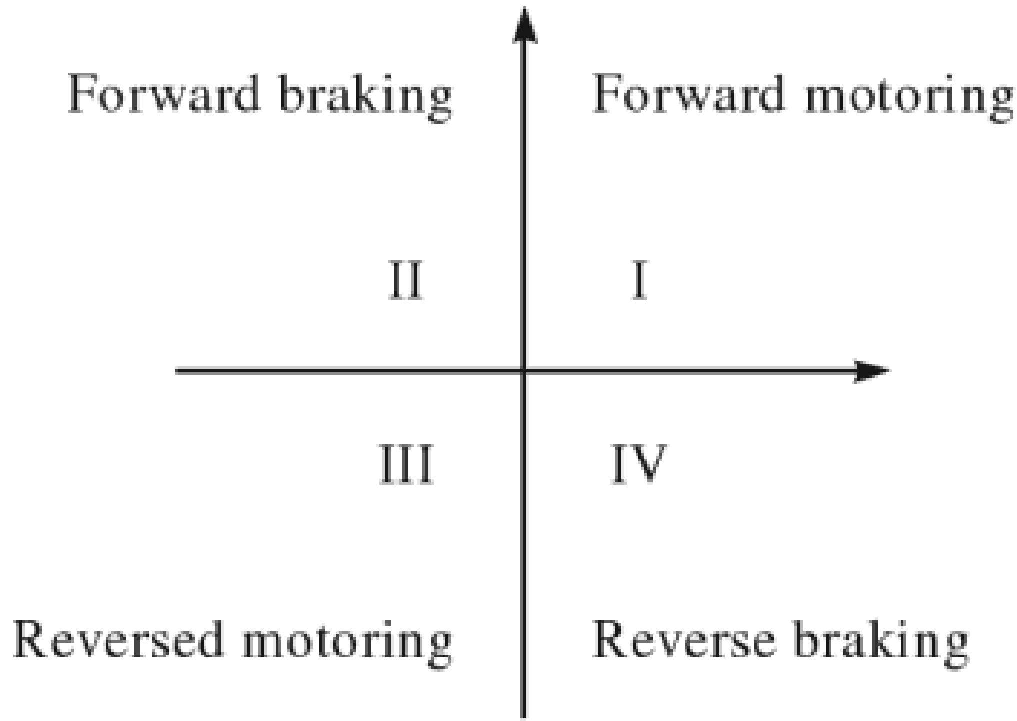


Fig. 3.2 Speed–torque characteristics of four-quadrant operations.

In quadrant I, power is positive; hence the machine works as forward motoring.

In quadrant II, power is negative; hence the machine works as an action generator. These action is called *forward braking*.

In quadrant III, power is positive; hence the machine works as a motor. This action is called *reverse motoring*.

In quadrant IV, power is negative; hence the machine works as a generator. This action is called *reverse braking*.

Dual Converter for Multi-Quadrant or Four-Quadrant Operation

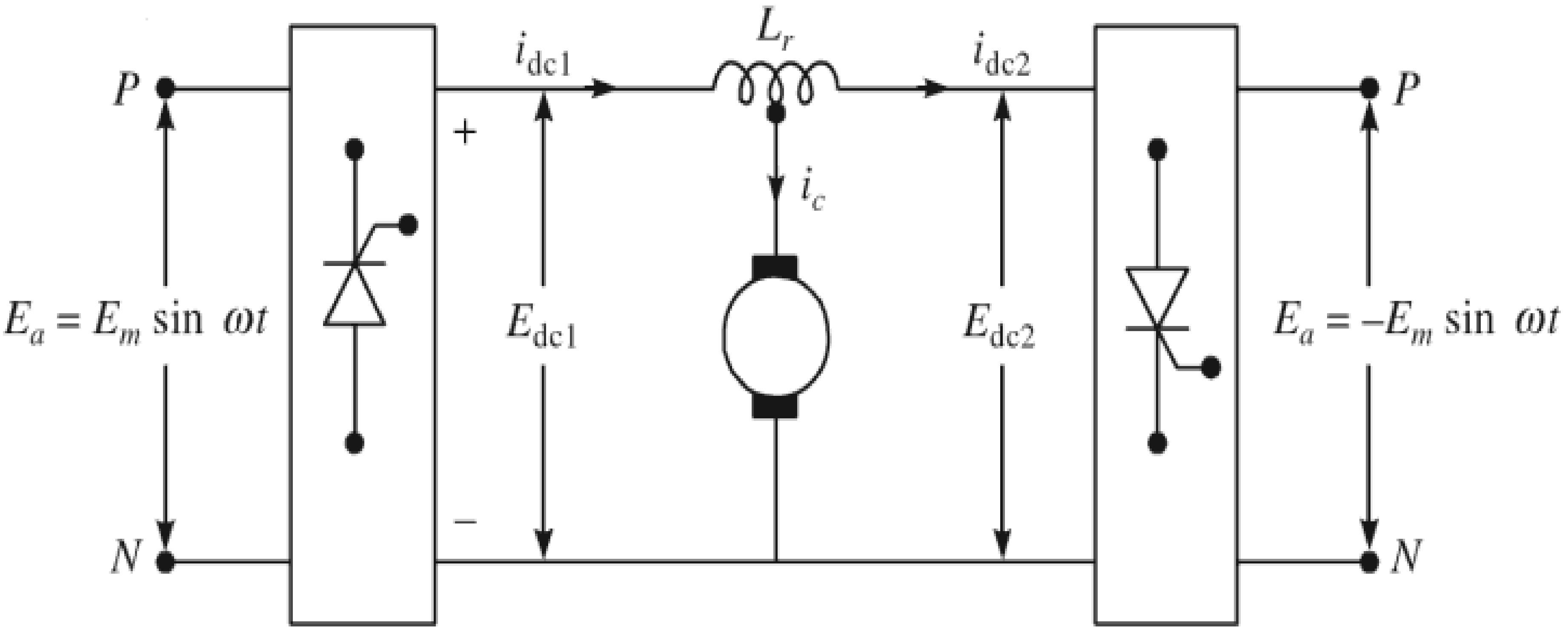


Fig. 3.3 Block diagram of dual converter.

Dual converters are used in high-power applications. It can also be used for suddenly bringing down the speed of the drive. Four-quadrant operation of a dc motor is required, i.e. (i) reversible motoring, (ii) reversible braking. A single converter needs the addition of either a change over contact to reverse the armature connections, or a means of reversing the field current in order to change the relationship between (i) the converter voltage and (ii) the direction of rotation of the motor. It is the connection of two fully controlled converters back-to-back across the load circuit. Such a system is known as a *dual converter* and is shown in Fig. 3.3. Both voltage and current of either polarity are obtained with a dual converter. In full converters, the direction of the current cannot be reversed because of unidirectional property of the thyristor, but polarity of the output voltage can be reversed. Thus the full converter can be operated in first quadrant if

firing angle $< 90°$ (both E_{dc1}, I_{dc1} positive). If firing angle $> 90°$, it can be operated in fourth quadrant. E_{dc1} is positive and I_{dc1} is negative. Therefore in first quadrant, the power flows from ac source to dc source and in fourth quadrant power flows from dc source to ac source. Therefore we can perform these dual converters neither in circulating current nor in non-circulating current mode operation.

Principle of Dual Converter

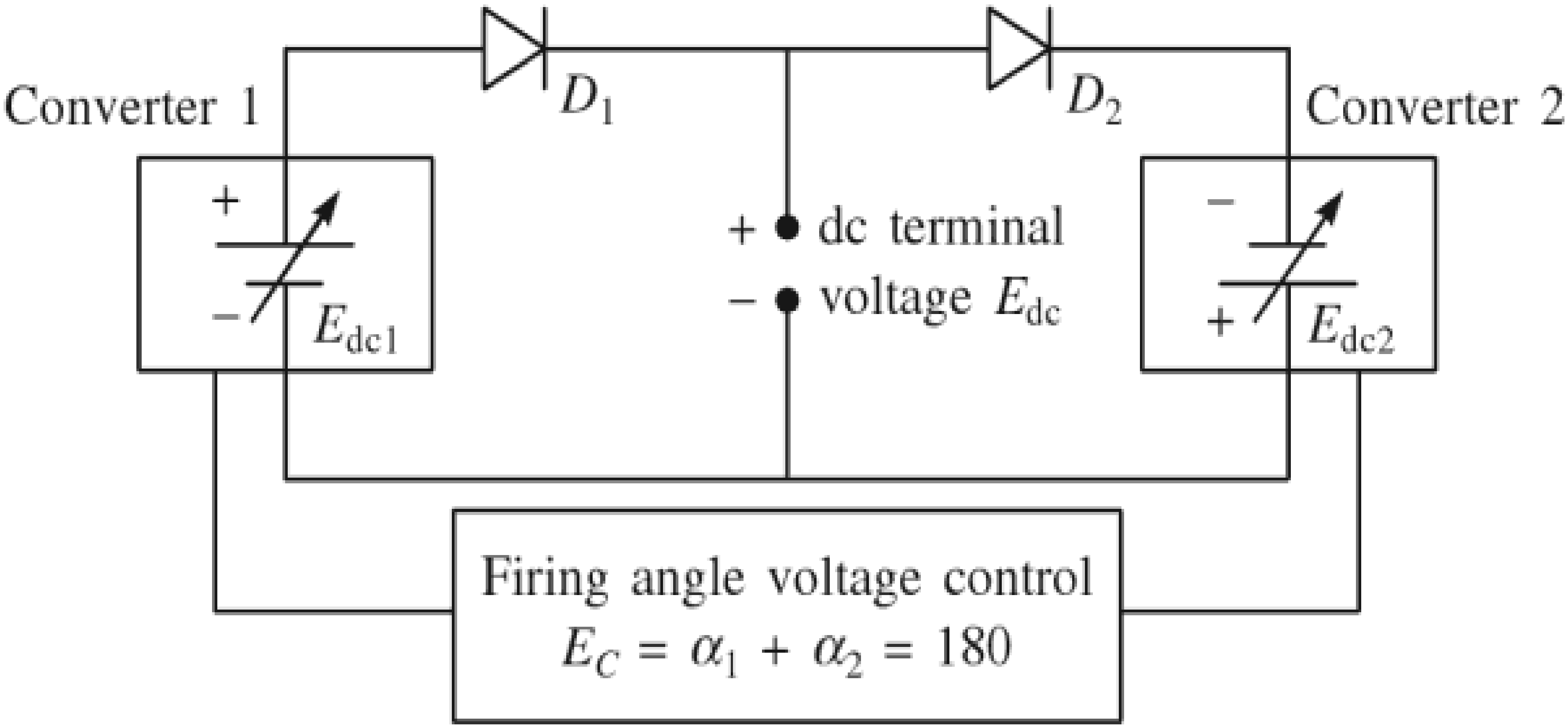


Fig. 3.4 Ideal dual converter.

Dual converters are ideal and they produce pure dc output voltage, that is, there is no ac ripple at the dc output terminals. As shown in Fig. 3.4, each two-quadrant converter is assumed to be a controllable direct voltage source connected in series with a diode. Diodes D_1 and D_2 represent the unidirectional current flow characteristics of the converters. The current in load circuit can however flow in either direction.

The firing angles of the individual converter of the dual converter are regulated by a firing angle control voltage E_C, so that their dc voltages are equal in magnitude but opposite in polarity. Therefore, they can drive the current in opposite directions through the load. Thus, when one converter operates as a rectifier having a given dc terminal voltage, the other converter operates as an inverter with exactly the same voltage. The converter working as a rectifier is called *positive group converter* and the inverter is called *negative group converter*.

The average output voltages for both single-phase and three-phase converters are of the form

$$E_{dc1} = E_{max} \cos \alpha_1 \tag{3.3}$$

$$E_{dc2} = E_{max} \cos \alpha_2 \tag{3.4}$$

1-φ Full wave converter

In the case of the average output voltage of a positive group converter or negative group converter, if its firing angle α_1 or $\alpha_2 = 0$, then its value is

$$E_{\max} = \frac{2E_m}{\pi} \tag{3.5}$$

3-φ Full-wave converter

In the case of the average output voltage of a positive group converter or negative group converter, if its firing angle α_1 or $\alpha_2 = 0$, then its value is

$$E_{\max} = \frac{3\sqrt{3}\,E_m}{\pi} \tag{3.6}$$

Ideal converter

For ideal dual converter, either in circulating or non-circulating modes, the average of converter I is equal to the average of converter II.

$$\therefore \qquad E_c = E_{\mathrm{dc1}} = -E_{\mathrm{dc2}} \tag{3.7}$$

$$\cos\,\alpha_1 = -E_{\max}\cos\,\alpha_2$$

$$\cos\,\alpha_1 = -\cos\,\alpha_2 = \cos\,(180 - \alpha_2)$$

$$\alpha_1 = 180 - \alpha_2$$

$$\alpha_1 + \alpha_2 = 180°$$

Dual Converter without Circulating Current

In a no-circulating dual converter, only one converter is operated at a time and other converter will provide the entire load current. If one converter operates, which means it receives its pulse from the thyristor gate control circuit, the other converter is blocked from the conduction. This can be done by removing the gate pulses from the thyristor gate control circuit. This arrangement of the dual converter is shown in Fig. 3.5. Without any limiting reactors, while performing the operation of non-circulation current, we have to consider a likely situation. Suppose converter 1 is in operation and is supplying the load current for blocking converters and turn on converter 2. Then either its first gating pulses are immediately removed or the firing angle $\alpha = 180°$ is turned for its maximum value. With this, the load current decays to zero and then the converter 2 starts its conduction by generating the pulses. Now, converter 2 builds load current in reverse direction. So long as converter 2 is in operation, converter 1 is ideal as firing

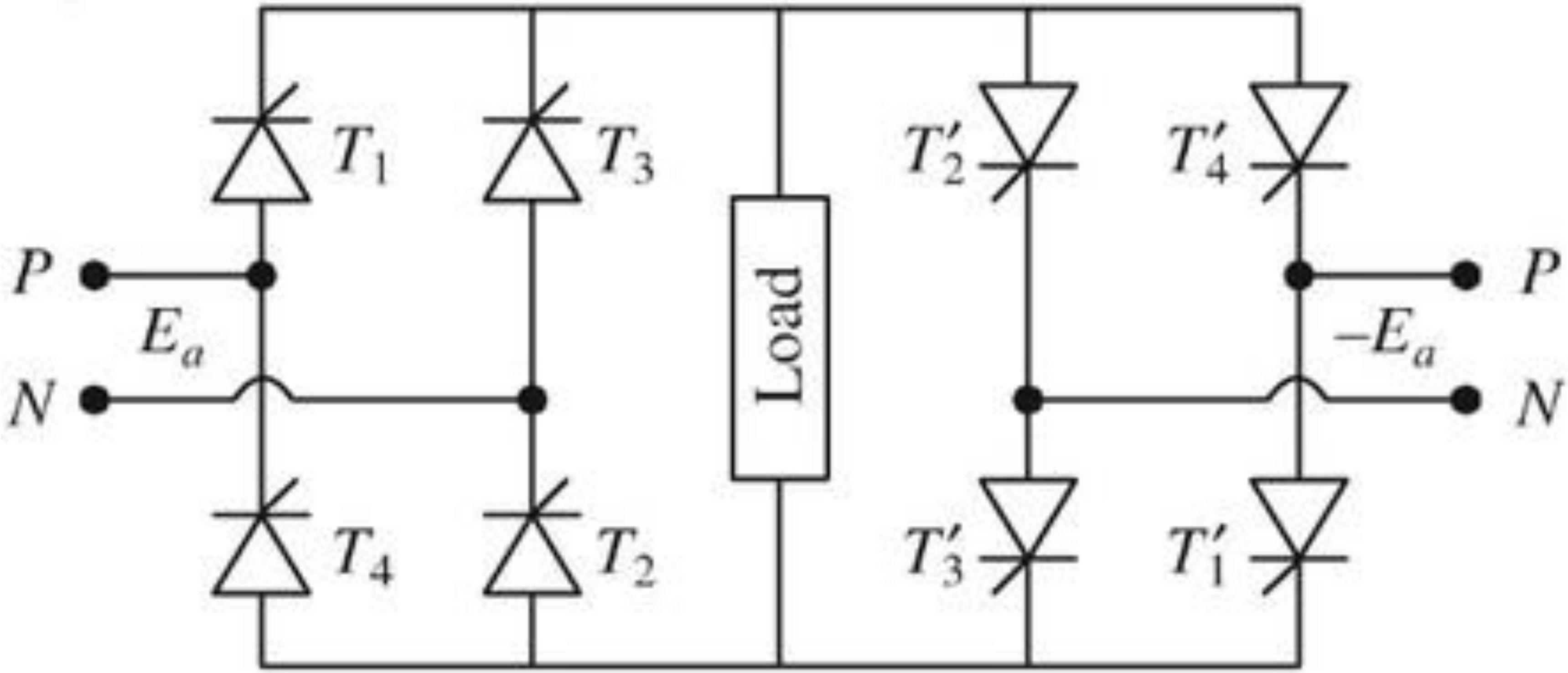


Fig. 3.5 Dual converter without circulating current.

angles are withdrawn from it. This time delay ensures reliable commutation of SCRs in the outgoing converter. If the incoming converter is triggered before the outgoing thyristor has been completely turned off, a large circulating current would flow between the two converters. Therefore, with non-circulating current mode of dual converter, the load current may be continuous or discontinuous. The control circuitry of the dual converter is so desired as to provide satisfactory operation during continuous as well as discontinuous load current.

Dual Converter with Circulating Current

In circulating current mode of dual converter, a reactor is inserted in converter 1 and converter 2 as shown in Fig. 3.6. This reactor limits the magnitude of a circulating current to a reasonable value. Now, from the condition of ideal converts, $\alpha_1 + \alpha_2 = 180°$ if the firing angles of converter 1 is $\alpha_1 = 30°$ and the firing angle of converter 2 is $\alpha_2 = 150°$. Therefore converter 1 and converter 2 has the same average value and also has the same polarity. The circulation current is limited by the reactor; if the load current is to be reversed, the output of two converters is interchanged. This means that converter 1 is made on the inverter and by making its firing angle greater than 90°. The converter is made to work on the rectifier $\alpha < 90°$. In this manner we can perform the circulating mode of operation.

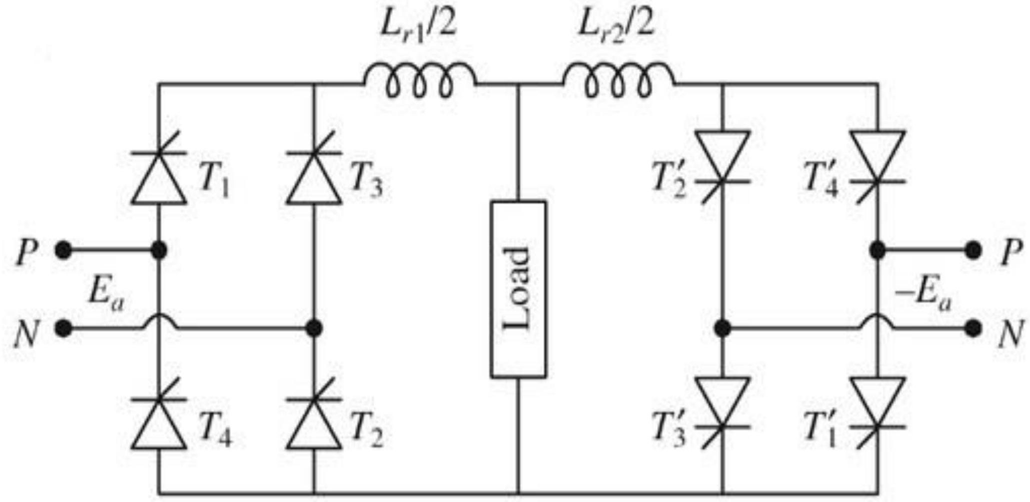


Fig. 3.6 Dual converter with circulating current.

The comparison can be made as follows:

	Non-circulating mode	*Circulating mode*
1.	In this mode, load current is discontinuous.	In this mode, load current is continuous.
2.	Two converters are operated separately.	Two converters are operated simultaneously.
3.	It doesn't require any limiting reactors.	It required current limiting reactors.
4.	Due to non-existence of reactors, it is efficient and the losses are less.	Losses are more and efficiency is less.
5.	It is a slow process.	It is a fast process.
6.	Without limiting reactors, if any high currents is present while doing the operation, it will damage the circuit.	With limiting reactors, high currents will be limited while doing the operation. It will protect the circuit.
7.	The average output load will be less than the load.	The average output load will be more than the load.

Single Phase Dual Converter

Single-phase full converters with inductive loads allow only a two-quadrant operation. If two of these full converters are connected back-to-back as shown in Fig. 3.7, both the output voltage and the load current flow can be reversed. The system provides a four-quadrant operation and is called a *dual converter*. Dual converters are normally used in high power variable speed drives. If α_1 and α_2 are the delay angles of converters 1 and 2 respectively, the corresponding output voltages are E_{dc1} and E_{dc2} respectively. The delay angles are controlled so that one converter operates as a rectifier and the other converter operates as an inverter. But both converters produce the same average output voltage.

Figure 3.8 shows the output waveforms for two converters, where the two average output voltages are the same. The dual converters can be operated with or without a circulating current. In case of operation without circulating current, only one converter operates at a time and carries the load current, and the other converter is completely blocked by inhibiting gate pulses.

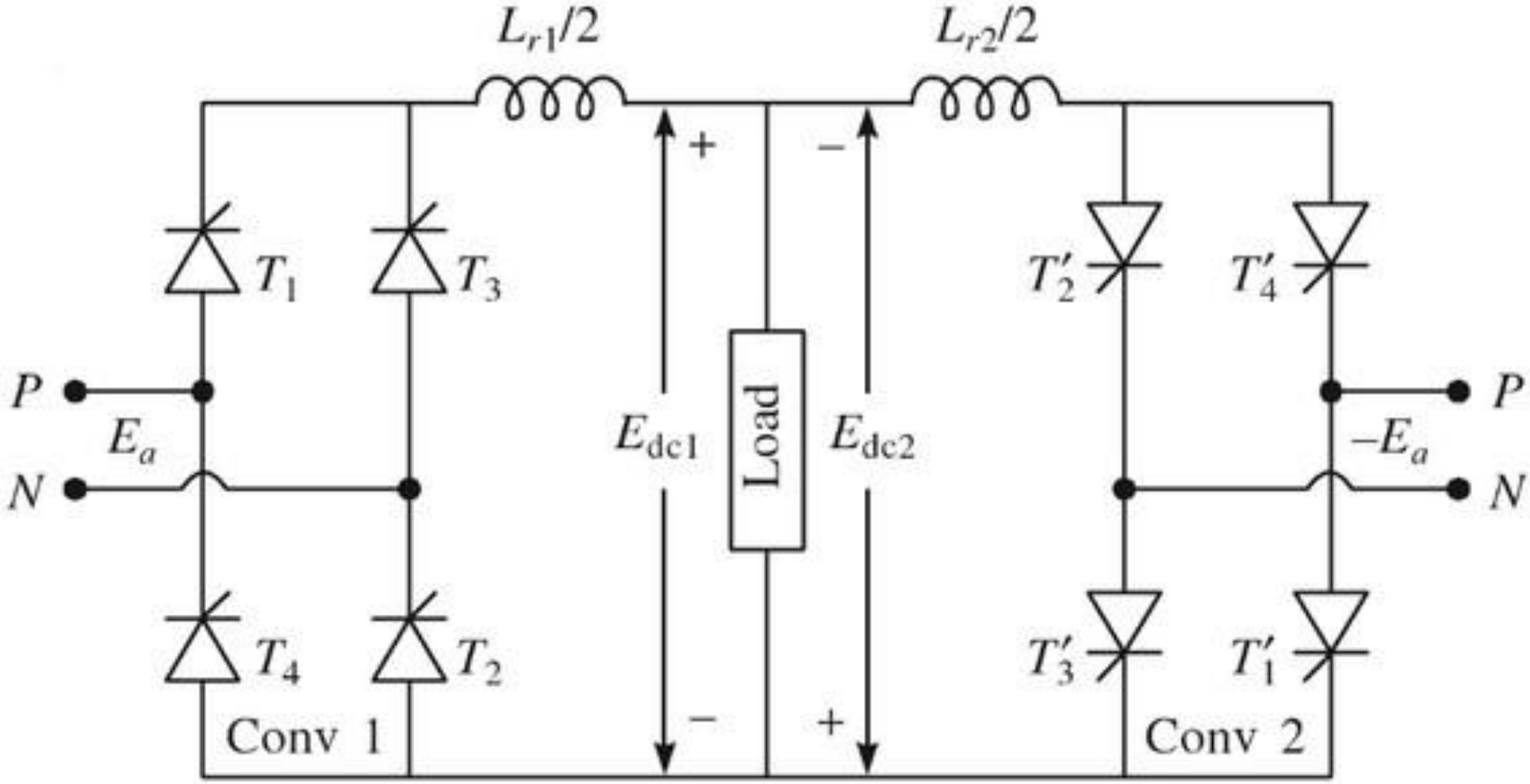


Fig. 3.7 Single-phase dual converter.

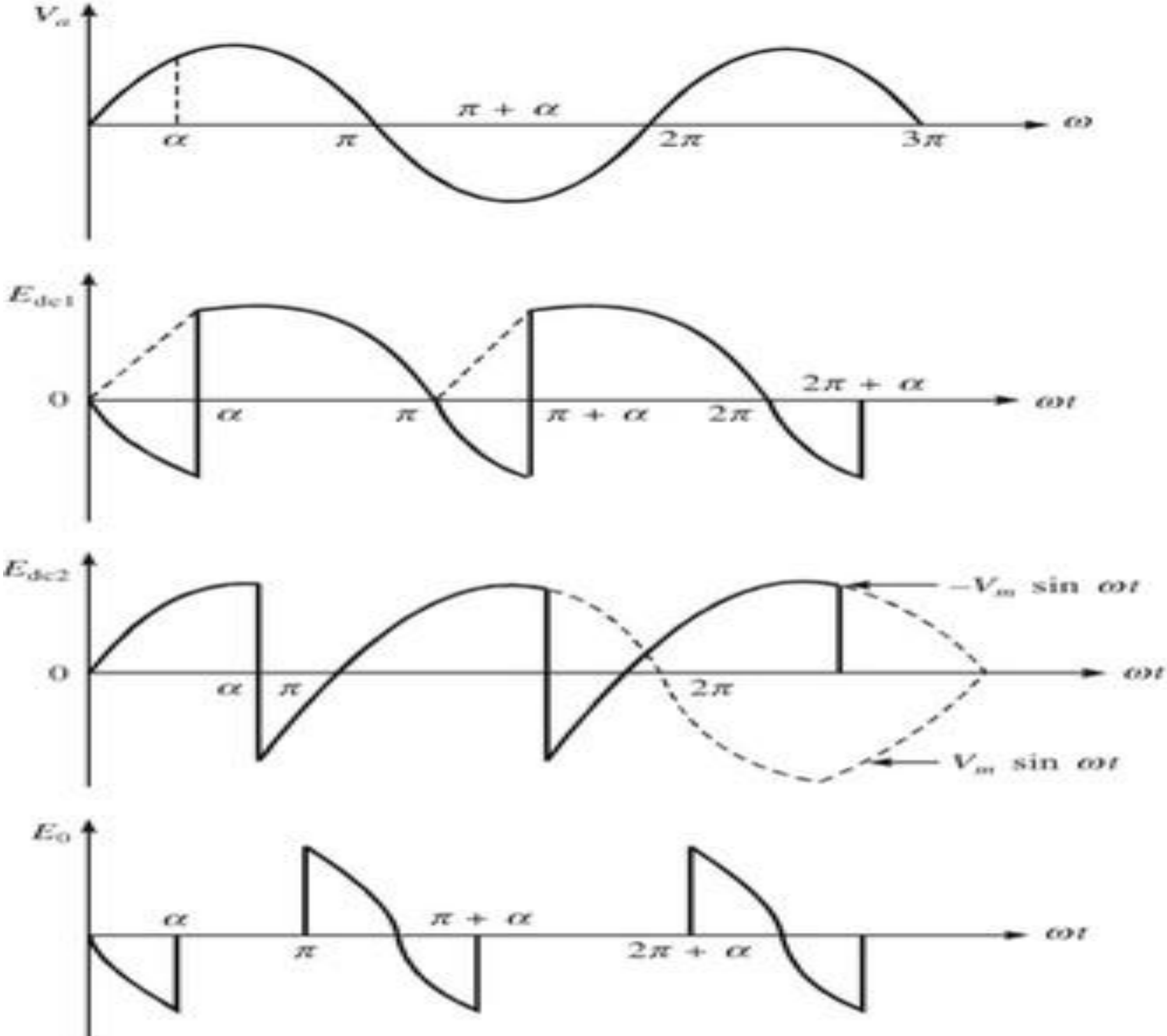


Fig. 3.8 Output waveforms.

Three Phase Dual Converter

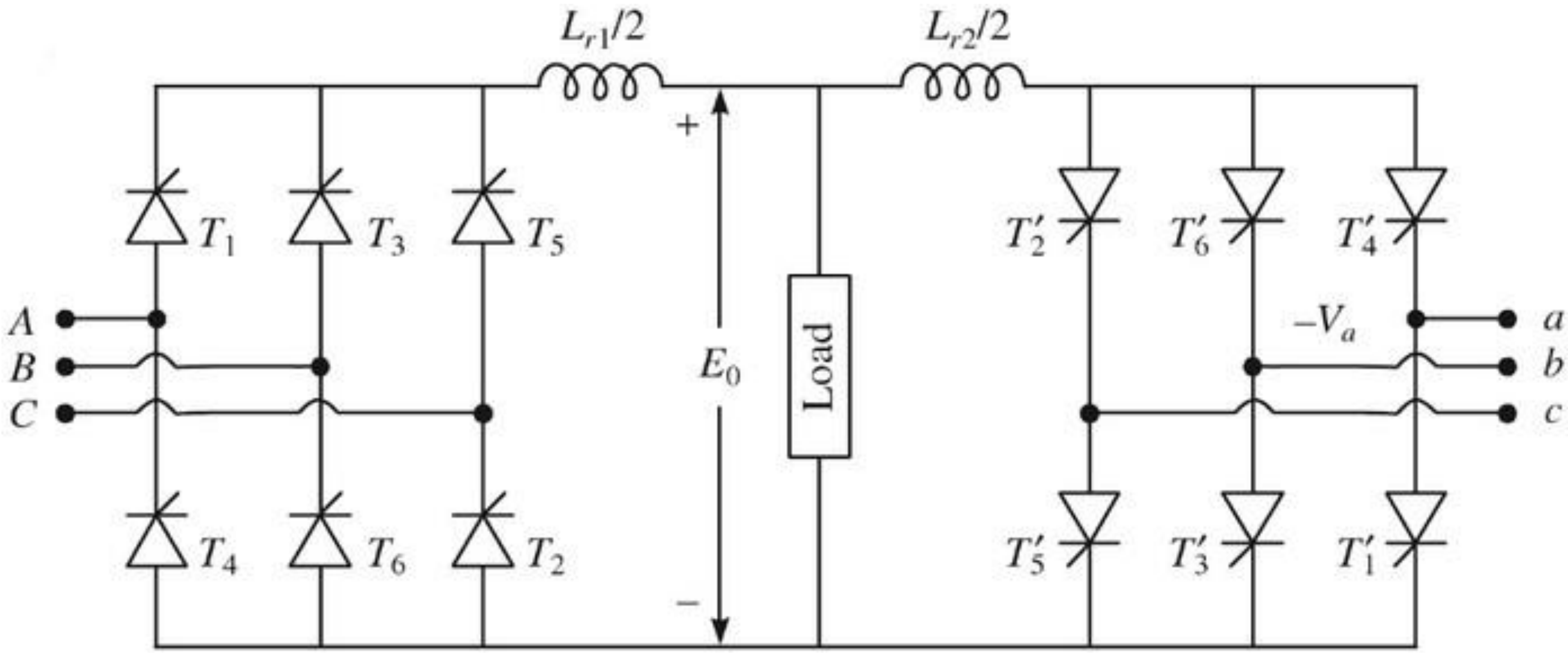


Fig. 3.9 Three-phase dual converter.

Three-phase dual converters are extensively used in applications up to 2 MW level. Three-phase full converters with inductive loads allow only a two-quadrant operation. Two of these full converters are connected back to back as shown in Fig. 3.9. In many variable speed drives, the four-quadrant operation is generally required.

The circulating current is normally limited by circulating reactor L_r as shown in Fig. 3.9. The two converters are controlled in such a way that if α_1 is the delay angle of converter 1, the delay angle of converter 2 is $\alpha_2 = \pi - \alpha_1$.

Figure 3.10 shows the waveforms for input and output voltages. The operation of each converter is identical to that of a three-phase full converter. During the interval $(\pi/6 + \alpha_1) \le \omega t \le (\pi/2 + \alpha_1)$, the line-to-line voltage V_{ab} appears across the output of converter 1, and V_{bc} appears across converter 2.

If the line-to-neutral voltages are

$$E_{an} = E_m \sin \omega t$$

$$E_{bn} = E_m \sin \left(\omega t - \frac{2\pi}{3}\right)$$

$$E_{cn} = E_m \sin \left(\omega t + \frac{2\pi}{3}\right)$$

The corresponding line-to-line voltages are

$$E_{ab} = E_{an} - E_{bn} = \sqrt{3}E_m \sin \left(\omega t + \frac{\pi}{6}\right)$$

$$E_{bc} = E_{bn} - E_{cn} = \sqrt{3}E_m \sin \left(\omega t - \frac{\pi}{2}\right)$$

$$E_{ca} = E_{cn} - E_{an} = \sqrt{3}E_m \sin \left(\omega t + \frac{5\pi}{6}\right)$$

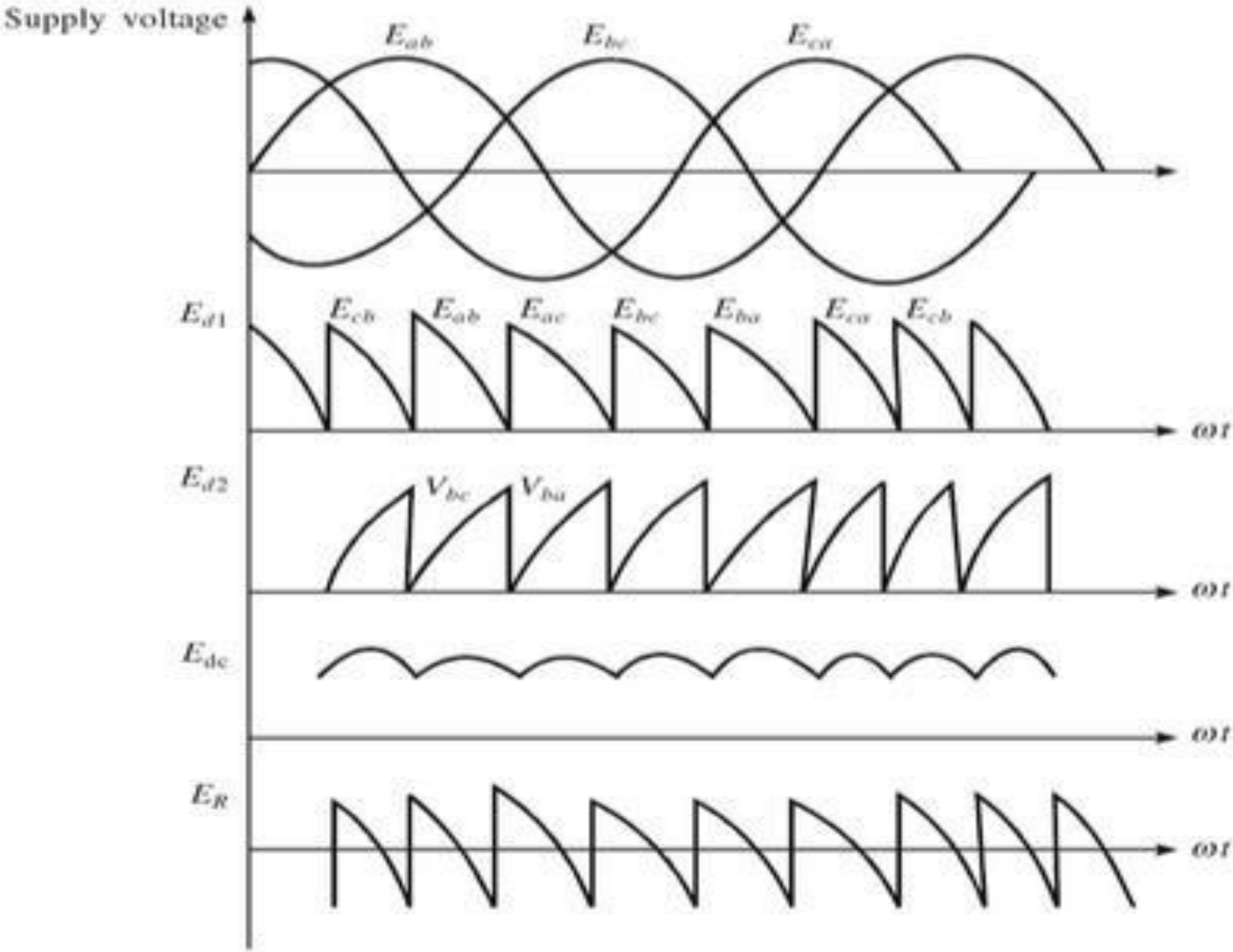


Fig. 3.10 Input-output waveforms.

Problem-1

A 220 V, 1000 rpm, 60 A separately excited dc motor with armature resistance of 0.6 Ω is fed from a circulating current dual converter with ac source voltage (line voltage) of 165 V. Determine converter firing angles for the following operating points:

(i) Motoring operation at rated motor torque and 900 rpm
(ii) Braking operation at rated motor torque at 900 rpm
(iii) Motoring operation at rated motor torque and –900 rpm
(iv) Braking operation at rated motor torque and –900 rpm

Solution We have

(i) Back emf,

$$E_{b1} = E_a - I_a R_a$$

$$= 220 - 60\ (0.6)$$

$$E_{b1} = 184\ \text{V}$$

At 900 rpm,

$$E_{b2} = \frac{900}{1000} \times 184 \qquad (\because \quad E = (N/N_{\text{rated}}) \times E_b)$$

$$E_{b2} = 165.6\ \text{V}$$

$$E_a = E_{b2} + I_a R_a$$

$$= 165.6 + 60\ (0.6)$$

$$E_a = 201.6\ \text{V}$$

Now

$$E_a = \frac{3}{\pi} E_m \cos\ \alpha_1$$

Taking $\alpha = 0$ for rated terminal voltage,

$$E_m = 162 \times \sqrt{2} = 243.72\ \text{V}$$

$$E_a = \frac{3}{\pi} E_m \cos \alpha$$

$$\cos \alpha_1 = \frac{E_a \pi}{3V_m}$$

$$= \frac{201.6 \times 3.14}{3 \times 234.72} = 0.8989$$

$$\alpha_1 = 25.27°$$

$$\alpha_1 + \alpha_2 = 180°$$

$$\alpha_2 = 154.27°$$

$$E_a = E_b - I_a R_a$$

$$= 165 - 60\ (0.6) = 129\ \text{V}$$

$$\cos \alpha_1 = \frac{E_a}{E_m} \times \frac{\pi}{3}$$

$$= \frac{129}{233.38} \times \frac{\pi}{3}$$

$$\cos \alpha_1 = 0.586$$

$$\alpha_1 = 54.49°$$

$$\alpha_2 = 180° - \alpha_1$$

$$\alpha_2 = 157.72°$$

$$\alpha_1 = 54.49^\circ$$

$$\alpha_2 = 180^\circ - \alpha_1$$

$$\alpha_2 = 157.72^\circ$$

(iii) For negative signs, $\alpha_2 < 90^\circ$ and $\alpha_1 > 90^\circ$.
Hence from (i), $\alpha_1 = 25.27^\circ$ and $\alpha_2 = 154.72^\circ$.

(iv) Here also the controlled rectifiers interchange their operation compared to α_2; thus,

$$\alpha_1 = 54.09^\circ \text{ and } \alpha_2 = 125.9^\circ$$

Problem-2

A 220 V, 50 Hz, 1-ϕ dual converter feeding drive has armature resistance $R_a = 10\ \Omega$, circulating inductance $L_r = 50$ mH, and delay angles $\alpha_1 = 30°$ and $\alpha_2 = 150°$. Calculate peak circulating current and peak current of converter 1 and converter 2 (inductance of motor neglected) without back emf.

Problem-3

Two 3-ϕ full converters are connected anti-parallel to form a 3-ϕ dual converter of circulating current type. The input to dual converter is 3-ϕ, 400 V, 50 Hz, and the peak valve of circulating current is to be limited to 20 A. Find the value of inductance needed for a firing angle of 60°.

Problem-4

Calculate the peak value of the circulating current for 3-ϕ circulator current type dual converter consisting of two 3-ϕ fully controlled bridges for the following given data: rms voltage per phase is 230 V, f = 50 Hz, L = 0.015 H, α_1 = 60° and α_2 = 120°.

Problem-5

A 220 V, 750 rpm, 200 A, separately excited dc motor has an armature resistance of 0.05 Ω. Armature is fed from a 3-ϕ non-circulating current mode dual converter, consisting of fully controlled rectifiers *A* and *B*. Rectifier *A* provides motoring operation, in the below forward direction, and rectifier *B* is in reverse direction. Supply voltage of ac source is 400 V. Calculate the firing angle of the rectifier for the motoring operation at rated torque and 600 rpm, assuming continuous conduction.

Braking

In any semiconductor drive, it is very important to brake or stop the motor and its work for a reasonably short period of time. Electrical braking is usually employed in applications to stop the unit driven by motors in an exact position, or to have the speed of the drive unit suitably controlled during its de-acceleration in applications requiring fast response, or where rapid emergency stop braking is used. When a loaded input is lowered, the electric braking keeps speed within the limits; otherwise the drive speed will reach a dangerous value.

Generally braking systems are two types:

(i) Mechanical or friction braking
(ii) Electrical braking.

3.3.1 Mechanical or Friction Braking

In this type of braking, the motor is stopped by using a brake shoe or band on a brake drum. It requires frequent maintenance and replacement of brake shoe, and braking power is wasted as well as it dissipates more heat energy. In spite of disadvantages, mechanical braking is used along with electrical braking to ensure reliable operation of the drive. Mechanical braking is also used to hold the standstill condition; many braking methods do not torque at standstill conditions.

3.3.2 Electrical Braking

The process of braking motors rapidly and smoothly in order to properly carry out the work operations in industrial installations by use of electrical power is known as electrical braking.

Need for electrical braking

If the load is removed from an electrical motor and supply is cut off from the motor, its speed will decrease and come to rest gradually. The time required for the motor to come to rest may be long if the motor is massive and has a run at high speed. Thus it means that it has to be provided to stop the motor quickly, which can be use in mechanical braking or electrical braking, which requires kinetic energy of moving parts, thereby reducing the time taken to stop the motor within its specified limits.

In mechanical braking, stored energy of rotating parts is dissipated in the form of heat by a brake shoe or brake drum, whereas in electrical braking, stored energy of rotating part is converted into electrical energy and dissipated in the form of heat.

Comparison of electrical braking over mechanical braking

The following are the major points of comparison:

- Mechanical braking causes excessive wear on brake shoe; therefore, it requires replacement of brake shoe usually, which makes equipment costly when compared to electrical braking. In electric braking, the part of energy is returned to supply, thereby affecting considerable savings in operating cost which is not possible in electrical braking.
- Proper maintenance is required in mechanical braking i.e., greasing of bearings, etc. which is not required in case of electric braking.
- Heat produced in electric braking does not affect the braking system, but the heat produced in mechanical braking will affect brake linings, which results in failures of brake.
- In electric braking, as supply is cut off and connected across the resistance, the driving motor acts as the generator during the period of breaking, and the motor ceases to operate as a generator at standstill condition, so that an electrical braking almost stops the machine but cannot hold it stationary. Therefore, mechanical braking is required.

3.3.3 Electrical Braking of dc Motors

Electrical braking is usually employed in applications to stop an infinite unit driven by motors to an exact position, to have the speed of the driven unit suitably controlled during its duration. In applications requiring frequency, quick, accurate or rapid emergency stops braking is used. When infinite load hoist is lowered, electrical braking keeps the speed within safe limits; otherwise the drive speed will reach a dangerous value.

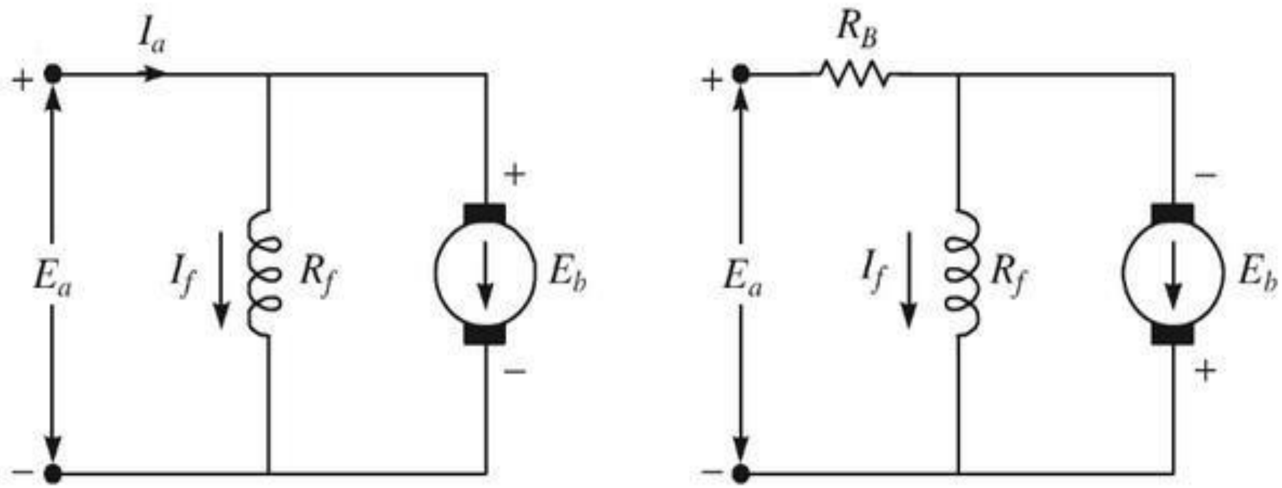
Electrical braking is classified into three types and they are:

(i) Plugging
(ii) Rheostatic or dynamic braking
(iii) Regenerative braking

Plugging

In plugging operation, the armature terminals of the dc drive are reversed, so that the dc drive or motor tends to rotate in the reverse direction, which provides the necessary braking effect. The plugging operation can be performed in separately excited series motor, which can be explained as follows:

Plugging in separately excited dc motor: The armature terminals are reversed with respect to the field terminals, so that the armature current reverses. During normal operation, the back emf E_b is opposite to the direction of the armature current but during the braking the back emf E_b and the armature current are in the same direction. At the instant of reversal, the voltage equal to $E_a + E_b$ is impressed across the armature circuit, E_a being the supply voltage. Since E_b is very nearly equal to E_a, the impressed voltage is approximately $2E_a$; therefore, this will cause increased current in armature circuit. To protect this sudden current, the starting resistance is connected in series with armature terminals as shown in Fig. 3.11.



(a) Normal operation (b) Braking operation

Fig. 3.11 Plugging operation in separately excited dc motor.

Plugging in dc series motor: The armature terminals are reversed with respect to the field terminals, so that armature current reverses. During normal operation, the back emf E_b is opposite to the direction of the armature current, but during braking the back emf E_b and the armature current are in the same direction. At the instant of reversal, the voltage equal to $E_a + E_b$ is impressed across the armature circuit, E_a being the supply voltage. Since E_b is very nearly equal to E_a, the impressed voltage is approximately $2E_a$; therefore this will cause a increase current in armature circuit. To protect this sudden current, the starting resistance is connected in series with armature terminals as shown in Fig. 3.12.

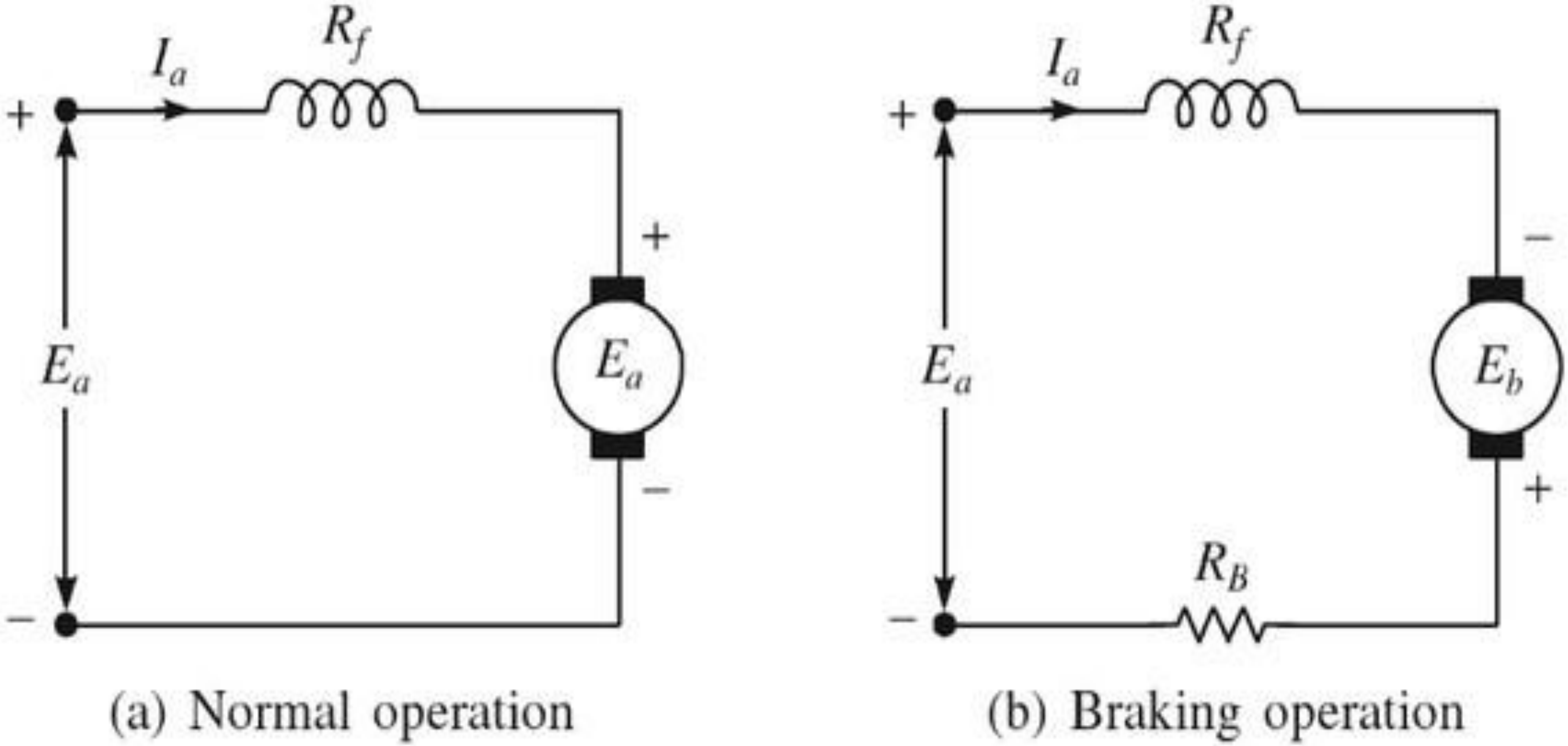


Fig. 3.12 Plugging operation in dc series motor.

Electrical braking torque, $T_B \propto \phi I$

But
$$I = \frac{E_a + E_b}{R_B}$$

where

E_a = Armature voltage
E_b = Back emf
R_B = Current limit resistance circuit.

$$\therefore \qquad T_B = K_1 \phi \frac{V_a + E_b}{R_B}$$

Back emf is proportional to motor speed and flux, i.e.,

$$E_b \propto N\phi$$
$$E_b = K_2 N\phi$$

Substituting Eq. (3.11) in Eq. (3.10),

$$\therefore \qquad T_B = K_1 \phi \left(\frac{V_a + K_2 N\phi}{R_B} \right)$$

$$= \frac{K_1 \phi V_a}{R_B} + \frac{K_1 K_2 N \phi^2}{R_B} = K_3 \phi + K_4 N \phi^2$$

In case of a series motor, ϕ is proportional to the current, and the value of the torque can only be determined from the magnetization curve. For a shunt motor, ϕ is constant.

$$T_B = K_3\phi + K_4N\phi^2 = K_5 + K_6N$$

Plugging gives fast braking due to high average torque, even with one section of current limit resistance R_B. Where torque is not zero for its zero speed when used for stopping load, the supply must be disconnected when close to zero speed.

Advantages: This is the simplest type of braking. This method can be applied to direct current motors or alternating current induction and synchronous motors. This method is used to get either a quick reversal or to get a rapid stop.

The main disadvantage is heavy in-rush of current at the time of braking.

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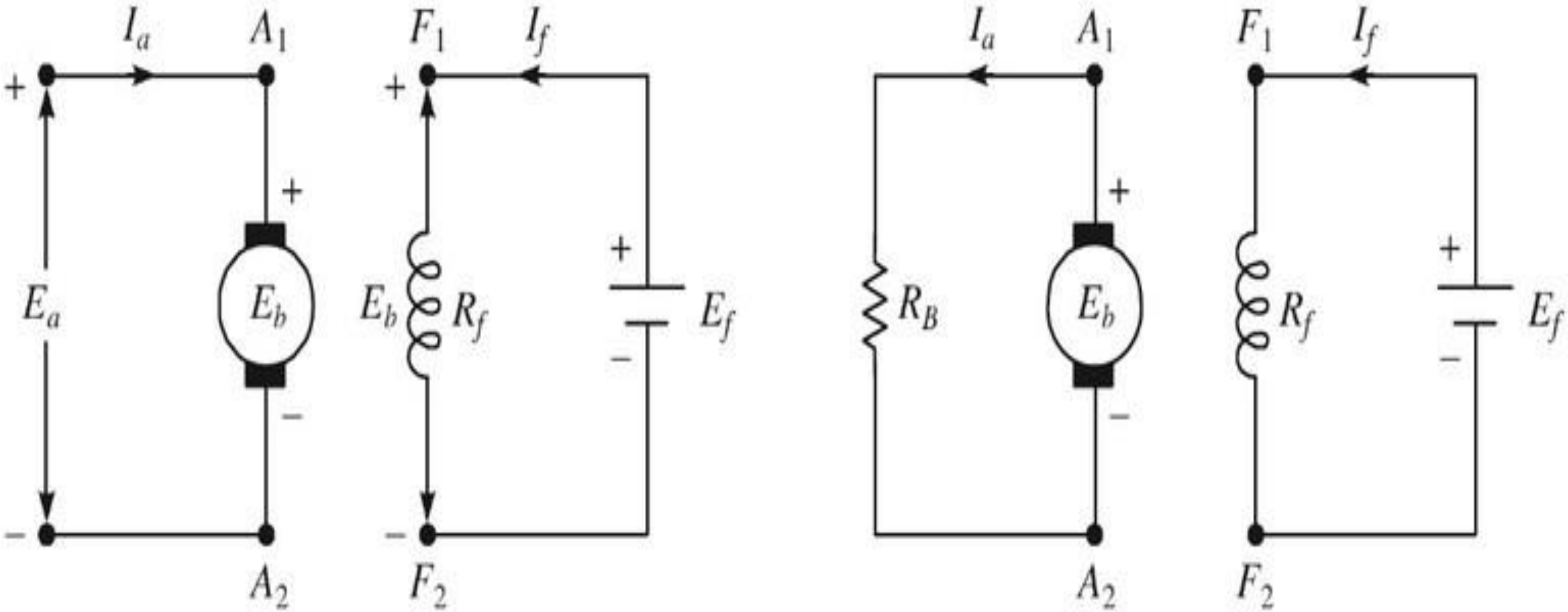
Rheostat or dynamic braking

In this braking, the motor armature terminals is disconnected from the source armature voltage, and it is connected with external resistance R_B across the motor terminals, the kinetic energy is converted into electrical energy and acts as a generator and wasted energy is dissipated in resistance R_B. The dynamic braking can be performed both in separately and series motors as explained in the following lines:

Dynamic braking in separately excited dc motor: The armature terminals are disconnected from the supply voltage and it is connected across a braking resistance. Now the motor works as a separately excited dc generator, and its braking torque as applied by the armature current will abstract to the braking resistance. If supply fails, the braking operation vanishes as its excitation disappears. Due to the action of this winding, the motor self-excites as a series generator and the current delivered by the armature terminals providing braking action is shown in Fig. 3.13.



(a) Normal operation

(b) Braking operation

Fig. 3.13 Dynamic braking operation in separately excited dc motor.

Dynamic braking in dc series excited motor: After the motor is disconnected from the supply, an additional or braking resistance is connected, which acts as a series generator. In order to ensure that the flux may build up, the connections of the armature with respect to the field are as shown in Fig. 3.14.

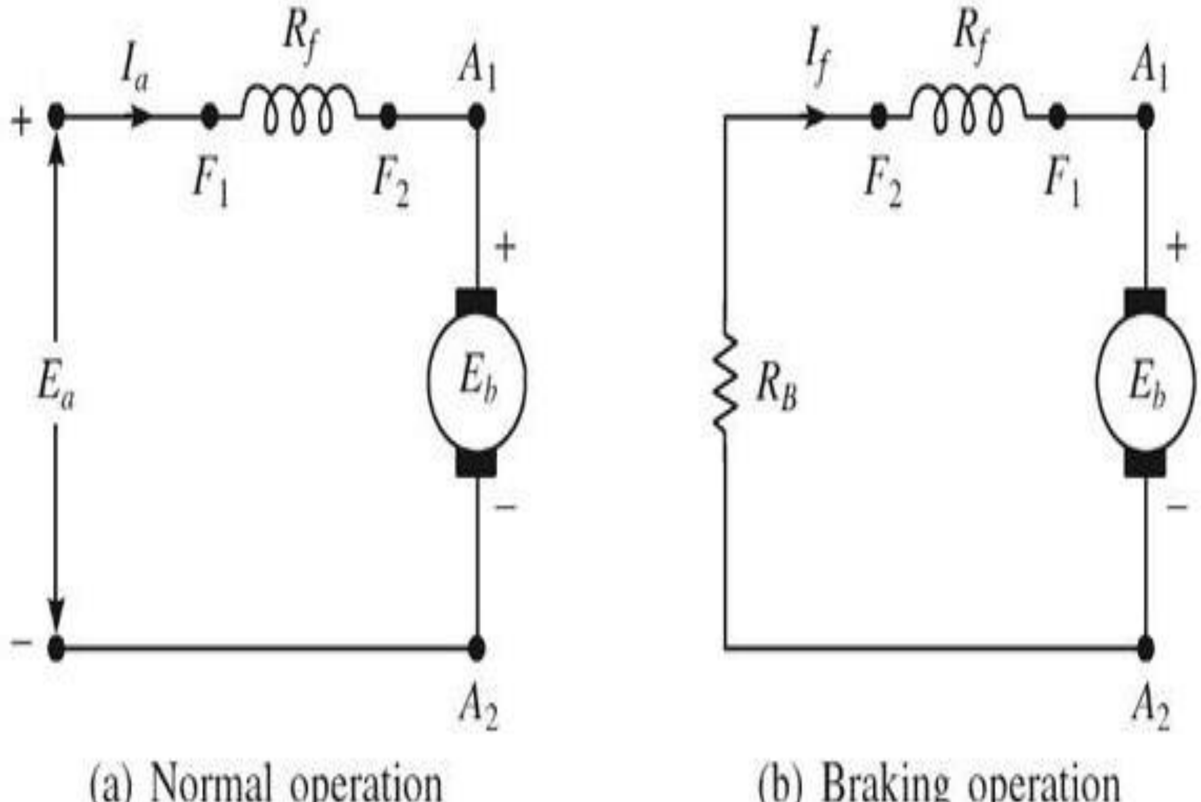


Fig. 3.14 Dynamic braking in a dc series excited motor.

Electrical braking torque $$T_B = K_1 \phi I$$

where $$I = \frac{E_b}{R_B}$$

$$\therefore \quad T_B = K_1 \phi = \frac{E_b}{R_B} = \frac{K_1}{R_B} \phi (K_2 N \phi) \qquad (\because \quad E_b = K_2 N \phi)$$

$$= \frac{K_1 K_2}{R_B} \phi^2 N$$

$$T_B = K_3 N \phi^2$$

For a shunt motor, ϕ is constant. Therefore,

$$T_B = K_4 N$$

Advantages and disadvantages: The second method of braking is advantageous compared to the first one as, if the direction of rotation of the machine armature reverses, the machine will fail to excite in the first case and therefore will not produce any braking effect. In the second case the machine will build up in series and, being short-circuited on them, will provide emergency braking. Rheostat braking cannot be employed with 3-phase induction motors. This method involves loss of power in its operation.

Regenerative braking

In regenerative braking, the generated energy is supplied to the source. For this, the following conditions should be satisfied: $E_b > E_a$ and I_a is negative. In this braking, the motor is run as generator by the kinetic energy of the load, which is returned to the mains electrical energy. It can be used in separately and series excited dc motors.

Regenerative braking in a separately excited dc motor: If the emf generated by motor is greater than the supply voltage, the power will be fed back into the supply. The shunt motor depends upon its exciting current and speed. If the field is disconnected from the supply and the field current is increased by exciting it from another source, the induced emf will exceed the supply voltage and the motor will feed energy into the supply.

Regenerative braking in dc series motor: Regenerative braking with series motors is employed mainly in traction work and operation, just like in the case of separately excited motors.

Advantages

- A part of energy is returned to the supply system, so that energy consumption for the run is considerably reduced.
- A higher value of braking retardation is obtained, so that the vehicle can be brought to rest quickly and running time can be considerably reduced.
- A small amount of brake dust is produced when brakes are applied.
- Higher speeds are possible while going down the gradients.

Disadvantages: The disadvantages are that additional equipment is required for control of regeneration and for protection of equipment and machines; hence initial as well as maintenance cost is increased. Owing to the recaptured energy, the operation of the substations becomes complicated and difficult. In case of substations employing mercury arc rectifiers for conversion purpose, additional equipment is required either to deal with regenerated energy separately or to change one or more of the ordinary rectifiers over to inverted operation. No such difficulty is experienced in case of substations employing rotary converts of motor generator sets for converting purpose.

Problem-6

A 400 V, 750 rpm, 70 A, dc shunt motor has an armature resistance of 0.3 Ω. When running under rated condition, the motor is to be braked by plugging with armature current limited to 90 A. What external resistance should be connected in series with the motor? Calculate the initial braking torque and its value when the speed is increased to 300 rpm.

Control of DC Motors By Choppers

Introduction

Speed control of industrial drives is essential in present-day industrial applications. These drives and process takes power from dc voltage sources. A number of these drives being operated by dc sources, their speed control involve variable dc supply voltage at their input.

The different techniques to get desired variable dc from fixed dc voltage source are given in the following lines.

Resistance Control

In this method, variable resistance is inserted between load and source. This method is highly wasteful of energy and involves power loss. Also, different values of resistance are needed for different values of load current. But still this method is used for older traction systems.

Motor Generator Set

Separate generator excitation gives a voltage which can be varied from zero to rated value with either polarity. The set-up is bulky and costly, slow in response as well as less efficient because of the generator field time constant.

AC Link Chopper

In this method, dc is first converted to ac by inverter, stepped up or down by a transformer, and then rectified back to dc by a rectifier. This method is costly, bulky and less efficient. Also, static transformer provides isolation between load and source voltage.

Chopper is a power electronic device that converts power directly from fixed dc to variable dc voltage. Therefore chopper may be considered the dc equivalent of an ac transformer, since its performance is identical. It provides smooth speed control and possesses high efficiency, fast dynamic response and even regeneration capability when applied in drive control. Due to various

advantages, they are widely used in trolley cars, battery-operated vehicles, as well as for control of a large number of dc motors from a common dc bus with a considerable improvement of power factor. The objective here is to discuss the principle operation of chopper and more common types of chopper circuits.

Principle of Chopper Operation

A chopper is a thyristor on/off switch that connects the load to and disconnects it from the supply, and produces a chopped load voltage from a constant input supply voltage. This process is illustrated in Fig. 4.1.

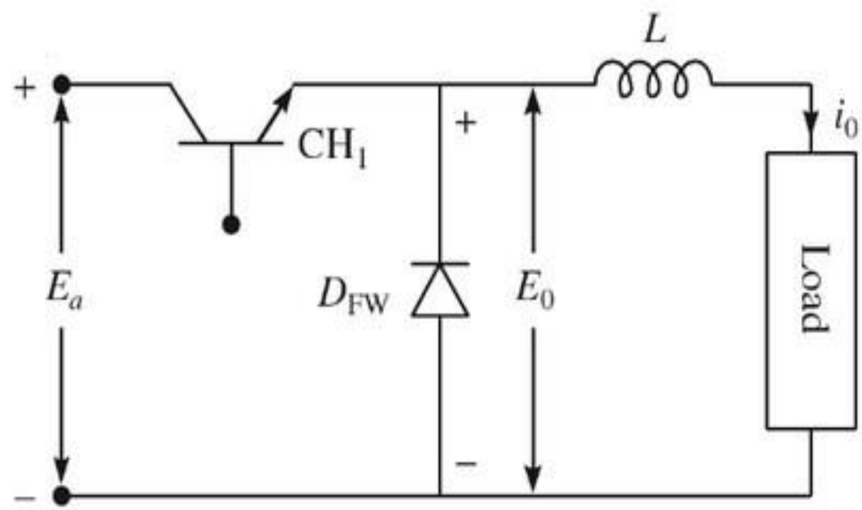


Fig. 4.1 Basic chopper circuit.

The chopper is represented by an SCR inside a dotted square. During the period t_{on} the chopper is on and the supply terminals are connected to the load terminals. During the period t_{off} the chopper is off, the load current flows through the freewheeling diode, and the load terminals are shorted. Therefore a chopped dc voltage is produced at the load terminals. Hence, the average load voltage E_0 is given by

$$E_0 = E_a \frac{t_{on}}{t_{on} + t_{off}}$$

$$= E_a \frac{t_{on}}{T}$$

where

t_{on} = Total on-time period (in seconds)

t_{off} = Total off-time period (in seconds)

T = Total time period

$$E_0 = \alpha E_a$$

$$T = t_{on} + t_{off}$$

$$\alpha = \frac{t_{on}}{T} = \text{Duty cycle}$$

Thus the load voltage can be varied by varying the duty cycle of the chopper.

4.3 CONTROL TECHNIQUES USED IN DC CHOPPERS

The average value of output voltage can be controlled with periodic on and off switches. For this, two types of control techniques are employed in dc choppers. They are:

(i) Time ratio control (TRC) or pulse-width control
(ii) Current limit control (CLC) or frequency modulation control.

4.3.1 Time Ratio Control (TRC)

In this control, again the on-period time is controlled in two ways, and they are:

(a) Constant frequency TRC control
(b) Variable frequency TRC control.

Constant frequency TRC control

In constant frequency control, the on-time is varied but chopping frequency and hence chopping time interval T is kept constant. This is called *pulse-width modulation control.*

Variable frequency TRC control

In variable frequency control, the chopping period T is varied and either t_{on} is kept constant or t_{off} is kept constant; α is controlled. This is called *frequency modulation control.*

$V_O = (T_{ON} / T_{ON} + T_{OFF}) V_{dc}$

$= (T_{ON} / T_{ON} + T_{ON}) V_{dc} (T_{ON} = T_{OFF})$

$= 0.5V_{dc}$

- If the chopper ON time is kept ¼ times chopper OFF time, the output voltage becomes 20% of the input voltage.

$V_O = (T_{ON} / T_{ON} + T_{OFF}) V_{dc}$

$= (T_{ON} / T_{ON} + 4T_{ON}) V_{dc} \; (T_{ON} = T_{OFF} / 4)$

$= 0.2V_{dc}$

$= 20\% \; V_{dc}$

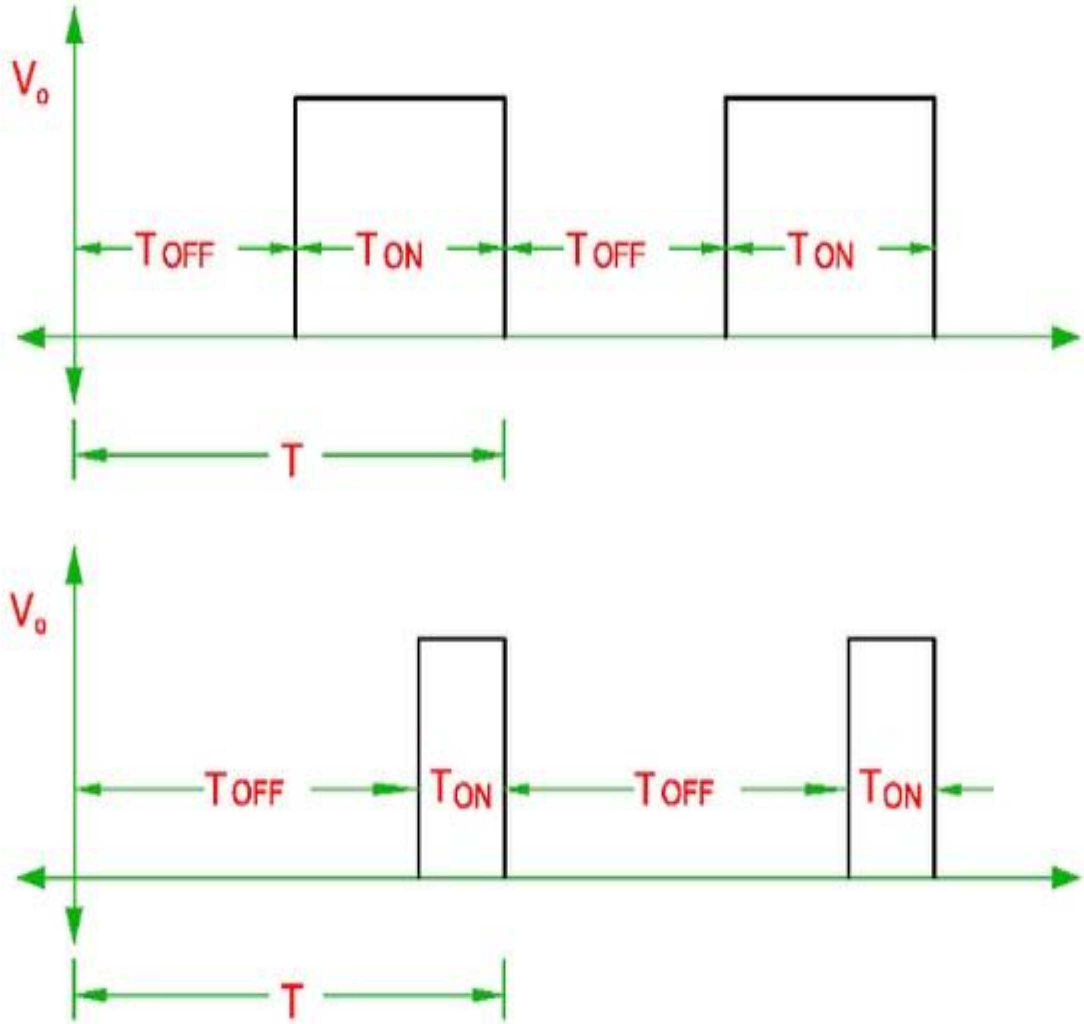


FIG A : CONSTANT FREQUENCY CONTROL

(A) $T_{ON} = T_{OFF}$

(B) $T_{ON} = 1/4 \; T_{OFF}$

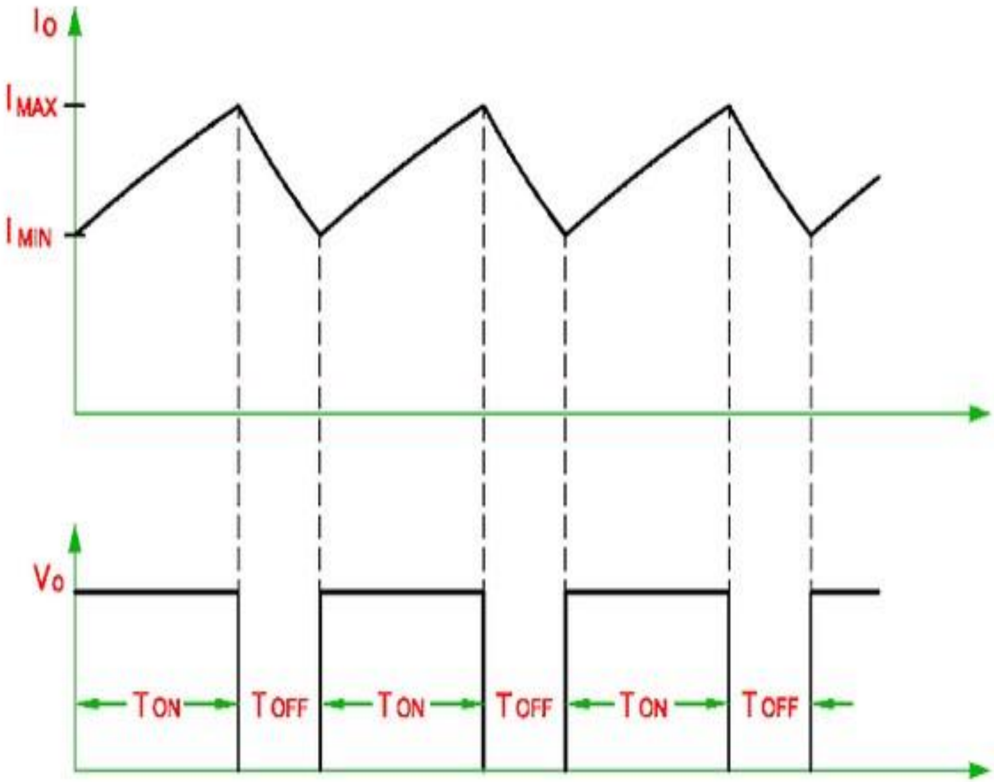


FIG D : CURRENT LIMIT CONTROL

Current Limit Control (CLC)

Here, α is controlled by controlling the load current between maximum and minimum values. The switch disconnects the load from the source and reconnects it when the load current reaches its minimum value current.

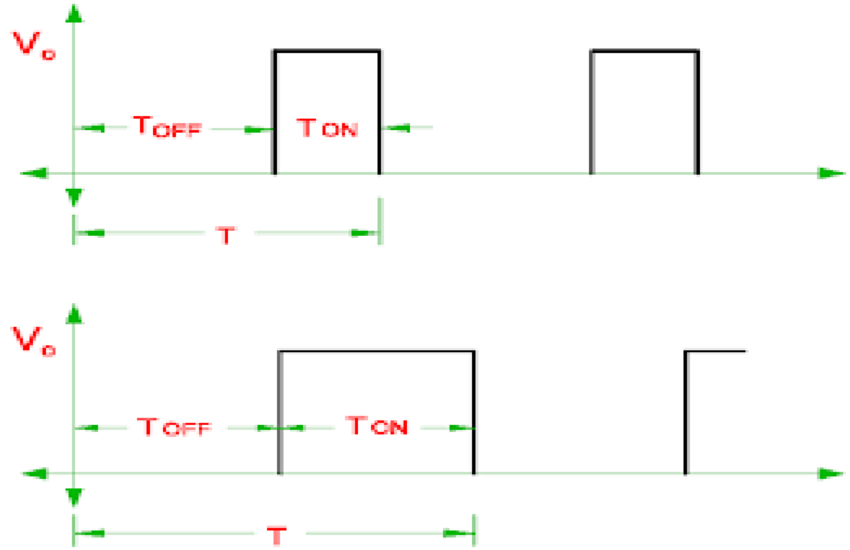


FIG B : VARIABLE FREQUENCY CONTROL
(T_{OFF} CONSTANT)

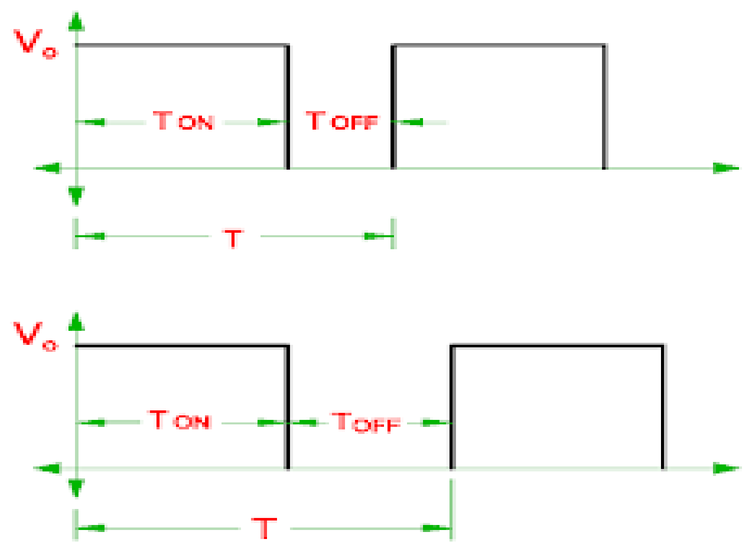


FIG C : VARIABLE FREQUENCY CONTROL
(T_{ON} CONSTANT)

Chopper Configuration

Generally, choppers may be classified according to the four quadrant operations of the E_0–I_0 diagram in which they are capable of operating by various combinations of operational performance. It is possible to realize and combination of output voltage as well as current polarity with reference to the combination operation performance shown in Fig. 4.2. The load

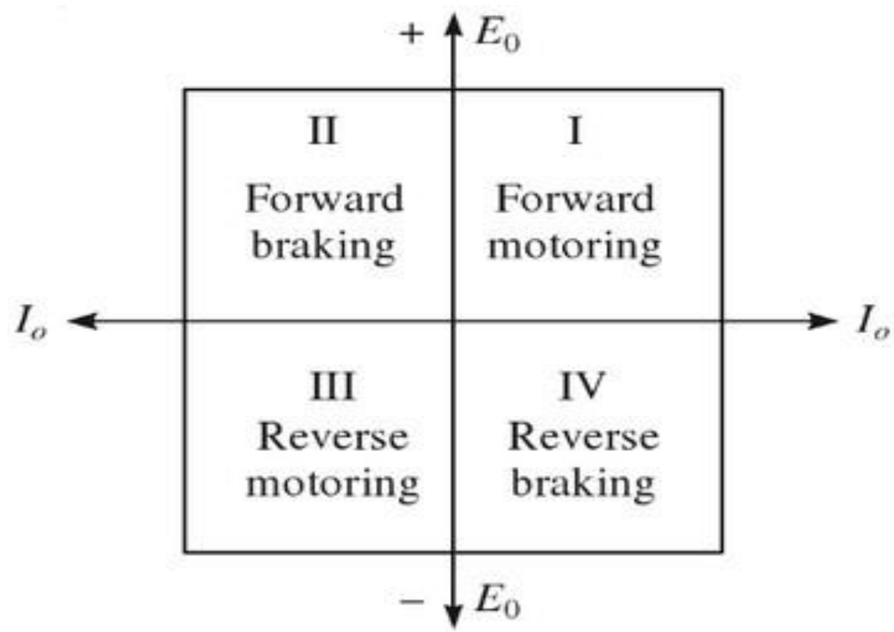


Fig. 4.2 Basic chopper configuration.

is either separately excited motor of constant field or series excited motor. Then the polarity of the first quadrant will be positive voltage and positive current, which gives rise to a *forward motoring operation*. Changing the polarity of both armature voltage and current results in a reverse direction, which results in a *reverse motoring operation* in second and fourth quadrants. The direction of energy flows in reverse direction and motor operates as braking rather than driving.

In regenerative braking process, the kinetic energy is referred from the load to source, which provides the condition in such a way that the rotational back emf must be grater than the applied voltage. Here, when the current is reversed, the mode of operation changes from motoring to generating. Therefore, the chopper which gives this regenerative braking facility is widely compared to systems without regenerative braking, especially in automotive vehicles during typical urban traction system.

Therefore, in chopper configuration circuits the dc motor assumed as a load is required to operate in the first and third quadrant. For instance, the resistance may also serve as a load. But generation mode can be maintained over any significant span of time if the load is capable of delivering sustained power. The following section describes the classification of chopper configurations.

Classification of Chopper Circuits

According the operation of different chopper circuits, the choppers can be classified as follows:

(i) First-quadrant type chopper

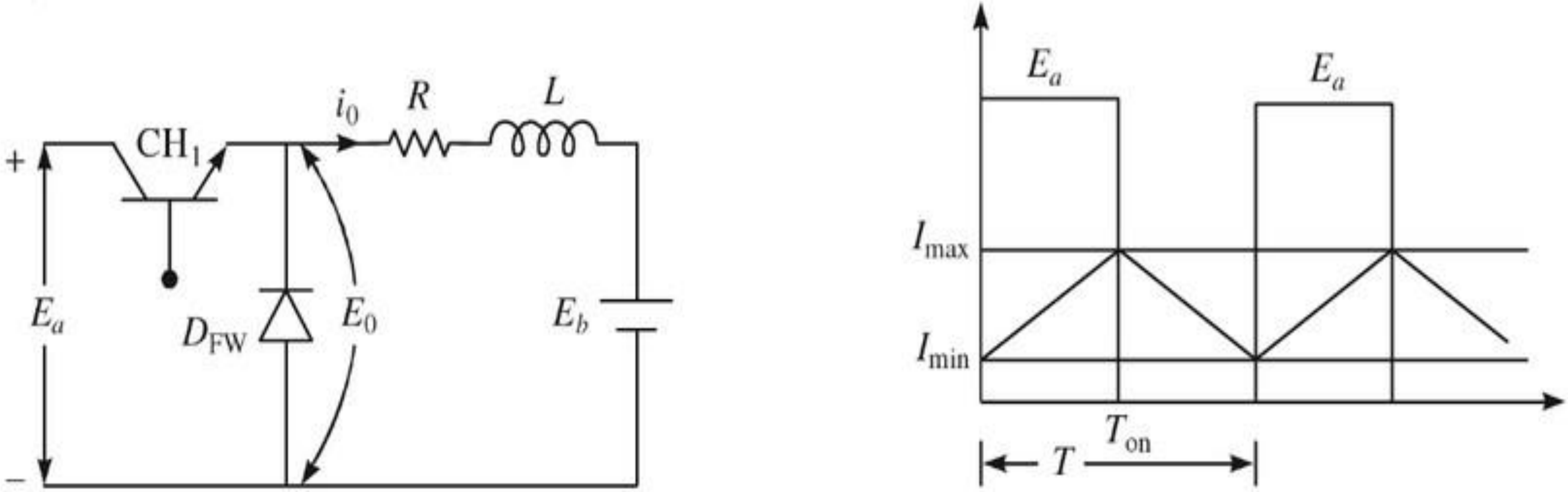
(ii) Second-quadrant type chopper

(iii) Four-quadrant type chopper

First-quadrant Type Chopper

The chopper controlled separately excited dc motor drive is shown in Fig. 4.3. Therefore the chopper CH_1 is operated periodically with period T and remains on for period t_{on} and makes the chopper operate at a higher frequency to ensure continuous conduction. During the chopper's on-period $0 \leq t \leq t_{on}$, the chopper conducts and makes the load current flow from source to load, thereby the voltage is E_0.

Due to current limit control, the armature current increases from I_{min} to I_{max}. Since the motor is connected to the source during this interval, the interval is called *duty interval*. At instant $t = t_{on}$, the chopper is turned off, and the armature current passing through the freewheeling diode D_{FW} and the motor terminal voltage is zero during the interval $t_{on} \leq t \leq T$. Due to current limit control, the armature current decreases from I_{max} to I_{min}.

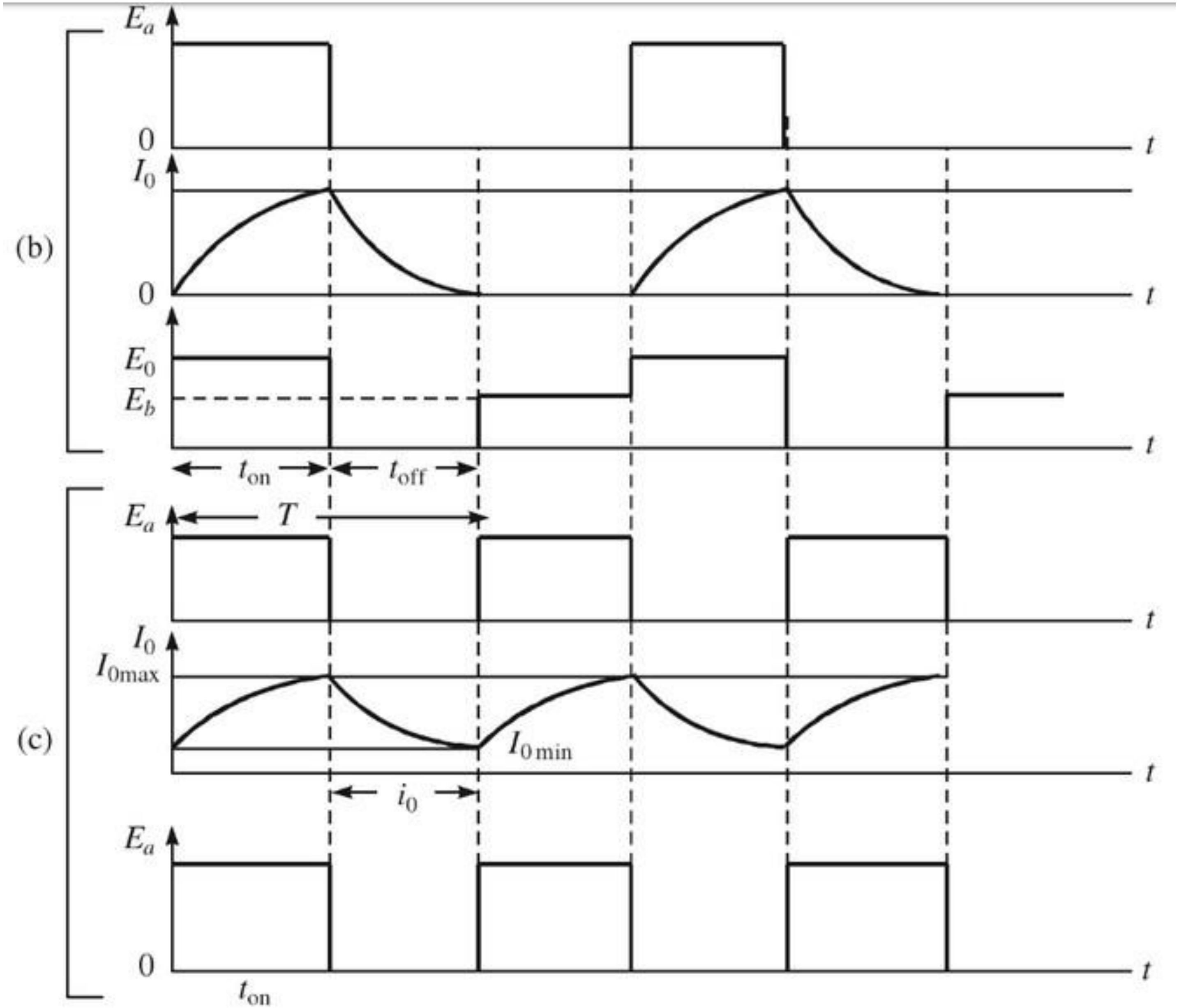


(a) First quadrant type chopper.

Mode 1: During $0 \le t \le T_{on}$, when the chopper is on, the current flows through the path $E_a^+ - R - L - E_b - E_a^-$. For this mode of operation, the differential equation governing its performance is given by

$$E_a = Ri_o + L\frac{di_o}{dt} + E_b \qquad \text{for } 0 \le t \le T_{on} \tag{4.3}$$

Mode 2: During $T_{on} \le t \le T$, when the chopper is off, the load current continuously flows through the frequency diode D_{FW}. For this mode of operation, the differential equation governing its performance is given by



(b) Discontinuous load current. (c) Continuous load current.

$$O = Ri_0 + L\frac{di_0}{dt} + E_b \qquad \text{for } T_{\text{on}} \le t \le T \tag{4.4}$$

Now, by taking Laplace transform of Eqs. (4.3) and (4.4),

$$\frac{E_a - E_b}{S} = RI_{0(S)} + L[SI_{0(S)} - I_{0\min}] \tag{4.5}$$

$$\frac{-E_b}{S} = RI_{0(S)} + L[SI_{0(S)} + I_{0\max}] \tag{4.6}$$

Equation (4.5) can also be written as

$$I_{0(S)} = \frac{(E_a - E_b)}{S(R + LS)} + \frac{LI_{0\min}}{(R + LS)}$$

$$I_{0(S)} = \frac{(E_a - E_b)}{SL[S + (R/L)]} + \frac{LI_{0\min}}{L[S + (R/L)]}$$

$$I_{0(S)} = \frac{(E_a - E_b)}{SL[S + (R/L)]} + \frac{I_{0\min}}{[S + (R/L)]} \tag{4.7}$$

Now, by taking inverse Laplace of Eq. (4.7), we get

$$i_{0(t)} = \frac{(E_a - E_b)}{R}[1 - e^{-R/L^t}] + I_{0\,\min}\, e^{-R/L^t} \qquad 0 \le t \le T_{\text{on}} \quad (4.8)$$

Let us define time constant, $\tau = L/R$, so that Eq. (4.8) becomes

$$i_{0(t)} = \frac{(E_{\text{dc}} - E_b)}{R}[1 - e^{-t/\tau}] + I_{0\,\min}\, e^{-t/\tau} \qquad 0 \le t \le T_{\text{on}} \quad (4.9)$$

When chopper is commutated at $t = T_{\text{on}}$,

$$i_{0(t)} = I_{0\max}$$

Thus, Eq. (4.9) becomes

$$I_{0\max} = \frac{(E_a - E_b)}{R}(1 - e^{-T_{\text{on}}/\tau}) + I_{0\,\min}\, e^{-T_{\text{on}}/\tau} \qquad (4.10)$$

From Eq. (4.6), we can write

$$I_{0(S)} = R + LS = \frac{-E_b}{S} + LI_{0\max}$$

$$I_{0(S)} = \frac{-E_b}{S(R + LS)} + \frac{LI_{0\,\max}}{(R + LS)}$$

$$I_{0(S)} = \frac{-E_b}{SL[S + (R/L)]} + \frac{LI_{0\,\max}}{[S + (R/L)]}$$

$$I_{0(S)} = \frac{-E_b}{SL[S + (R/L)]} + \frac{I_{0\,\max}}{S + (R/L)} \qquad (4.11)$$

Now, by taking inverse Laplace transform of Eq. (4.11), we get

$$I_{0(t)} = \frac{-E_b}{R}(1 - e^{-t/\tau}) + I_{0\min}\, e^{-t/\tau} \qquad T_{\text{on}} \le t \le T \tag{4.12}$$

For interval $T_{\text{on}} \le t \le T$, let us define

$$t' = t - T_{\text{on}}$$

so that when $t = T_{\text{on}}$, $t' = 0$, and for $t = T$, and $t' = T - T_{\text{on}} = T_{\text{off}}$. Substituting t' in Eq. (4.12), we get

$$i_0(t') = \frac{-E_b}{R}(1 - e^{-t'/\tau}) + I_{0\min}\, e^{-t'/\tau} \qquad T_{\text{on}} \le t \le T \tag{4.13}$$

Now, at $t' = T - T_{\text{on}} = T_{\text{off}}$, $i_0(t') = I_{0\min}$.
Thus, Eq. (4.14) becomes

$$I_{0\min} = \frac{-E_b}{R}(1 - e^{-(T-T_{\text{on}})/\tau}) + I_{0\max}\, e^{-(T-T_{\text{on}})/\tau} \tag{4.14}$$

Equation (4.10) can be solved for $I_{0\max}$ and $I_{0\min}$ as follows:

$$I_{0\max} = \frac{E_a}{R}(1 - e^{-T_{\text{on}}/\tau}) - \frac{E_b}{R}(1 - e^{-T_{\text{on}}/\tau}) + I_{0\min}\, e^{-T_{\text{on}}/\tau} \tag{4.15}$$

Substituting $I_{0\min}$ from Eq. (4.14) in Eq. (4.15), we get

$$I_{0\max} = \frac{E_a}{R}(1-e^{-T_{on}/\tau}) - \frac{E_b}{R}(1-e^{-T_{on}/\tau}) - \frac{E_b}{R}e^{-T_{on}/\tau}(1-e^{-(T-T_{on})/\tau}) + I_{0\max}\, e^{-(T-T_{on})/\tau}\, e^{-T_{on}/\tau}$$

$$= \frac{E_a}{R}(1-e^{-T_{on}/\tau}) - \frac{E_b}{R} + \frac{E_b}{R}e^{-T_{on}/\tau} - \frac{E_b}{R}e^{-T_{on}/\tau} + \frac{E_b}{R}e^{-(T-T_{on})/\tau} \times e^{-T_{on}/\tau}$$

$$+ I_{0\max}\, e^{-T/\tau} e^{+T_{on}/\tau} e^{-T_{on}/\tau}$$

$$= \frac{E_a}{R}(1-e^{-T_{on}/\tau}) - \frac{E_b}{R}(1-e^{-T/\tau}) + I_{0\max}\, e^{-T/\tau}$$

or

$$I_{0\max} - I_{0\max}\, e^{-T/\tau} = \frac{E_a}{R}(1-e^{-T_{on}/\tau}) - \frac{E_b}{R}(1-e^{-T/\tau})$$

$$I_{0\max} = \frac{E_a}{R}\left(\frac{1-e^{-T_{on}/\tau}}{1-e^{-T/\tau}}\right) - \frac{E_b}{R} \tag{4.16}$$

Now, substituting the value of $I_{0\max}$ from Eq. (4.16) in Eq. (4.14), we get

$$I_{0\min} = \frac{-E_b}{R} + \frac{E_b}{R} e^{-(T-T_{on})/\tau} + \frac{E_a}{R}\left(\frac{1-e^{-T_{on}/\tau}}{1-e^{-T/\tau}}\right) \times e^{-(T/T_{on})/\tau} - \frac{E_b}{R} e^{-(T-T_{on})/\tau}$$

$$= \frac{E_a}{R}\left(\frac{1-e^{-T_{on}/\tau}}{1-e^{-T/\tau}}\right)\frac{e^{T_{on}/\tau}}{e^{T/\tau}} - \frac{E_b}{R}$$

$$= \frac{E_a}{R}\frac{e^{T_{on}/\tau}}{e^{T/\tau}} - \frac{E_b}{R}$$

When chopper CH_1 is continuously turned on, then $T_{on} = T$ and both $I_{0\max}$ and $I_{0\min}$ have the value given by the equation $I_0 = (E_a - E_b)/R$, i.e.,

$$I_{0\max} = I_{0\min} = \frac{E_a - E_b}{R} \tag{4.18}$$

Second-Quadrant Chopper

From Figures 4.5(a) and (b), during the $0 < t < t_{on}$ period the chopper conducts, where its motor terminal current flows from load to the source. Thereby the armature current increases from I_{min} to I_{max}. This armature current makes the energy conversion, i.e., from mechanical energy to electrical energy, and then makes the motor load operate as a generator. Now the stored magnetic energy in the armature circuit inductance increases and is partly dissipated in R_a and chopper circuit. During $t_{on} < t < T$, the chopper does not conduct and it makes the load current flow through diode D_2 and source E_b. Then the armature current decays from I_{max} to I_{min} and thus this armature current makes the energy conversion in a manner opposite to what it had performed during the t_{on} period; thereby the regeneration process can be performed in two intervals, i.e., $0 < t < t_{on}$ as energy storage interval and $t_{on} < t < T$ as duty interval.

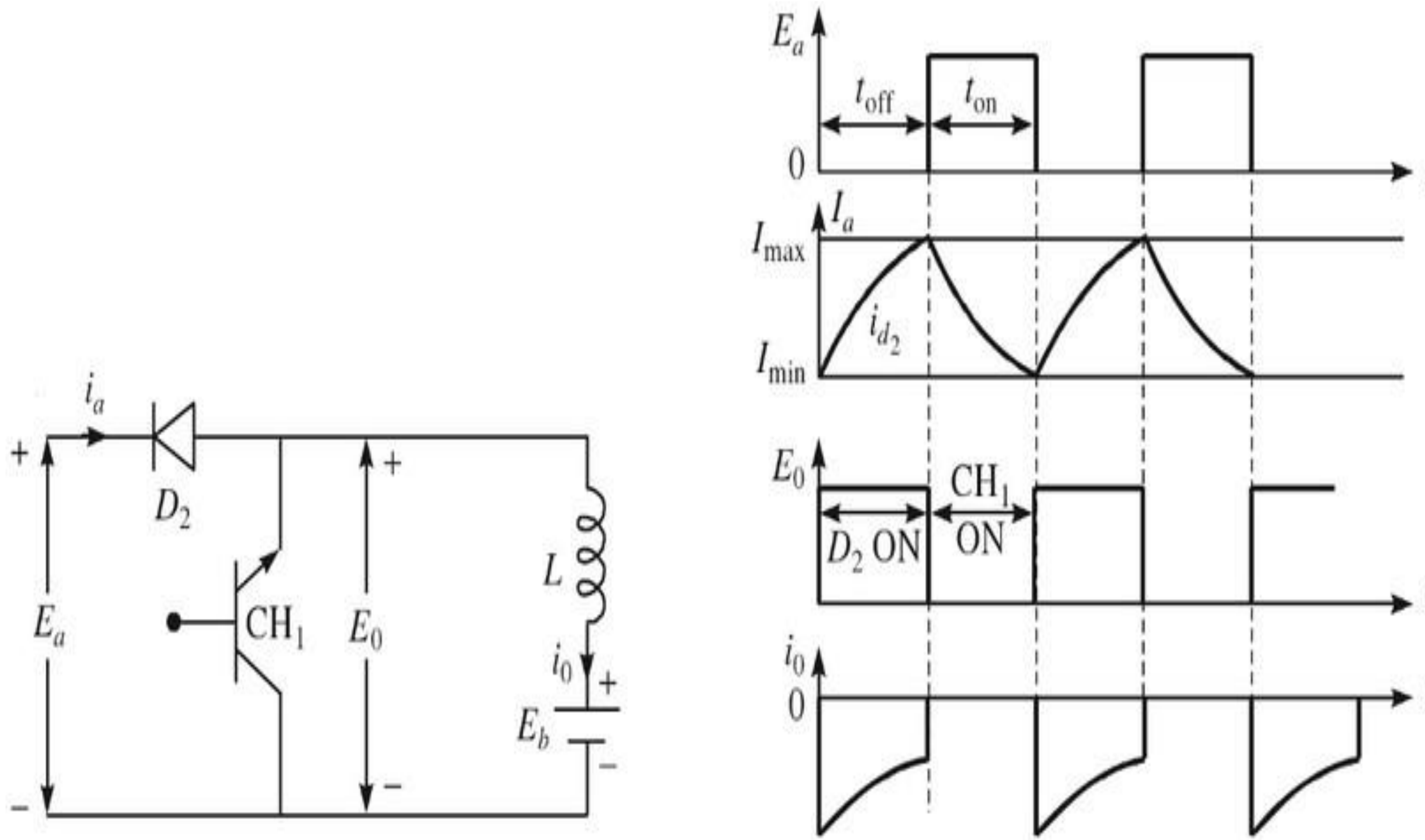


Fig. 4.5 (a) Second quadrant type chopper; (b) Input-output voltage waveforms.

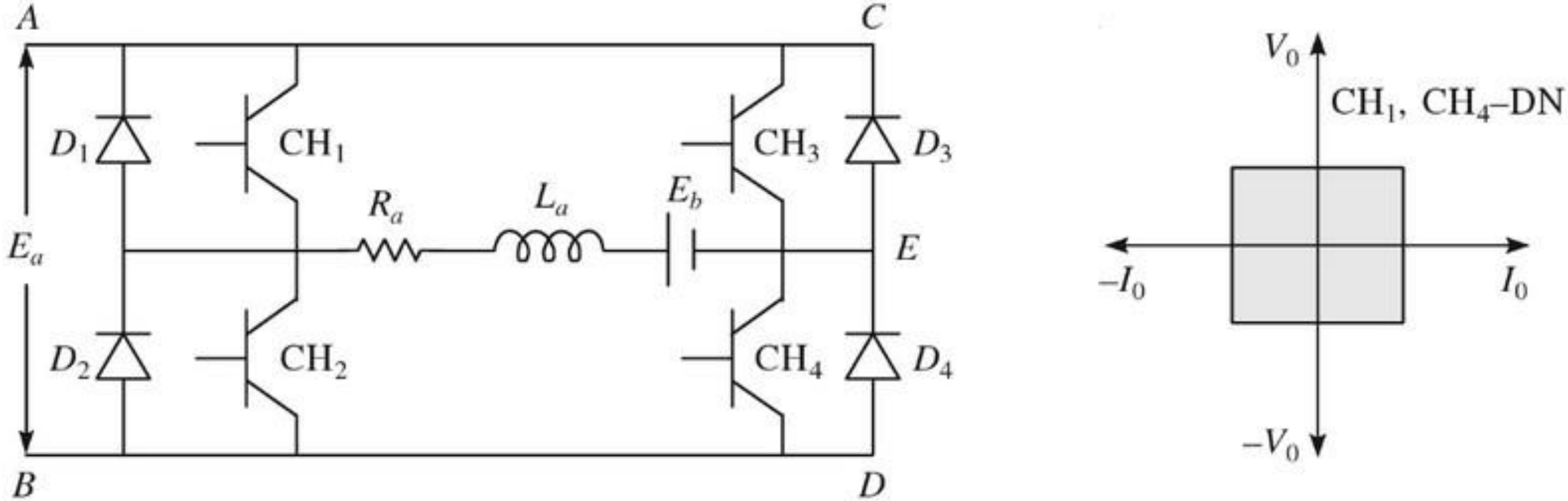
Four-Quadrant Chopper

The class E chopper drive or four-quadrant drive operation can be explained in four modes of operation. They are:

(a) First quadrant: Forward motoring operation
(b) Second quadrant: Forward braking operation
(c) Third quadrant: Reverse motoring operation, and
(d) Fourth quadrant: Reverse braking operation.

First quadrant: Forward motoring operation

From the circuit diagram which is shown in Fig. 4.6, the operation can be explained as follows: choppers CH_1 and CH_2 are turned on, the load is connected across the supply, and the voltage is positive. Therefore the motor load acts as a motor, which rotates in forward direction, and its motor voltage is equal to its supply voltage. For chopping CH_2 is turned off, the positive current freewheels through CH_2 and D_2, and the current direction is positive and its motor voltage is zero.



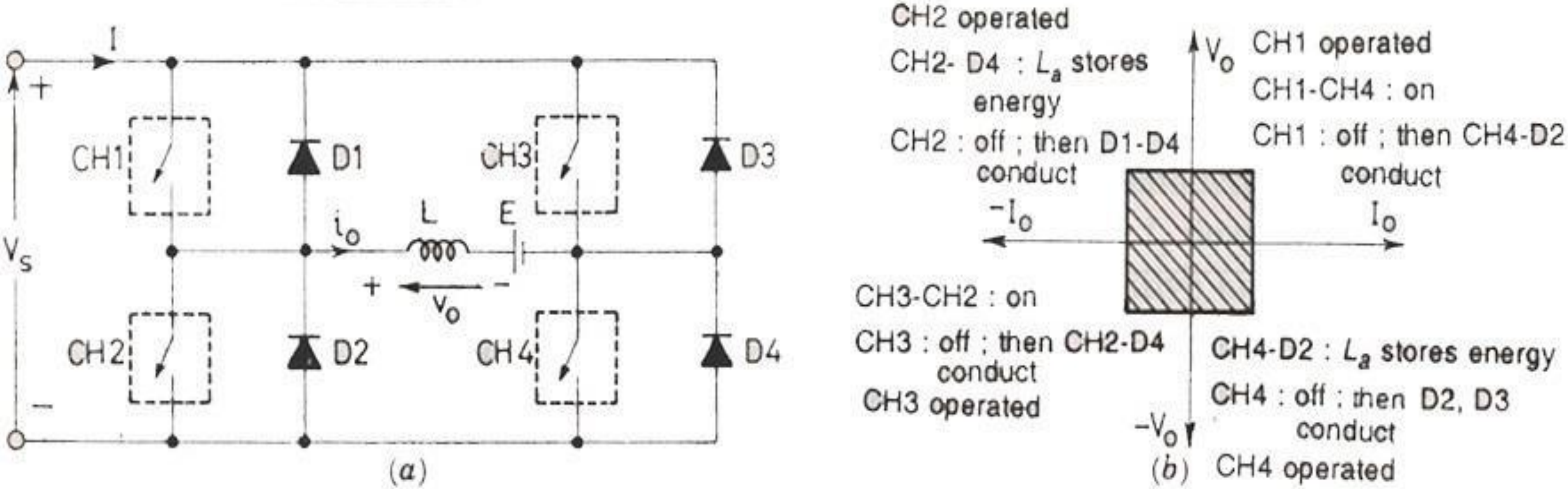


Fig.1 *Four-qudrant, or Type-E chopper*

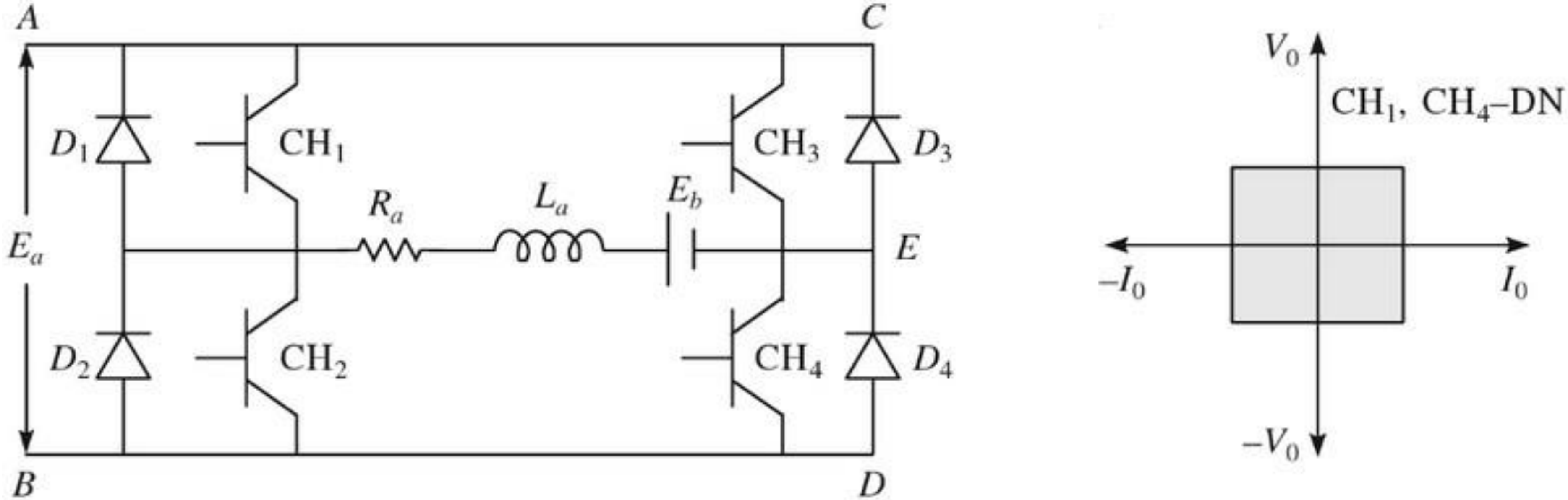


Fig. 4.6 –Four qudrant chopper or multi quadrant chopper

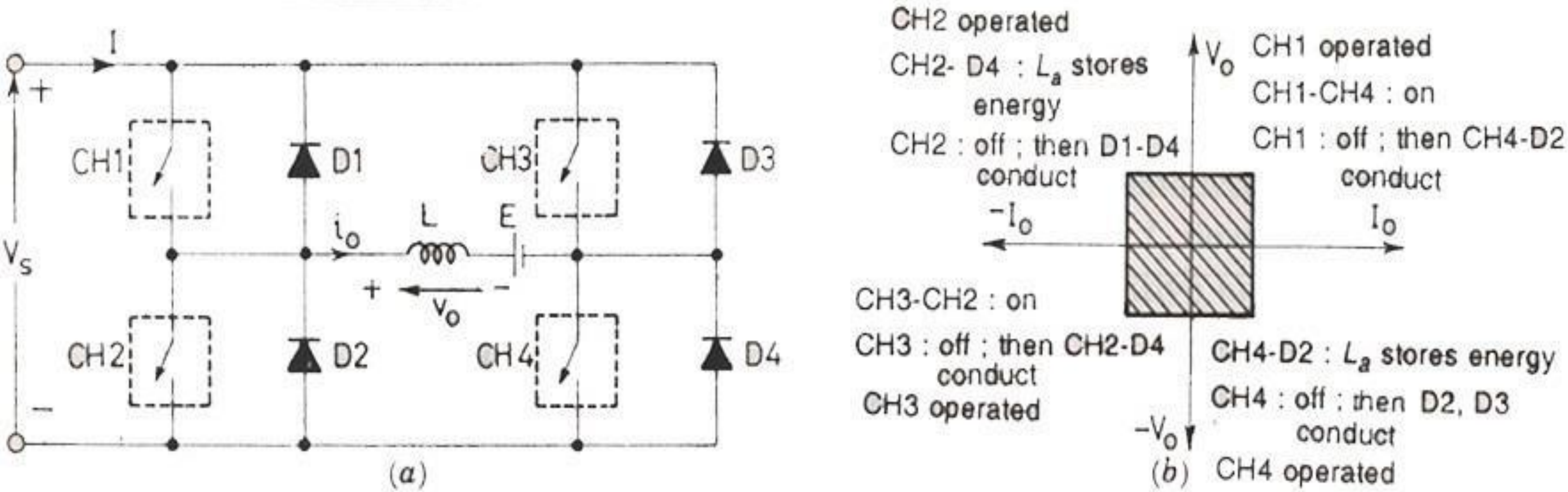


Fig.1 *Four-qudrant, or Type-E chopper*

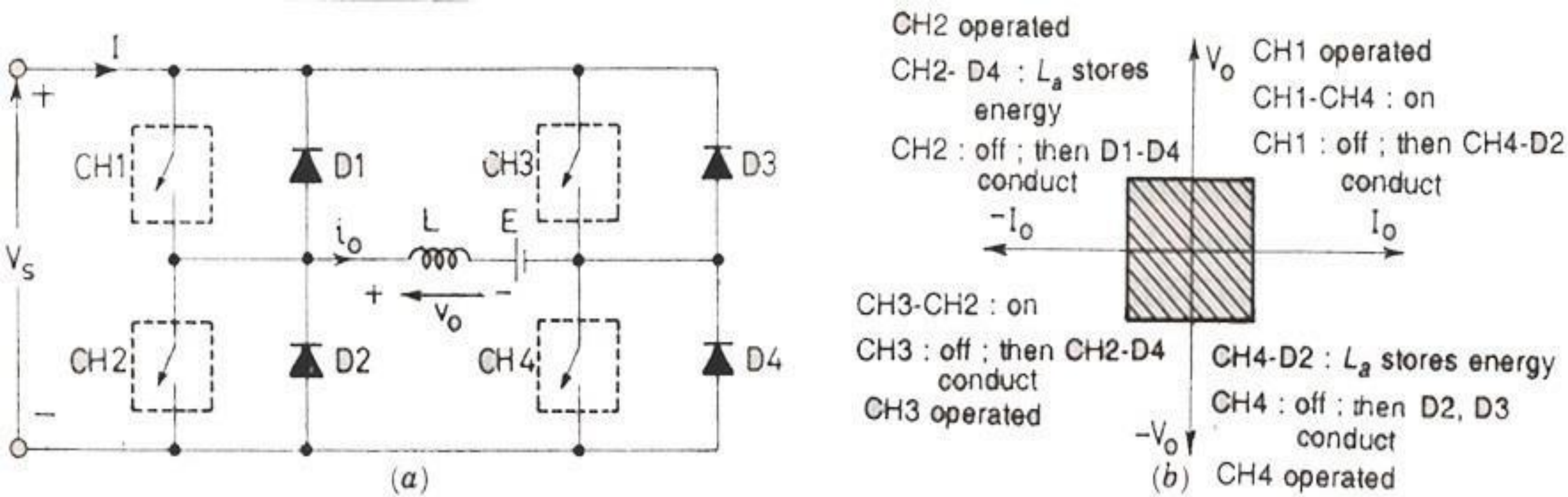


Fig.1 *Four-qudrant, or Type-E chopper*

Second quadrant: Forward braking operation

In this mode, CH_4 is operated and CH_1, CH_2 and CH_3 are kept off. With CH_4 on, reverse or negative current flows through L_a – CH_4 – D_4 – E_b. During on time, CH_4 and L_a store energy. When CH_4 is turned off, current is fed back to source through D_3 and D_4, and N is positive. The condition will be $[E_b + L_a(di/dt)] > E_a$, the armature current flows from B to A, i.e., negative, and its current path will be B – motor – A – D_3 – E – D_4, where I_a is negative and the torque is negative. When CH_4 is on, the current path is A – CH_4 – D_4 – B – motor – A. In a similar way, we can use the third and fourth quadrants for its reverse motoring or reverse braking operation.

Third quadrant operation: Reverse motoring operation

Instead of CH_1 and CH_2, we operate CH_3 and CH_4, and instead of D_1 and D_2, use the operation of D_3 and D_4, using the method which has been explained in the first quadrant operation.

Fourth quadrant operation: Reverse braking operation

Instead of CH_4 use CH_2, instead of D_3 and D_4 use D_2 and D_1, using the method which has been explained in the second quadrant operation.

Chopper fed Separately Excited DC Motors

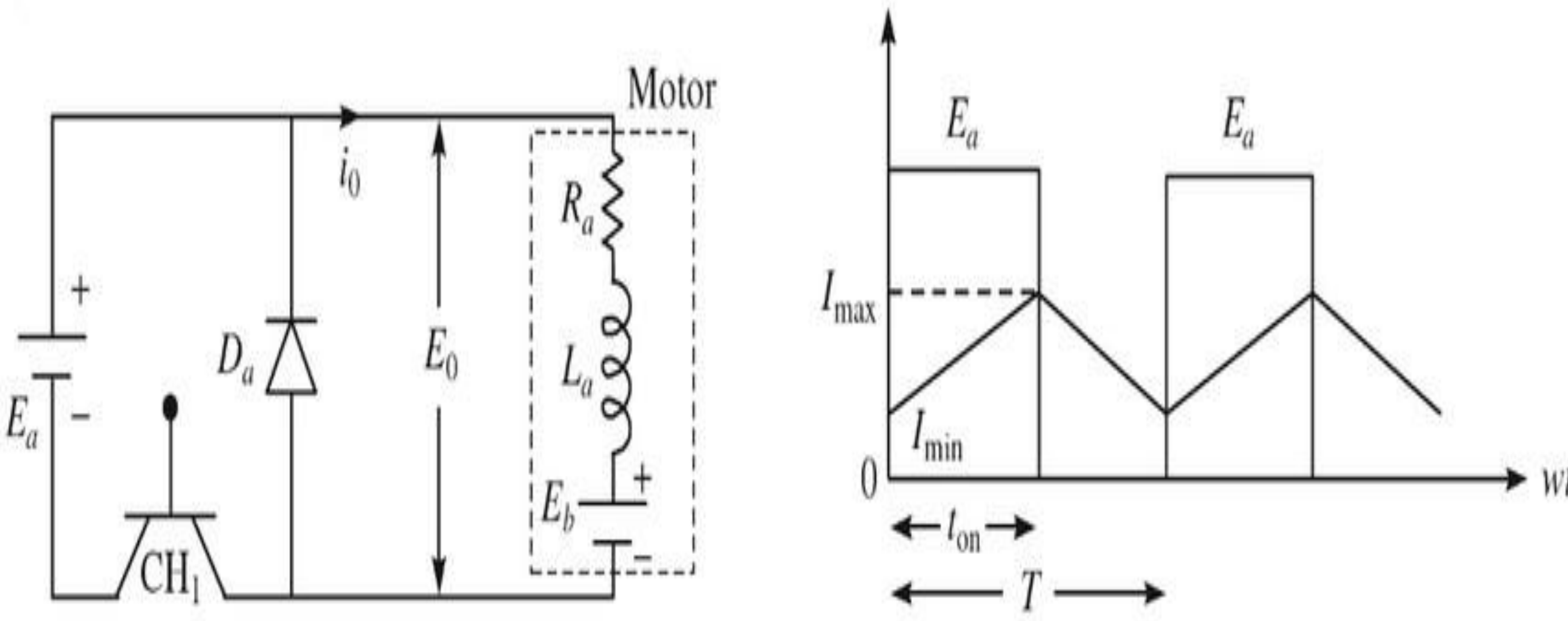


Fig. 4.7 Chopper control fed with separately excited dc motor.

As can be seen from Fig. 4.7, chopper CH_1 is operated periodically with period T and remains ON for period t_{on} and makes the chopper operate at a higher frequency to ensure continuous conduction. During the chopper's on-period $0 \leq t \leq t_{on}$, the chopper conducts and makes the load current flow from source to load. From Fig. 4.7, the motor terminal voltage is

$$R_a i_a + L_a \frac{di_a}{dt} + E_b = E_a \qquad 0 \leq t \leq t_{on} \tag{4.19}$$

Due to current limit control, the armature current increases from I_{min} to I_{max}. Since the motor is connected to the source to the load, this interval is called *duty interval.* During interval $t_{on} \leq t \leq T$, at the instant $t = t_{on}$ the chopper doesn't conduct but its armature current freewheels through freewheeling diode, and its motor terminal voltage will be equal to zero. Thereby its loop equation is

$$R_a i_a + L_a \frac{di_a}{dt} + E_b = 0 \qquad t_{on} < t \leq T \tag{4.20}$$

Due to current limit control, the armature current decreases from i_{max} to i_{min}, since the motor is connected to the freewheeling diode. Ratio of duty interval t_{on} to the chopper period T is called *duty ratio* or *duty cycle* (δ).

$$\therefore \qquad \delta = \frac{\text{Duty interval}}{T} = \frac{t_{on}}{T} \qquad (4.21)$$

$$\therefore \qquad E_0 = \frac{1}{T}\int_0^{t_{on}} E_a dt = \frac{t_{on}}{T} E_a = \delta E_a \qquad (4.22)$$

We know that $\quad E_0 = E_b + I_a R_a \qquad (4.23)$

$$\therefore \qquad \delta E_a = E_b + I_a R_a \qquad I_a = \frac{\delta E_a - E_b}{R_a} \qquad (4.24)$$

Also, we know that

$$E_b = K_e \phi \omega \quad \text{or} \quad K_\phi N$$

and $\quad T_a = K_e \phi I_a$

$$\therefore \qquad I_a = \frac{T_a}{K_e \phi} \qquad (4.25)$$

From Eq. (4.7), we get

$$E_b = E_0 - I_a R_a$$

$$K_e \phi \omega = E_0 - \frac{T_a}{K_e \phi} R_a$$

$$\omega = \frac{E_0}{K_e \phi} - \frac{T_a}{(K_e \phi)^2} R_a$$

$$\omega = \frac{\delta E_a}{K_e \phi} - \frac{T_a}{(K_e \phi)^2} R_a$$

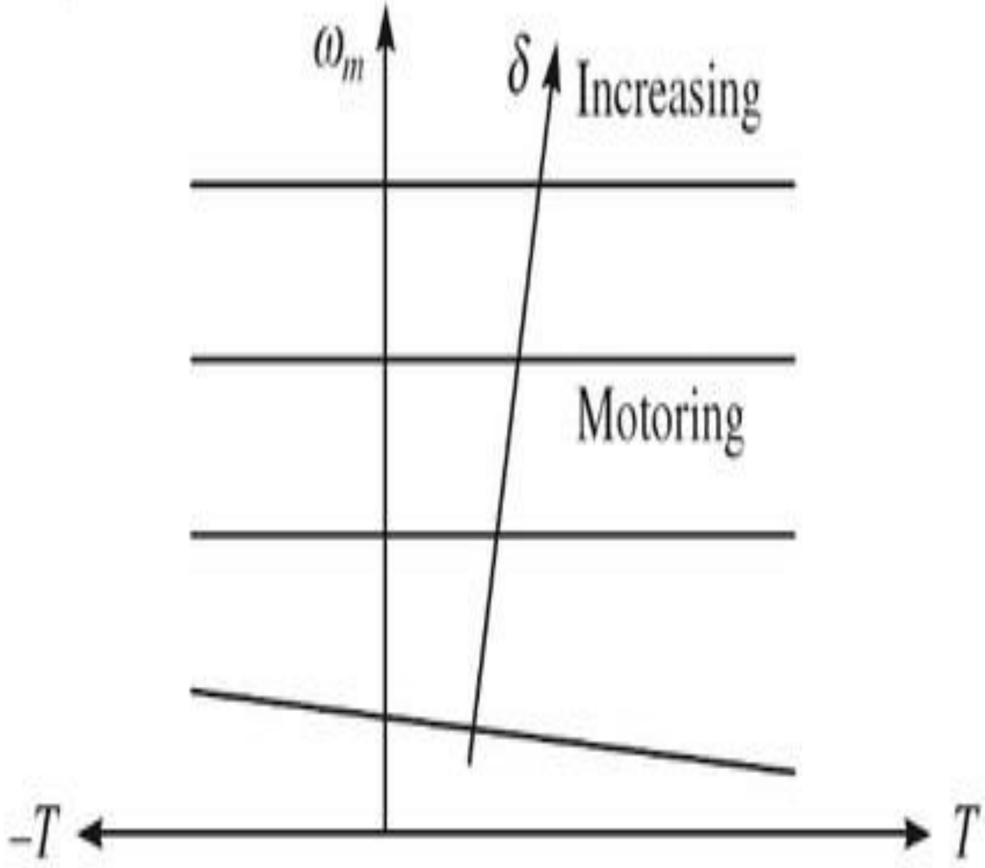


Fig. 4.8 Speed–torque characteristics of chopper motoring control separately excited motor.

Problem-7

The speed of 1 HP, 230 V, 500 rpm, 4.1 A separately excited dc motor has an armature resistance and armature inductance are 7.56 Ω and 55 mH respectively is driven with armature supplied from a class A chopper and a 240 V dc source. The field current is held constant at the value that gives rated operation on 230 V and the chopping frequency is constant at 50 Hz. The minimum load torque is 5 N-m. Determine

(a) The value of t_{on} for minimum load torque of 500 rpm

(b) Whether I_a is continuous for the conditions of part (a)

(c) The minimum value of t_{on} for which the current is continuous at 500 rpm, and the corresponding coupling torque.

Solution It is given that $N = 500$ rpm

$$\omega = \frac{2\pi N}{60}$$

$$= \frac{2 \times \pi \times 500}{60} = 52.36 \text{ rad/s}$$

and

$$E_b = E_a - I_a R_a = 230 - 4.1 \times 7.56$$

$$= 199 \text{ V}$$

$$K\phi = \frac{199}{52.36} = 3.801 \text{ N-m/A}^2$$

Armature power input

$$E_a I_a = 230 \times 4.1$$

$$= 943 \text{ W}$$

Coupling power output = 1 HP = 746 W

$$I_a^2 R_a = (4.1)^2 \times 7.56 = 127 \text{ W}$$

Rotational loss = 943 – 746 – 127 = 70 W

At 500 rpm,
$$T_a = \frac{\text{Rotational loss}}{\omega}$$
$$= \frac{70}{52.36} = 1.337 \text{ N-m}$$

(a) For minimum load torque at 500 rpm, the average internal torque is
$$T_a = 5 + 1.337 = 6.337 \text{ N-m}$$
$$I_a = \frac{6.337}{3.801} = 1.667 \text{ A}$$
$$E_0 = 199 + 7.56 \times 1.667 = 211.6 \text{ A}$$
$$T_{\text{on}} = \frac{E_0}{E_a} \times T$$
$$= \frac{211.6}{240} \times \frac{1}{500} = 1.763 \times 10^{-3} \text{ s}$$

(b)
$$T = \frac{L_a}{R_a} \times \left(\frac{55 \times 10^{-3}}{-7.56}\right) = 7.275 \times 10^{-3} \text{ s}$$
$$I_{\max} = \frac{E_a}{R_a}\left(\frac{e^{t_{\text{on}}/\tau_a} - 1}{e^{T/\tau_a} - 1}\right) - \frac{E_b}{R_a}$$

The boundary conditions between continuous and discontinuous current arise when $I_{max} = 0$.

$$\therefore \qquad 0 = \frac{240}{7.56}\left(\frac{e^{10^3 t_{on}/7.275} - 1}{e^{2/7.275} - 1}\right) - \frac{199.0}{7.56}$$

$$t_{on} = 1.695 \times 10^{-3} \text{ s}$$

Because this is less than the value of t_{on} obtained in (a), the current is continuous.

(c) The t_{on} value taken is the minimum value from the preceding two cases.

$$\therefore \qquad t_{on} = 1.695 \times 10^{-3} \text{ s}$$

$$T = \frac{1}{50} = 2 \times 10^{-3} \text{ s}$$

$$E_o = \frac{t_{on}}{T} E_a = \frac{1.695}{2} \times 240 = 203.4 \text{ V}$$

$$I_a = \frac{203.4 - 199}{7.56}$$

$$= 0.582 \text{ A}$$

$$T_a = K\phi I_a = 3.801 \times 0.582 = 2.212 \text{ N-m}$$

Minimum coupling torque $T_a - T_{loss}$

$$= 2.212 - 1.337 = 0.875 \text{ N-m}$$

Problem-8

A 230 V, 1750 rpm, 74 A dc motor has an armature resistance of 0.180 Ω and is driven with its armature supplied from a Class A chopper and a 240 V dc source, given rated operation on 230 V. The chopping frequency is constant at 500 Hz. If the average armature current is equal to the rated value and t_{on} is at the setting that gives the largest harmonic content, determine

(a) The motor speed

(b) The rms armature current

(c) The rms and line current ripple factors.

Problem-9

A dc shunt motor takes a current of 50 A on a 440 V supply, runs at speed of 1000 rpm, with an armature resistance of 0.5 Ω and a field resistance of 100 Ω. A chopper is used to control the speed of the motor in the range of 400–800 rpm having a constant torque. The on-period of the chopper is 2 ms, with its field supply voltage from 440 V. Determine the range of frequencies of the chopper.

$I_a = 50$ A

$E_a = 440$ V

$N = 1000$ rpm

$R_a = 0.5\ \Omega$

$R_f = 100\ \Omega$

Range of speed = 400 to 800 rpm

$T_{on} = 2$ ms

$\therefore$ Chopping frequency, $$f = \frac{1}{T} = 0.785 \text{ mHz}$$

$$\text{Now, back emf at 800 rpm} = \frac{800}{1000} \times 415 = 332 \text{ V}$$

$\therefore$ Terminal voltage, $E_0 = 332 + (50 \times 0.5) = 357$ V

$$\therefore \text{ Chopping frequency} = \frac{357}{440 \times 2} \times 1000$$

$$= 405.68 \text{ Hz}$$

Problem-10

A 220 V, 24 A, 100 rpm separately excited dc motor has an armature resistance of 2 Ω. The motor is controlled by a chopper with a frequency of 500 Hz and a source voltage of 230 V. Calculate the duty ratio for 1.2 times the rated torque and 500 rpm.

$E_a = 220$ V

$N_1 = 1000$ rpm

$I = 24$ A

$R_a = 2\ \Omega$

Source voltage $E_s = 230$ V

The motor is controlled by the chopper; so,

$$E_0 = \delta E_a$$

$$E_{b1} = E_a - I_a R_a$$

$$= 230 - (2 \times 24)$$

$$E_{b1} = 172 \text{ V}$$

$$E_{b2} = \frac{N_2}{N_1} E_{b1} = \frac{500}{1000} \times 172 = 86 \text{ V}$$

Motor terminal voltage,

$$E_0 = E_{b2} + I_a R_a$$

$$= 86 + (1.2 \times 2 \times 24)$$

$$= 143.6 \text{ V}$$

Duty ratio

$$E_0 = \delta E_a$$

$$\delta = \frac{143.6}{230} = 0.624$$

Problem-11

A separately excited dc motor is powered by a chopper having the armature resistance of 0.08 Ω from a 450 V dc source. The average and field currents are 275 A and 3 A respectively. The armature current is assumed to be continuous and ripple-free. The back emf constant of motor is $K_t = 1.527$ V/a rad/s. The duty cycle of the converter is 65%. Determine

(i) The input power from the generator source

(ii) The speed of the motor and the torque.

Given data:

Armature resistance, $R_a = 0.08\ \Omega$

Supply voltage, $E_a = 450$ V

Armature current, $I_a = 275$ A

Field current, $I_f = 3$ A

$K_t = 1.527$ V/A-rad/s

Duty cycle, $\delta = 0.65$

(i) Input power, $P_{\text{input}} = \delta E_a I_a$

$$= 0.65 \times 450 \times 275 = 80.43 \text{ kW}$$

Average voltage, $E_0 = \delta E_a = 0.65 \times 450 = 292.54 \text{ V}$

Back emf, $E_b = E_a - I_a R_a$

$$= 292.5 - 275 \times 0.08 = 270.5 \text{ V}$$

(ii) Speed, $N \text{ (or } \omega) = \dfrac{E_b}{K_f I_f} = \dfrac{270.5}{1.527 \times 3} = 59.04 \text{ rad/s}$

$$N = 563.87 \text{ rpm}$$

Torque developed, $T = K_f I_f I_a$

$$= 1.527 \times 275 \times 3 = 1259.7 \text{ N-m}$$

Problem-12

A separately excited dc motor is connected to the supply voltage of 230 V dc source through a chopper frequency of 300 Hz. The load torque is of 40 N-m with respective speed of 900 rpm. The motor parameters as follows: $R_a = 0\ \Omega$, $L_a = 12$ mH, and $K_m = 2$ V s/rad. Neglecting motor and chopper losses, determine

(i) The minimum and maximum values of armature current and the armature current excursion

(ii) The armature current expressions during on and off periods.

Solution Since R_a is zero, I_a is assumed to be varied between as minimum and maximum values.

Average armature current $$I_a = \frac{T_L}{K_m} = \frac{40}{2} = 20 \text{ A}$$

Motor emf, $$E_b = K_m\omega_m = 2 \times \frac{2\pi \times 900}{60}$$

$$= 188.49 \simeq 188.5 \text{ V}$$

Motor input voltage, $$\delta E_a = E_b + I_a R_a$$

$$= 188.5 + 0 \quad (\because \text{ armature resistance is neglected})$$

$$\delta = \frac{188.5}{230} = 0.819$$

Periodic time, $$T = \frac{1}{f} = \frac{1}{300} = 3.33 \text{ ms}$$

On-period, $$t_{on} = \delta T$$

$$= 0.819 \times 3.33 \text{ m} = 2.72 \text{ ms}$$

Off-period, $$t_{off} = (1 - \delta)T$$

$$= (1 - 0.819)\ 3.33 = 0.602 \text{ ms}$$

During the on-period, i.e., t_{on}, the armature current will rise and the required equation is

$$0 + L\frac{di_a}{dt} + E_b = E_a$$

(Here, zero represents neglecting of armature resistance.)

$$\frac{di_a}{dt} = \frac{E_a - E_b}{L} = \frac{230 - 188.5}{12 \times 10^3} = 3458.33 \text{ A/s}$$

During off-period t_{off},

$$\frac{di_a}{dt} = \frac{-E_b}{L} \qquad (\because E_a \text{ is absent, } E_a = 0)$$

$$= \frac{-188.5}{12 \times 10^3} = -15708.33 \text{ A/s}$$

The relationship between maximum current and minimum current is

$$I_{\max} = I_{\min} + \left(\frac{di_a}{dt} \text{ during } t_{\text{on}}\right) \times t_{\text{on}}$$

$$= I_{\min} + 3458.33 \times 2.72 \times 10^{-3}$$

$$= I_{\min} + 9.406$$

$$I_{\max} - I_{\min} = 9.406 \text{ A}$$

∴ The linear variation between I_{max} and I_{min} is the average value of armature current

$$I_a = \frac{I_{max} + I_{min}}{2} = 20 \text{ A}$$

$$\Rightarrow \quad I_{max} + I_{min} = 40$$

To find I_{max} and I_{min}, Eqs. (1) and (2) are solved.

$$I_{max} - I_{min} = 9.406$$

$$I_{max} + I_{min} = 40$$

$$2I_{max} = 49.406$$

$$I_{max} = \frac{49.406}{2}$$

$$= 24.703 \text{ A}$$

$$\therefore \quad 24.70 - I_{min} = 9.406$$

$$I_{min} = 24.703 - 9.406$$

$$I_{min} = 15.29 \simeq 15.3 \text{ A}$$

Armature curent excursion

$$I_{max} - I_{min} = 24.703 - 15.3$$

$$= 9.406 \text{ A}$$

Armature curent expressions during t_{on}

$$I_a(t) = I_{\min} + \left(\frac{di_a}{dt} \text{ during } t_{\text{on}}\right) \times t$$

$$= 15.3 + 3458.33t \qquad \text{for } 0 \le t \le t_{\text{on}}$$

Armature current expression during t_{off}

$$I_a(t) = I_{\min} + \left(\frac{di_a}{dt} \text{ during } t_{\text{off}}\right) \times t$$

$$= 24.7 - 15708.33t \qquad \text{for } 0 \le t \le t_{\text{off}}$$

Regenerative Braking

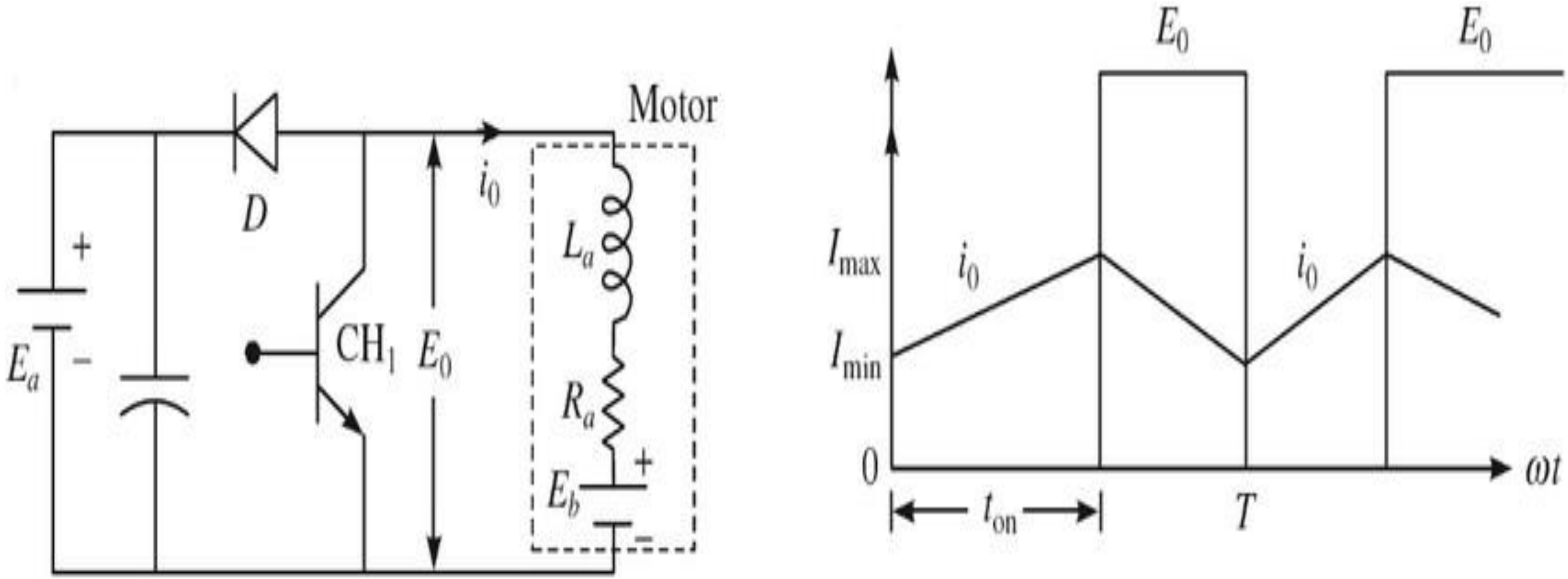


Fig. 4.10 Regenerative braking control of separately excited dc motor.

From Fig. 4.10, during $0 \le t \le t_{on}$ period the chopper conducts where its motor terminal current flows from load to the source; thereby the armature current increases from I_{min} to I_{max} and this armature current makes the energy conversion, i.e., mechanical energy to electrical energy, and then makes the motor load operate as a generator. Now the stored magnetic energy in the armature circuit inductance increases and is partly dissipated in R_a and chopper circuit. During $t_{on} \le t \le T$, the chopper does not conducts and makes the load current flows through diode D and source E_a; then the armature current decays from I_{max} to I_{min} and thus this armature current makes the energy conversion in the manner opposite to what it had performed during t_{on} period; thereby the regeneration process can be performed in two intervals; i.e, $0 < t < t_{on}$ as energy storage interval and $t_{on} < t < T$ as duty interval.

In regenerative braking, the amount of energy from the load is fed back to the supply. The power circuit diagram for chopper for regenerative braking operation as shown in Fig. 4.10. The chopper CH_1 is operated periodically with period T and on-period t_{on}. During regenerative braking the dc motor acts as a generator, and the kinetic energy of the motor and the shaft load is returned back to the supply. Usually in case of regenerative braking, an external source inductance L_a is added.

$$E_0 = \frac{1}{T}\int_{t_{on}}^{T} E_a dt \tag{4.27}$$

$$E_0 = \frac{1}{T}\int_{t_{on}}^{T} E_a dt = \frac{E_a}{T_a}\int_{t_{on}}^{T} dt$$

$$E_0 = E_a\left(\frac{T - t_{on}}{T}\right)$$

$$E_0 = (1 - \delta)\, E_a \tag{4.28}$$

$$E_b = K_e \phi \omega$$

$$T = -K_e \phi I_a \qquad \text{(since } I_a \text{ has reversed)}$$

$$I_a = \frac{-T_a}{K_e \phi}$$

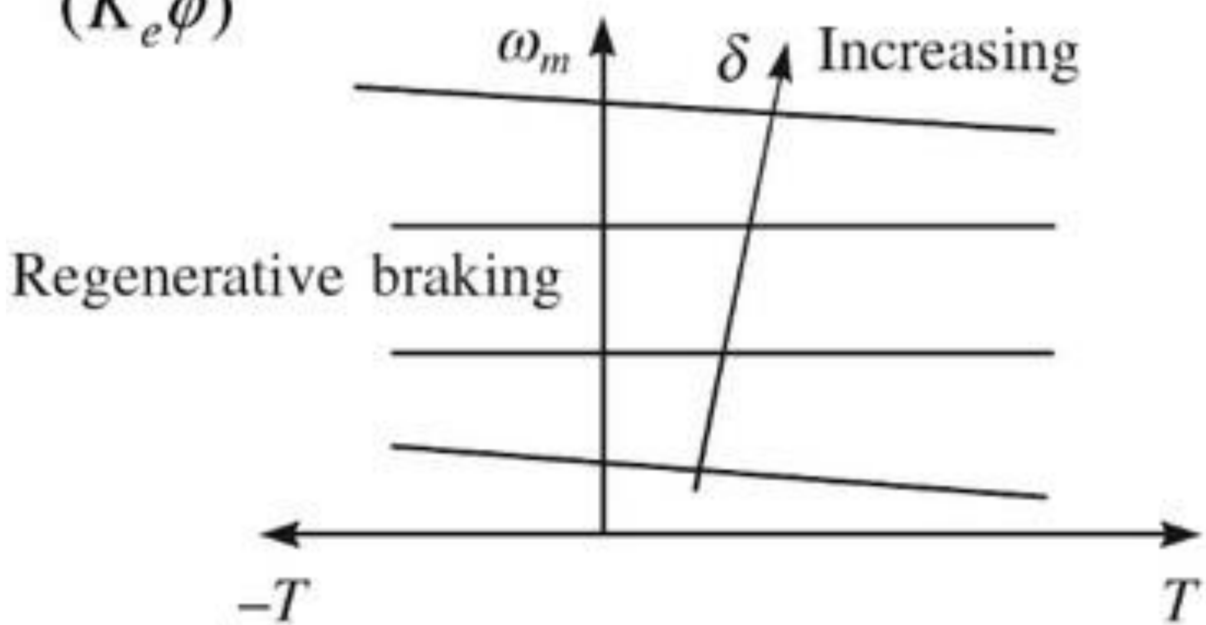
$$E_0 = I_a R_a + E_b \tag{4.29}$$

$$E_b = E_0 - I_a R_a$$

$$K_e \phi \omega = E_0 - \left(\frac{-T_a}{K_e \phi} \right) R_a$$

$$= (1 - \delta) E_a + \frac{T_a}{K_e \phi} R_a$$

$$\omega = \frac{(1-\delta)}{K_e \phi} E_a + \frac{R_a T_a}{(K_e \phi)^2}$$



Motoring and Regenerative Control

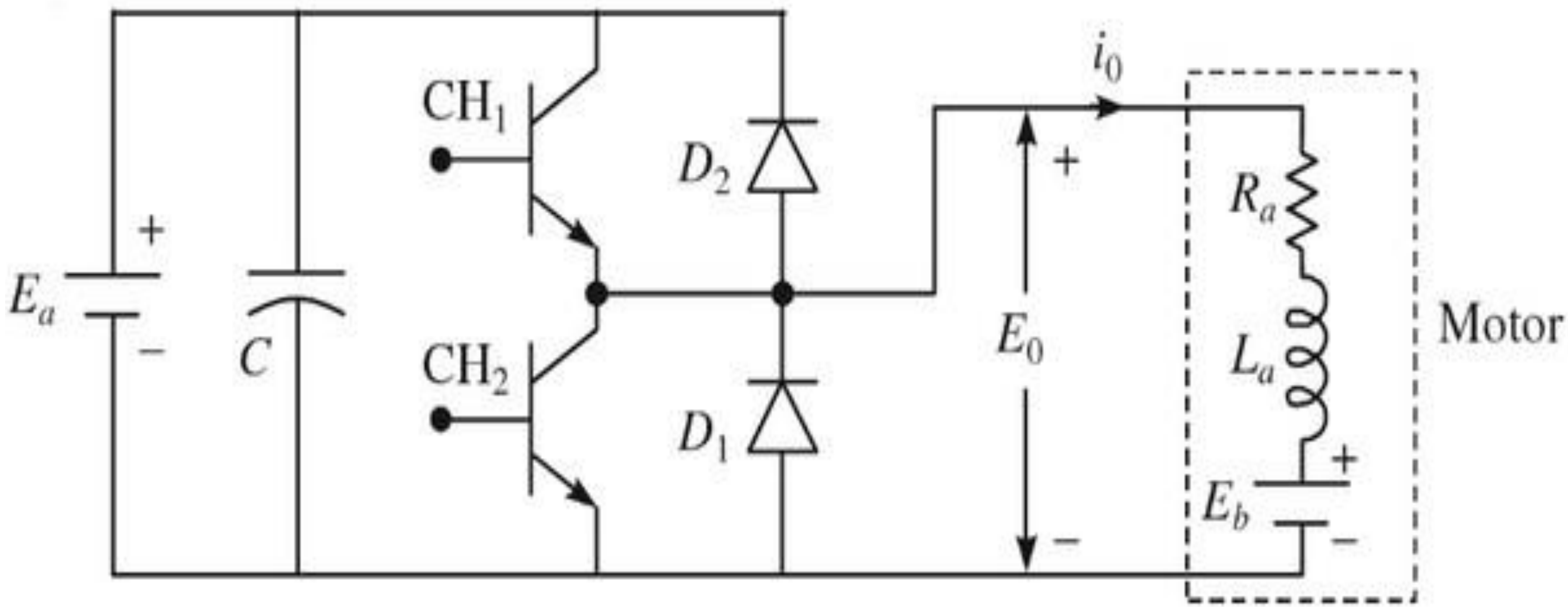


Fig. 4.12 Chopper for motoring and braking control.

We have seen that during forward motoring the power is controlled by the chopper, while the armature voltage and current, both positive, and power flows from dc source to the armature of the separately excited dc motor. On other hand, during the regenerative braking the armature voltage being remains positive, the armature voltage reverses, making the power flow from the armature to the supply. Figure 4.12 shows a chopper circuit that will allow power control as well as regenerative brake control, and the motor operates as the two-quadrant drive operation.

Figure 4.12 modifies the first quadrant operation and converts it to a second quadrant operation. For first quadrant operation, CH_1 and D_1 performs the functions and its average load current I_0 is high enough; CH_2 and D_2 don't conduct, even though CH_2 receives triggering signal. For second quadrant operation, CH_2 and D_2 perform the functions and its average load current I_0 has a sufficiently large negative value. CH_1 and D_1 don't conduct, even though CH_1 receives the gating signal.

In forward motoring drive, CH_1 and D_1 operate; as CH_1 is turned on, the motor receives the supply voltage. When CH_1 is turned off, the armature current flows through the freewheeling diode D_1 and get decayed.

During regeneration braking control, CH_2 and D_2 operate on being turned on, the motor acts as a generator and armature current increases. When CH_2 is turned off, the armature energy is returned back to the supply to the D_2. Then this circuit can acts as a two-quadrant chopper.

From forward motoring operation, we know that

$$E_0 = \delta E_a \qquad \text{and} \qquad E_0 = I_a R_a + E_b$$

$$\therefore \qquad \delta E_a = I_a R_a + E_b$$

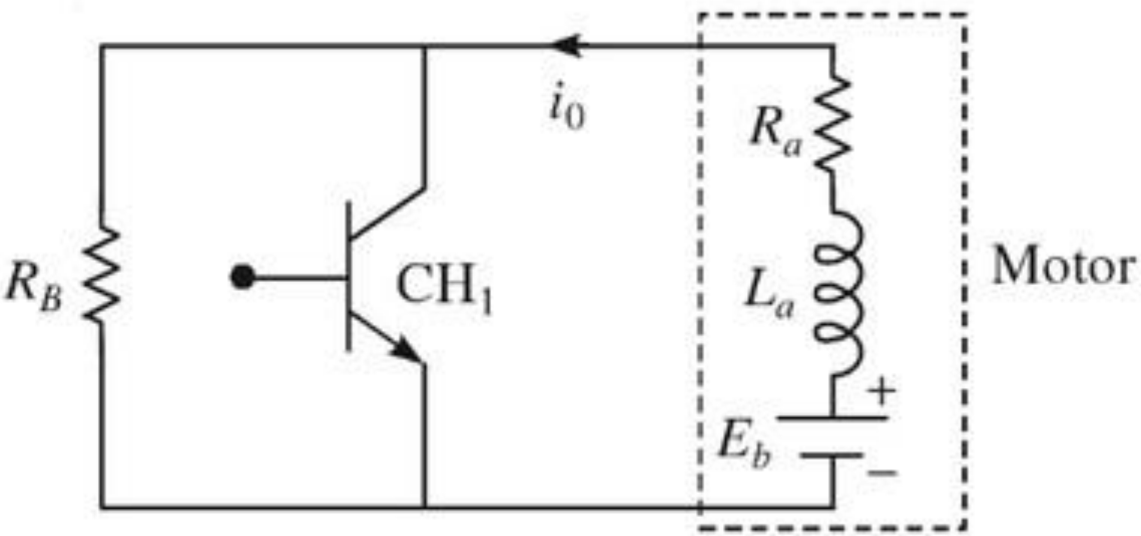
$$\therefore \qquad I_a = \frac{\delta E_a - E_b}{R_a} \tag{4.31}$$

From the preceding equations, we have conditions for duty interval in such a way that the armature current can be performed in two modes either in motoring operation nor in regenerative braking operation, i.e., in motoring operation, $\delta > E_b/E_a$, and in regenerative braking operation, $\delta < E_b/E_a$.

Dynamic Braking

In dynamic braking control, the motor armature terminals are disconnected from the supply source, and it is added with external resistance R_B which is shown in Fig. 4.13. During the interval $0 \leq t \leq t_{on}$, the armature current I_a increases from I_{min} to I_{max}. A part of generated energy will be stored in the magnetic inductance and the rest of it will be dissipated in R_a and CH_1. During the interval $t_{on} \leq t \leq T$, the armature current I_a decreases from I_{max} to I_{min} and whatever the energy stored will be dissipated in its braking resistance R_B, R_a and D. If I_a is assumed to be rippleless, the dc energy consumed E_N by R_B during a cycle of chopper operation is

$$E_N = I_a^2 R_B (T - T_{on}) \tag{4.32}$$



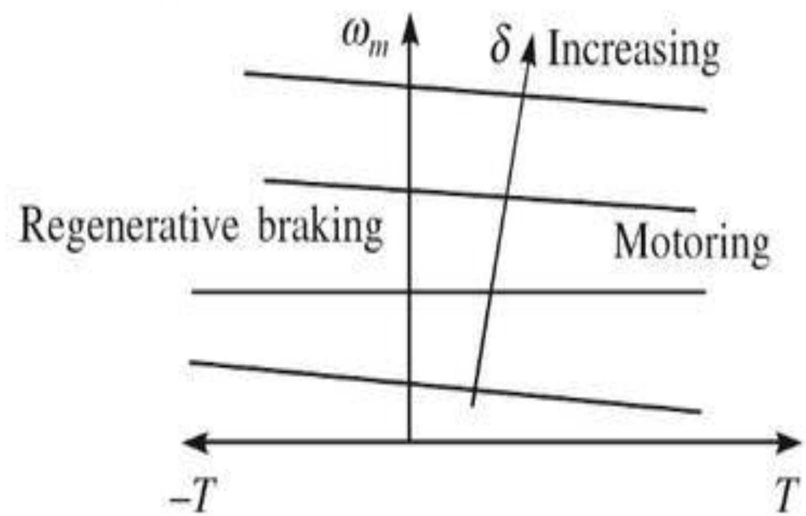
Average power consumed by R_B,

$$P = \frac{E_N}{T} = I_a^2 R_B (1 - \delta)$$

Effective value of R_B

$$R_{BE} = \frac{P}{I_a^2} = R_B (1 - \delta)$$

$$\delta = \frac{t_{on}}{T}$$



Equation (4.34) shows the effective value of the braking resistor. It can be changed to stepless from 0 to R_B as δ is controlled from 1 to 0. As the speed falls, δ can be increased steplessly to brake the motor at a constant maximum torque, as shown in Fig. 4.14.

Problem-13

A 230 V separately excited dc motor takes 50 A at a speed of 800 rpm. It has armature resistance of 0.4 Ω. This motor is controlled by a chopper with an input voltage of 230 V and frequency of 500 Hz. Assuming continuous conduction throughout, calculate the speed of motoring operation at duty ratios of 0.3 and 0.6, and regenerative braking operation at duty ratios of 0.7 and 0.4.

$$E_a = 230 \text{ V}$$
$$I_a = 50 \text{ A}$$
$$N_1 = 800 \text{ rpm}$$
$$R_a = 0.4\ \Omega$$
$$E_0 = \delta E_a$$

Problem-14

A 230 V, 1200 rpm, 15 A separately excited dc motor has an armature resistance of 1.2 Ω motor and is operated under dynamic braking, with chopper control braking resistance of 20 Ω.

(i) Calculate the duty ratio of the chopper for motor speed of 1000 rpm and braking torque equal to 1.5 times rated motor torque.

(ii) What will be the motor speed for duty ratio of 0.5 and motor torque equal to rated torque?

$$E_a = 230 \text{ V}$$
$$N_1 = 1200 \text{ rpm}$$
$$I = 15 \text{ A}$$
$$R_a = 1.2\ \Omega$$
$$R_B = 20\ \Omega$$

Problem-15

A dc series motor fed from a 400 V dc source through a chopper has the following parameters:

$R_a = 0.05\ \Omega$

$R_s = 0.07\ \Omega$

$K = 5 \times 10^{-3}$ N-m/A^2.

The average current of 200 A is ripple-free for a chopper duty cycle of 50%. Determine

(i) The input power from the source

(ii) The motor speed

(iii) The motor torque.

Problem-16

A series motor has an armature current of 80 A and is running at 1200 rpm with 210 V dc. The armature and the field winding resistances are 0.08 Ω each. Assuming the linear magnetic circuit, calculate the braking current and braking resistor when the series motor is at twice the rated torque and running at 1000 rpm under dynamic braking condition.

$$T_1 = K_f I_{a1}^2 \quad \text{and} \quad T_2 = K_f I_{a2}^2$$

$$I_{a2} = I_{a1}\sqrt{T_2/T_1} = 80\sqrt{2T_1/T_1}$$

$$= 113.13 \text{ A}$$

$$E_{b1} = K_e I_{a1} N_1$$

$$E_{b2} = K_e I_{a2} N_2$$

$$E_{b2} = \frac{I_{a2}}{I_{a1}} \times \frac{N_2}{N_1} \times E_{b1}$$

$$E_{b1} = E_a - I_a R_a = 210 - 80 \times 0.08$$

$$= 203.6 \text{ V}$$

$$E_{b2} = \frac{113.13}{80} \times \frac{1000}{1200} \times 203.6$$

$$= 239.92 \text{ V}$$

$$E_{b2} = I_{a2}\,(R_B + 0.08)$$

$$239.92 = 113.13\,(R_B + 0.08)$$

$$R_B = 2.0408\ \Omega$$

Problem-17

A constant frequency TRC system is used for the speed control of a dc series traction motor from a 220 V dc supply. The motor has armature and series field resistance of 0.025 Ω and 0.015 Ω respectively. The average current in the circuit is 125 A and the chopper frequency is 200 Hz. Calculate the pulse width if the average value of back emf is 60 V.

$E_a = 220\ \text{V}$

$R_a = 0.025\ \Omega$

$R_f = 0.015\ \Omega$

$I_a = 125\ \text{A}$

$f = 200\ \text{Hz}$

$E_b = 60\ \text{V}$

$$\delta = \frac{E_0}{E_a} = \frac{60 + 125 \times 0.04}{220} = 0.295$$

$$\delta = \frac{t_{\text{on}}}{T} = \frac{t_{\text{on}}}{1/200}$$

$$t_{\text{on}} = \delta \times \frac{1}{200} = 0.29 \times \frac{1}{200} = 1.45\ \text{ms}$$

Regenerative Braking Control

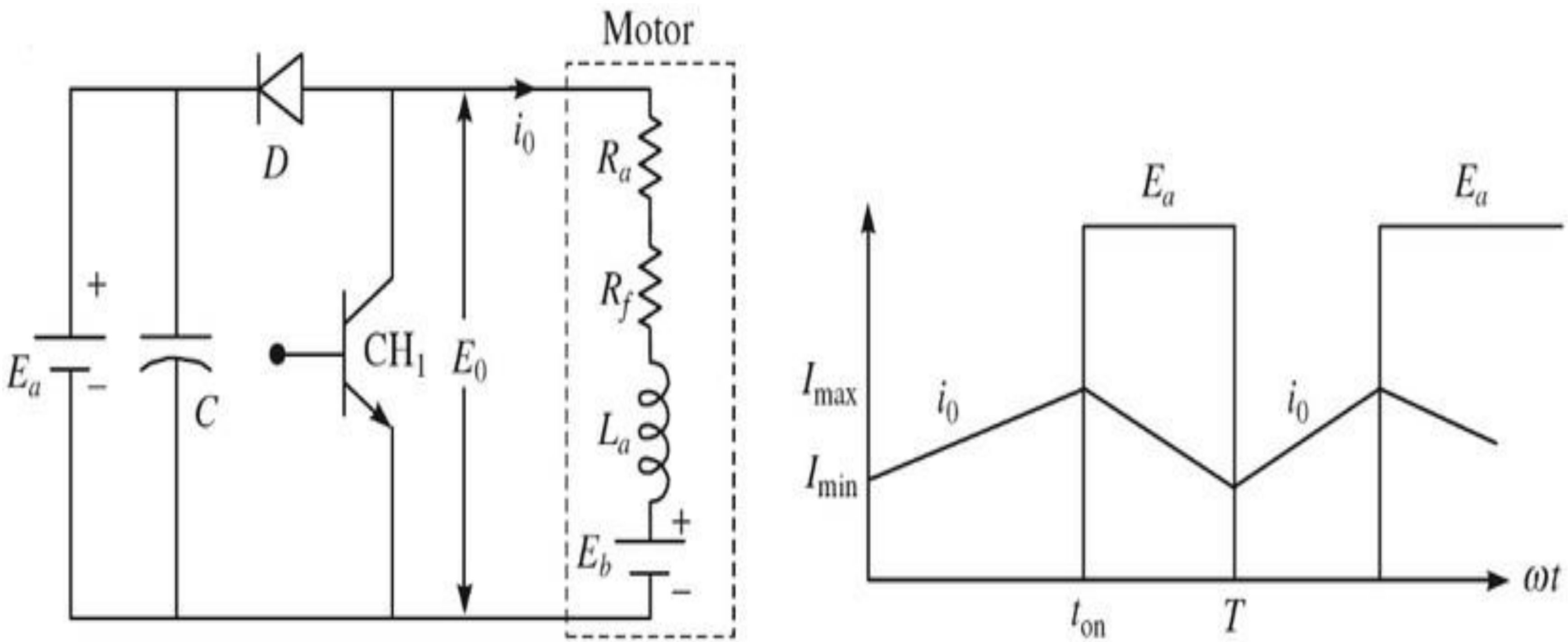


Fig. 4.19 Regenerative braking of dc series motor by chopper control.

During regenerative braking, series motor functions as a self-excited series generator as shown in Fig. 4.19. For self-excitation, current flowing through field winding should assist residual magnetism. Therefore, when changing from motoring to braking connection, while the direction of armature current should reverse or the field current should flow in the same direction. In regenerative braking, the amount of energy from the load is fed back to the supply; thereby the dc motor acts as a generator, and the kinetic energy of the motor and the shaft load is returned back to the supply, where its external source inductance L_a is added.

Operation

During the $0 \le t \le t_{on}$ period, the chopper conducts where its motor terminal current flows from load to the source; thereby the armature current increases from I_{min} to I_{max} and this armature current makes the energy conversion, i.e., mechanical energy to electrical energy and then makes the motor load operate as a generator. Now the stored magnetic energy in the armature circuit inductance increases and is partly dissipated in R_a and chopper circuit. During $t_{on} \le t \le T$, the chopper does not conduct and it makes the load current flow through diode D and source E. Then the armature current decays from I_{max} to I_{min} and thus this armature current makes the energy conversion in vice versa manner which had performed during t_{on} period, thereby the regeneration process can be performed in two intervals, i.e., $0 < t < t_{on}$, as energy storage interval and $t_{on} < t < T$ as duty interval.

$$\delta = \text{Duty interval} = \frac{t_{on}}{T} \tag{4.35}$$

$$E_0 = \frac{1}{T}\int_{t_{on}}^{T} E_a dt = \frac{E_a}{T}\int_{t_{on}}^{T} dt$$

$$E_0 = E_a\left(\frac{T - t_{on}}{T}\right)$$

$$E_0 = (1 - \delta)\, E_a \tag{4.36}$$

$$E_b = K_e \phi I_a \quad \text{and} \quad T = -K_e \phi I_a \qquad \text{(since } I_a \text{ has reversed)}$$

$$E_b = K_e \phi \omega \quad \text{or} \quad E_b = K \phi N$$

$$T_a = K_a \phi I_a^2$$

$$I_a = \sqrt{\frac{T_a}{K_f K_t}} \tag{4.37}$$

From Eq. (4.25), $E_b = E_0 - I_a(R_a + R_f)$

$$\omega = \frac{E_o}{K_t K_f I_a} \times \frac{1}{\sqrt{T_a}} - \frac{R_a}{K_t K_f}$$

$$\therefore \qquad \omega = \frac{(1-\delta)E_a}{\sqrt{K_t K_f}} \times \frac{1}{\sqrt{T_a}} - \frac{R_a}{K_t K_f}$$

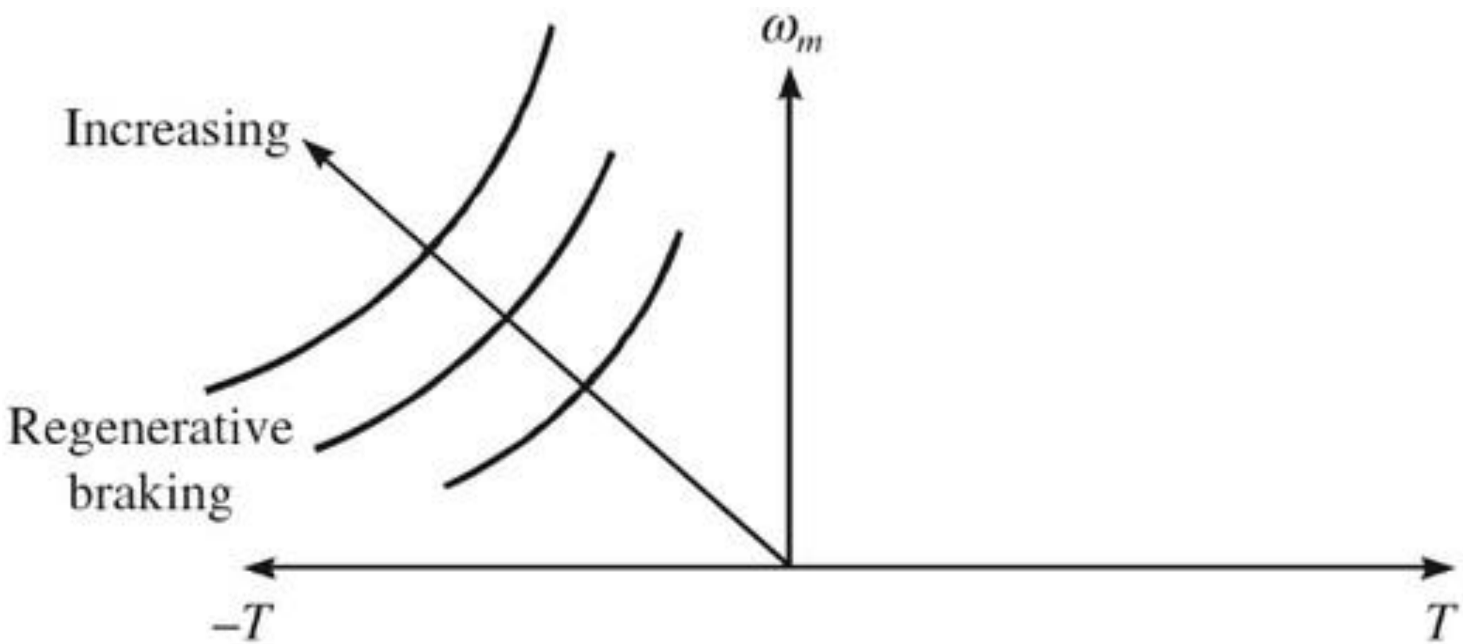


Fig. 4.20 Speed–torque curves of dc series motor under regenerative control.

Motoring and Regenerating Control

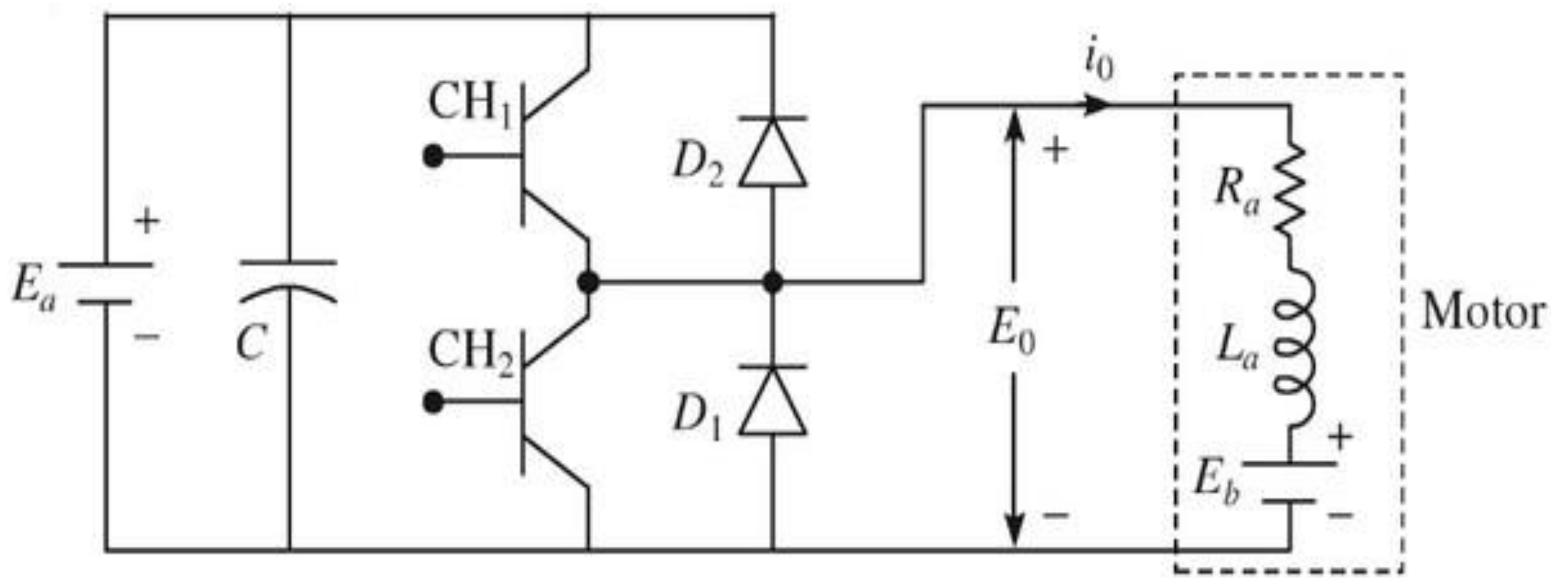


Fig. 4.21 Chopper for forward motoring and braking control with dc series motor.

We have seen that during forward motoring the power is controlled by the chopper, while the armature voltage and current (both positive) and power flows from dc source to the armature of the separately excited dc motor. On the other hand, during the regenerative braking the armature voltage remains positive, the armature current reverses making the power flow from the armature to the supply. Figure 4.21 shows a chopper circuit that will allow power control and regenerative brake control as well as motor operation as the two-quadrant drive operation.

Figure 4.21 modifies the first quadrant operation and converts it to second quadrant operation. For first quadrant operation, CH_1 and D_1 perform the functions and its average load current I_o is high enough, CH_2 and D_2 don't conduct, even though CH_2 receives triggering signal. For second quadrant operation, CH_2 and D_2 perform the functions and its average load current I_0 has a sufficiently large negative value. CH_1 and D_1 don't conduct, even though CH_1 receives the gating signal.

In forward motoring drive, CH_1 and D_1 operates as CH_1 is turned on, and the motor receives the supply voltage. When CH_1 is turned off, the armature current flows through freewheeling diode D_1 and get decayed.

During regeneration braking control, CH_2 and D_2 operate when CH_2 is turned on, the motor acts as a generator and armature current increases. When CH_2 is turned off, the armature energy is returned back to the supply to D_2. Then this circuit can act as a two-quadrant chopper.

From forward motoring operation, we know that

$$E_0 = E_a \quad \text{and} \quad E_0 = I_a R_a + E_b$$

$$\therefore \qquad \delta E_a = I_a R_a + E_b$$

$$\therefore \qquad I_a = \frac{\delta E_a - E_b}{R_a} \tag{4.40}$$

From the above equations, we have conditions for duty interval in such a way that the armature current can be performed in two modes, either in motoring operation or in regenerative braking operation. In motoring operation, $\delta > E_b/E_a$ and in regenerative braking operation, $\delta < E_b/E_a$.

Dynamic Braking Control

In dynamic braking control, the circuit diagram of Fig. 4.22 is used since the motor works as a self-excited generator. When changing from motoring to braking, field should be reversed. The motor armature terminals are disconnected from the supply connected to the external resistance R_B which is shown in Fig. 4.22. During the interval $0 \le t \le t_{on}$, the armature current I_a increases from I_{min} to I_{max}. A part of generated energy will be stored in the magnetic inductance and the rest of it will be dissipated in R_a and CH_1. During the interval $t_{on} \le t \le T$, the armature current I_a decreases from I_{max} to I_{min}, and whatever the energy stored will be dissipated in its braking resistance R_B, R_a and D. If I_a is assumed to be rippleless, the dc energy consumed by R_B during a cycle of chopper operation is

$$E_N = I_a^2 R_B (T - t_{on}) \tag{4.41}$$

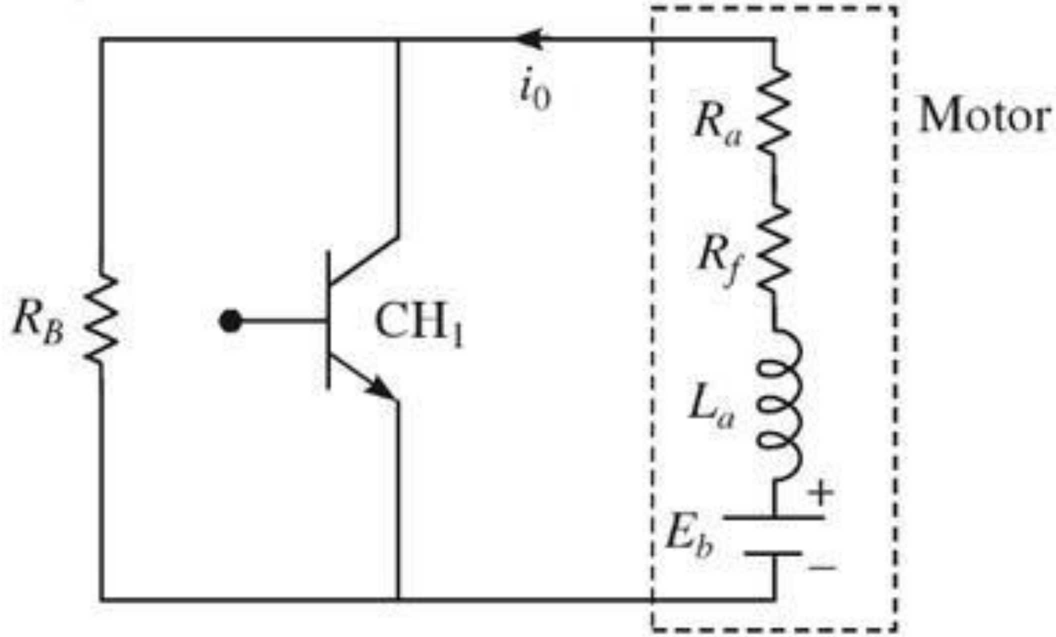


Fig. 4.22 Dynamic braking of dc series motor by chopper control.

Average power consumed by R_B,

$$\therefore \qquad P = \frac{E_N}{T} = I_a^2 R_B(1 - \delta)$$

Effective value of R_B,

$$R_{BE} = \frac{P}{I_a^2} = R_B(1 - \delta)$$

where

$$\delta = \frac{t_{on}}{T}$$

Therefore the preceding equation shows that the effective value of braking resistor can be changed steplessly from 0 to R_B as δ is controlled from 1 to 0. As the speed falls, δ can be increased steplessly to brake the motor at a constant maximum torque as shown in Fig. 4.23. The speed–torque characteristics of dc series motor are shown in Fig. 4.23.

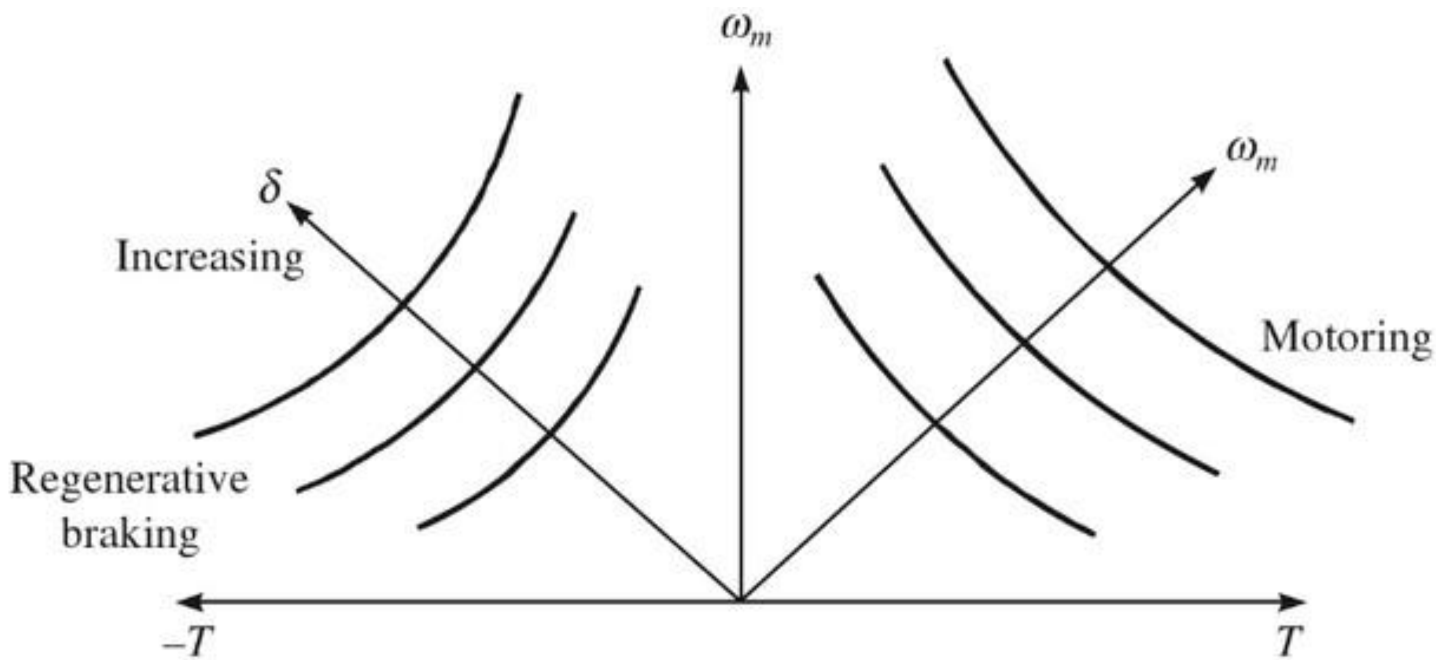


Fig. 4.23 Speed–torque characteristics of dc series motor.

Closed Loop Control of Drives

In all drives, where the speed and position are controlled, a power electronic device is provided as an interface between the input power and the motor load, where it provides accurate, fast and dynamic response, and reduced effects of load discontinuity and system nonlinearity. In a closed loop the control drives for various closed loop configurations, which are associated with control circuit, will be represented by a complete block diagram converter with certain constraints which are discussed in the following sections.

1. Current Limit Control

In this, current limit control (shown in Fig. 4.28) is provided to limit the control of the converter and the motor current for the safe limit during transient operations. The feedback loop does not affect the operation of the drive as long as current is set to a maximum value. If the current exceeds the maximum set value, its feedback loop becomes activated. Thus the current fluctuates around an infinite set maximum limit during the transient operation until the drive conduction is such that the current does not have a tendency to cross the set maximum value. Under steady state operating point, current will not have tendency to cross the maximum value.

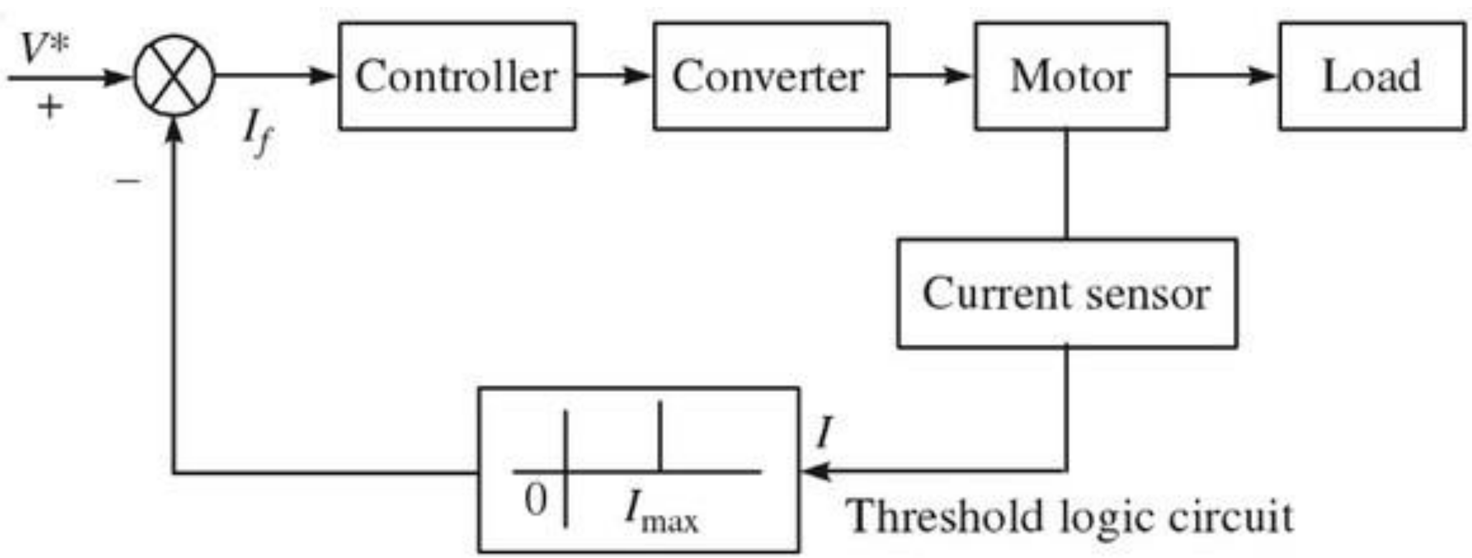


Fig. 4.28 Current limit control.

2. Closed Loop Torque Control

In closed loop torque control, whenever motor drive activates the acceleration to the reference torque (T_{ref}), through closed loop control of the torque the actual motor torque T follows T_{ref}. Now, by providing the appropriate acceleration it adjusts the speed depending on traffic condition and speed limit, and also provides closed loop torque control as shown in the block diagram (Fig. 4.29).

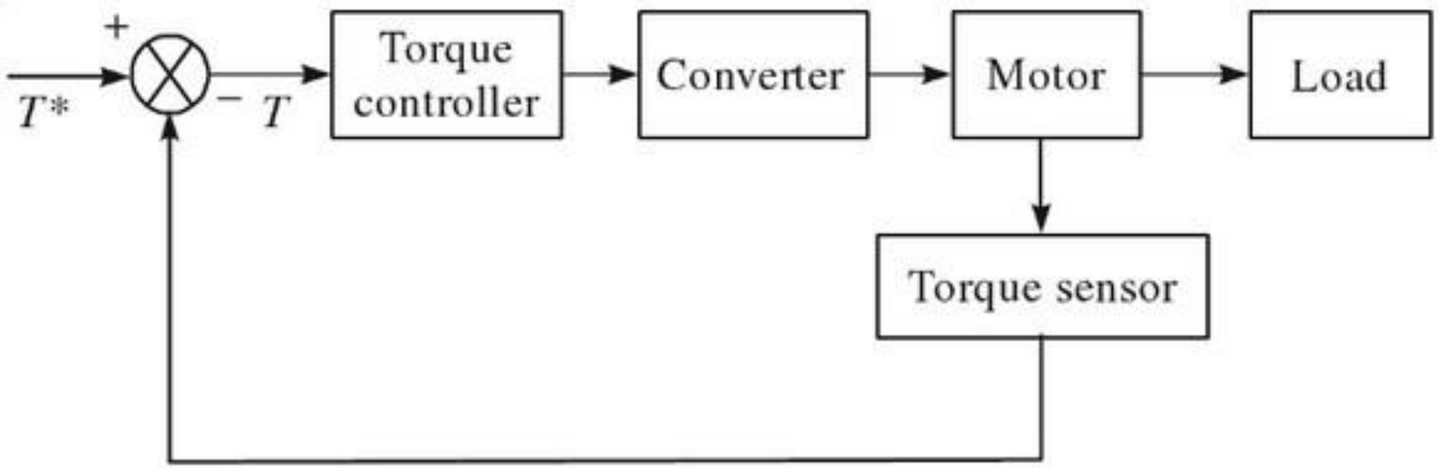


Fig. 4.29 Closed loop torque control.

3. Closed Loop Speed Control

It is combination of both current limit control and torque control, where inner loop for current control and outer loop is provided to limit the converter and motor for its drives torque below infinite safe limit. With the positive reference, speed produces a error $\Delta\omega_{ref}$. This speed error is processed through infinite speed controller and applied to a current limit which saturates even for the inner current control loop at a value comparable to its maximum value. The drive valuates to the maximum allowable current. When close to the desired speed, the current limiter desaturates, if the decrease in ω_{ref} produces a negative speed current loop for its allowable maximum current. When close to the desired speed limits desaturates the operation is transferred from braking to motoring drive—those drives where the current does not reverse for braking operation. Current and speed controllers may consist of P, PI, PID controllers depending on steady state accuracy and transient response requirements, which have been shown in Fig. 4.30.

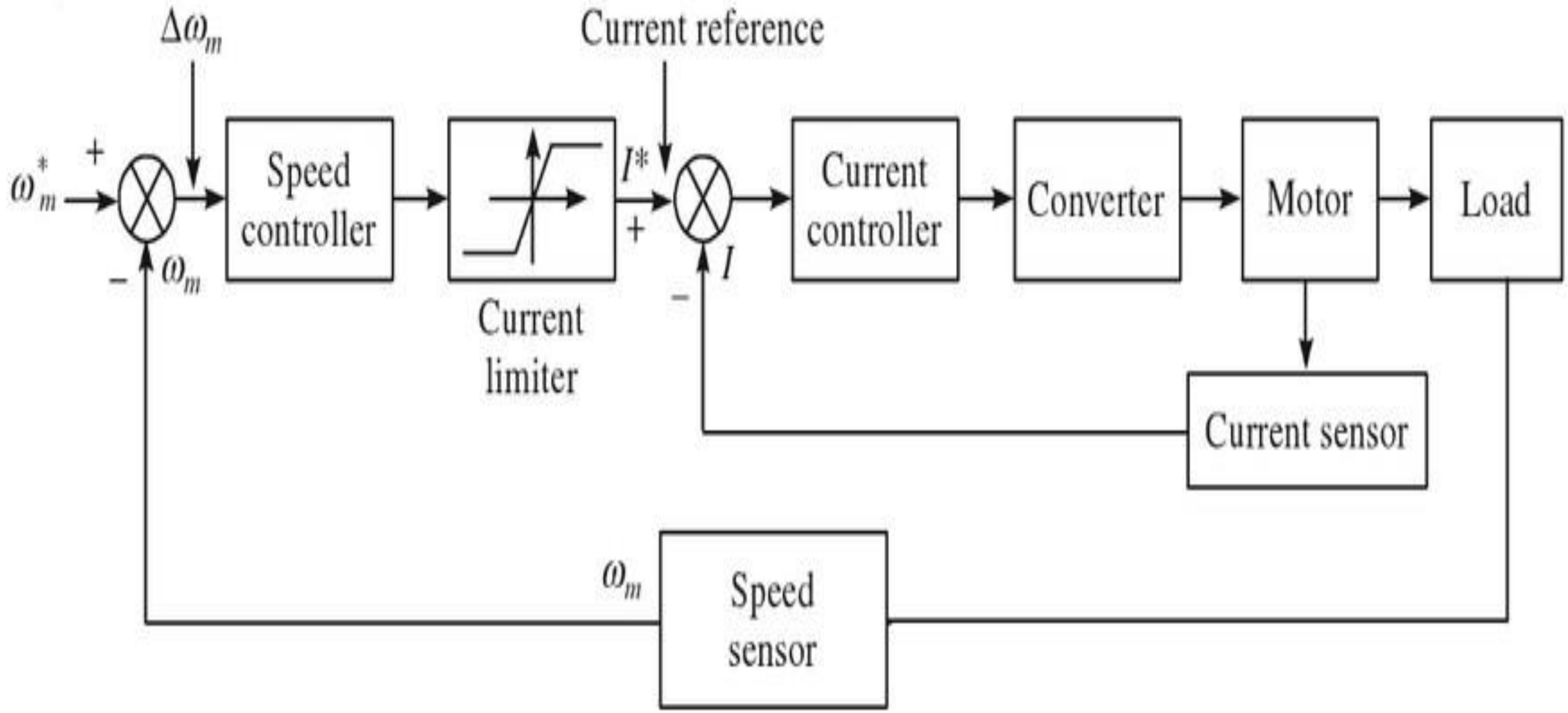


Fig. 4.30 Closed loop speed control.

4. Closed Loop Control for DC Excited Motors

In order to protect the converter against current loads, open loop drives are used with current limit control. It should be noted that the acceleration at maximum current or torque will be possible when the converter used has also the capability for braking operation. It may be further noted that controlled rectifier will be used when supply is ac and chopper is used when supply is dc. The basic approach of closed loop speed control below and above the speed is explained by the drive shown in Fig. 4.31. Below a base speed, a drive will operate at a constant field current and variable armature voltage. Above the base speed, the drive will operate at constant armature voltage and variable field current.

Operation below base speed

In the field current loop the back emf E_b is compared with a reference voltage E_{ref} which is chosen to be between 0.85 to 0.95 of the rated armature voltage. The higher value is used for motors with low armature circuit resistance. For speeds below the base speed, the field control saturates due to large value of error. The firing angle of rectifier α is maintained at zero, applying

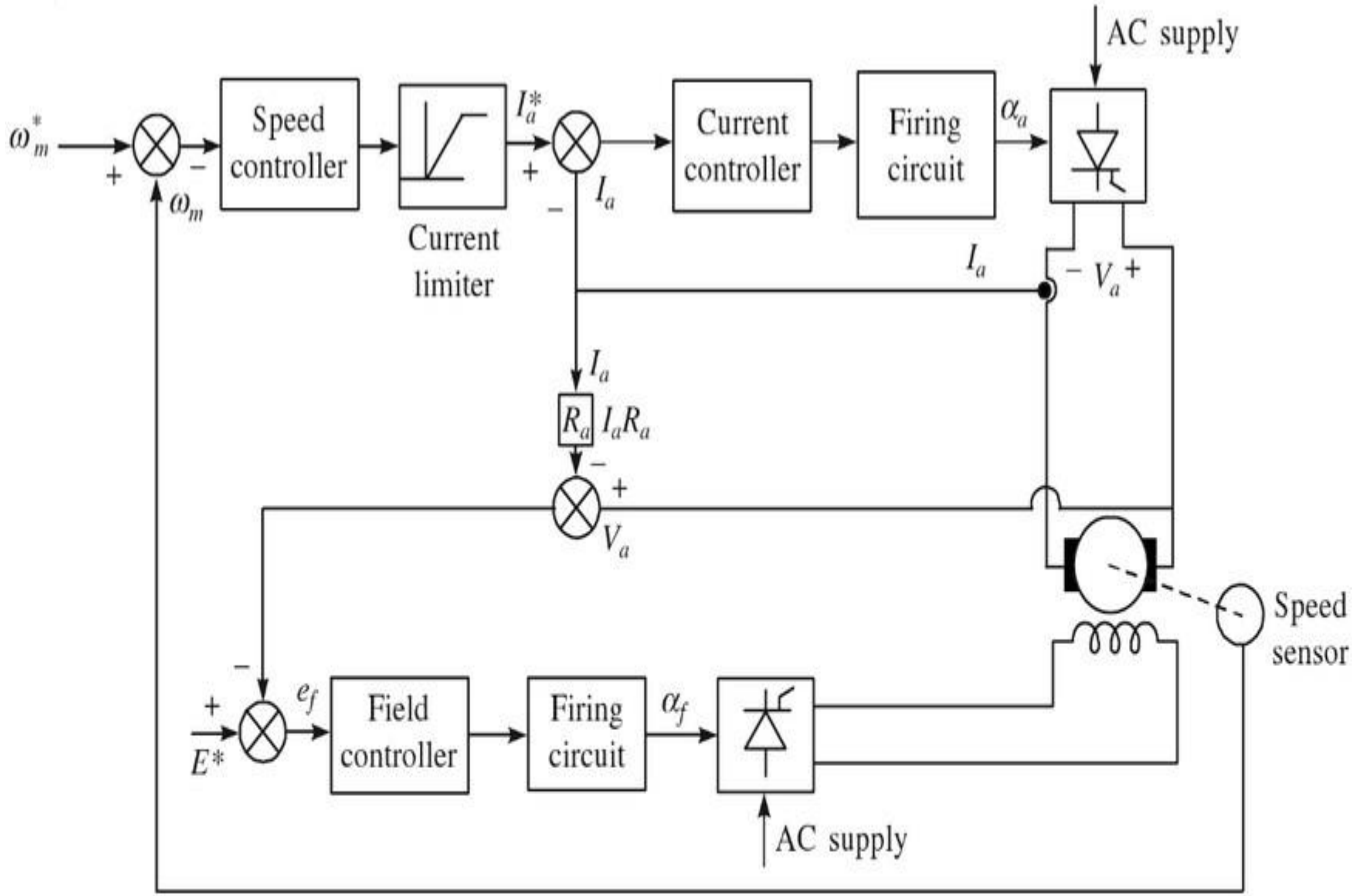


Fig. 4.31 Closed loop control for dc excited motors.

rated voltage to the field. This ensures rated field current for motor operation. When speed reference is increased from ω_{m1} to ω_{m2} ($\omega_{m1} < \omega_{m2}$), due to large speed error the current limiter saturates and sets the current reference at the maximum permissible value. The drive accelerates at the maximum available current and torque. When speed reaches close to ω_{m2}, the current limiter desaturates and the drive settles at speed ω_{m2} and at the current which gives motor torque equal to the load torque. It speed reference is reduced back to ω_{m1}; the current reference is set at zero and the drive de-accelerates due to load torque. When reference speed is increased again, making speed error positive, the charged PI controller takes a longer time to respond, making the transience response slower.

Operation above base speed

When close to base speed the field controller comes out of saturation. Now, if the reference speed is set for a speed above base speed, the current reference is set at the maximum permissible value. The firing angle of the armature rectifier α_a is reduced to initially increase V_a; the motor acceleration E_b increases, and E_f decreases, reducing the field current. Thus the motor speed continues to increase and field current continues to decrease, until the motor speed becomes equal to the reference speed.

Since the speed error will now be small, V_a will return to a value close to a original value. Thus the speed control above base speed is obtained by field control with the armature voltage maintained near the rated value. In the field control region, the drive responds very slowly due to large value of the field time constant.

1. For high frequency choppers, the device that is preferred is ________.
   (a) Thyristor
   (b) TRIAC
   (c) Transistor
   (d) GTO
2. Identify the speed–torque related equation from the following:
   (a) $\frac{\delta V}{K} - \frac{T}{K^2}$
   (b) $\frac{\delta V}{K} - \frac{TR_a}{K^2}$
   (c) $\frac{\delta V}{K^2} - \frac{T}{R_a K^2}$
   (d) $\frac{\delta V}{K} + \frac{T}{K^2}$
3. In the third quadrant of operation of a chopper power is ________.
   (a) Positive
   (b) Negative
   (c) Both (a) and (b)
   (d) None of these
4. Name any one chopper device ________.
   (a) Step up chopper
   (b) Step down chopper
   (c) Both
   (d) None of these
5. Name any one controlling technique for varying the duty ratio.
   (a) TRC control
   (b) CLC control
   (c) Both
   (d) None of these

6. Duty ratio of chopper has the units of ________.
   (a) Seconds (b) Degrees
   (c) Radians (d) None of these
7. If f is the chopping frequency, then the duty ratio of chopper is ________.
   (a) $1/f$ (b) t_{on}/f
   (c) 0 (d) $t_{on} \times f$
8. Maximum speed is obtained with chopper fed dc motor for duty ratio of ________.
   (a) 0 (b) 0.33
   (c) 0.5 (d) 1
9. During regenerative braking mode, the back emf is ________ than supply voltage.
   (a) Less (b) More
   (c) Equal to (d) None of these
10. Both torque and speed will be –ve while drive is operating in ________ quadrant.
   (a) First (b) Second
   (c) Third (d) Fourth
11. First quadrant operation of dc drive is called ________.
   (a) Forward motoring (b) Forward braking
   (c) Reverse motoring (d) Reverse braking
12. Second quadrant operation of dc drive is called ________.
   (a) Forward motoring (b) Forward braking
   (c) Reverse motoring (d) Reverse braking

13. Third quadrant operation of dc drive is called ________.
   (a) Forward motoring (b) Forward braking
   (c) Reverse motoring (d) Reverse braking

14. Fourth quadrant operation of dc drive is called ________.
   (a) Forward motoring (b) Forward braking
   (c) Reverse motoring (d) Reverse braking

15. dc–dc converter or chopper has ________.
   (a) Only step-down dc voltage (b) Only step-up dc voltage
   (c) Step-up or step-down dc voltage (d) None of these

16. In a chopper control of series motor under regenerative braking, the series motor functions as a self-excited series generator. For self excitation,
   (a) Field winding should oppose the residual magnetism
   (b) Field winding should assist the residual magnetism
   (c) Both (a) and (b)
   (d) None of these.

17. In a chopper control of series motor, the relation between e and i_a is nonlinear
   (a) Due to saturation of magnetic circuit
   (b) Due to variation in terminal voltage
   (c) Due to variable speed of motor
   (d) Both (a) and (b).

18. A chopper can be considered a dc equivalent to a
   (a) Transformer
   (b) Cycloconverter
   (c) Dual connector
   (d) None of these.

19. In a chopper control circuits, transistor choppers are preferred over thyristors because these can be operated at
   (a) Very high frequency
   (b) Very low frequency
   (c) Medium frequency
   (d) Supply frequency.

20. What are the types of control strategies in a dc chopper?
   (a) Time ratio control
   (b) Current limit control
   (c) Both (a) and (b).

21. Regenerative braking of a dc motor may be achieved by
   (a) Phase-controlled converter
   (b) Inverter
   (c) Cycloconverter
   (d) None of these.

22. In a multiquadrant operation, quadrant I operation provides
   (a) Forward motoring
   (b) Reverse motoring
   (c) Forward braking
   (d) Reverse braking.

23. What is the advantages of closed loop control scheme?
   (a) Accurate speed control
   (b) High amount of loss
   (c) Low efficiency
   (d) All of these.

24. A chopper is a static device that converts __________.
   (a) ac to dc
   (b) ac to ac
   (c) dc to dc
   (d) None of these

25. A chopper is a ________ speed on/off semiconductor switch.

(a) Low
(b) High
(c) Both (a) and (b)
(d) None of these

26. A chopper will conduct for the ________ period.

(a) t_{on}
(b) t_{off}
(c) Both (a) and (b)
(d) None of these

27. δ represents ________.

(a) Duty cycle
(b) Firing angle
(c) Both (a) and (b)
(d) None of these

28. The control function of chopper can be performed by using ________.

(a) TRC
(b) CLC
(c) Both (a) and (b)
(d) None of these

29. In step-down chopper, V_0 = ________.

(a) δE_a
(b) $(1 - \delta)E_a$
(c) E_a
(d) None of these

30. In step-up chopper, E_0 = ________.

(a) δE_a
(b) $(1 - \delta)E_a$
(c) E_a
(d) None of these

31. The value of δ ranges from ________.
(a) 0 to 1
(b) 0 to 2
(c) 0 to 0.5
(d) None of these

32. In TRC control, the constant frequency system is also called ________.
(a) Pulse width scheme
(b) Frequency modulation
(c) Both (a) and (b)
(d) None of these

33. In TRC control, the variable frequency system is also called ________.
(a) Pulse width scheme
(b) Frequency modulation
(c) Both (a) and (b)
(d) None of these

34. The rms value of output voltage of basic chopper is ________.
(a) $\sqrt{\delta}\, E_a$
(b) $(1 - \delta)E_a$
(c) E_a
(d) None of these

35. The average value for thyristor voltage of basic chopper is ________.
(a) $\sqrt{\delta}\, E_a$
(b) $(1 - \delta)E_a$
(c) E_a
(d) None of these

36. The type A chopper is also called ________ chopper.
(a) Step-down
(b) Step-up
(c) Both (a) and (b)
(d) None of these

37. The type B chopper is also called ________ chopper.

(a) Step-down
(b) Step-up
(c) Both (a) and (b)
(d) None of these

38. The type E chopper is also used in the ________.

(a) First-quadrant
(b) Second-quadrant
(c) Third-quadrant
(d) None of these

39. Average output voltage at $\delta = 1$, $E_0 =$ ________.

(a) E_a
(b) E_b
(c) $-E_a$
(d) $-E_b$

1. In case of travelling cranes, the motor preferred for boom hoist is ________.
   (a) AC slip ring motor
   (b) Ward Leonard controlled dc shunt motor
   (c) Synchronous motor
   (d) Single-phase motor
2. The characteristics of the drive for crane hoisting and covering is ________.
   (a) Smooth movement
   (b) Precise control
   (c) Fast speed control
   (d) All of these
3. The range of horse power of electric motor drives for rolling miles is of the order of ________.
   (a) 1 to 10 HP
   (b) 15 to 25 HP
   (c) 50 to 100 HP
   (d) 100 to 500 HP
4. Motors preferred for rolling nice drive are
   (a) DC motor
   (b) AC slip ring motor with speed control
   (c) Any of these
   (d) None of these
5. A motor of less than full load power rating can be used if the load is ________.
   (a) Continuous duty
   (b) Short time duty
   (c) Intermittent periodic duty
   (d) None of these
6. To get speed higher than the base speed of the dc shunt motor, ________.
   (a) Armature resistance control is used
   (b) Field resistance control is used
   (c) Armature voltage control is used
   (d) None of these
7. In case of contactors the duty in which the main contacts remain closed, for a period bearing a definite relation to the no-load periods, is known as ________.
   (a) Standard duty
   (b) Intermittent duty
   (c) Temporary duty
   (d) Uninterrupted duty

8. In overhead traveling cranes, ________.
   (a) Continuous duty motors are used
   (b) Slow speed motors are preferred
   (c) Short time rated motors are preferred
   (d) None of these

9. Light duty cranes are generally used in ________.
   (a) Automobile workshop
   (b) Pumping stations
   (c) Power houses
   (d) All of these

10. Heavy duty cranes are used in ________.
   (a) Heavy engineering workshops
   (b) Steel plants
   (c) Ore handling plants
   (d) All of these

11. The number of sets used in pole changing type squirrel cage motors, for derricks and winches, is ________.
   (a) 2
   (b) 3
   (c) 4
   (d) 6

12. A pole changing type squirrel cage motor used in derricks has four, eight and twenty-four poles. In this, medium speed is used for ________.
   (a) Lifting
   (b) Hoisting
   (c) Lowering
   (d) Landing the load

13. Belt conveyors offer ________.
   (a) Zero starting torque
   (b) Low starting torque
   (c) Medium starting torque
   (d) High starting torque

14. Torque is proportional to ________.
(a) I_a
(b) E
(c) W
(d) E_b

15. Speed is proportional to ________.
(a) I_a
(b) T
(c) W
(d) E_b

16. To make a dc machine operate in reverse motoring, ________.
(a) E and I should be negative
(b) E should be positive and I should be negative
(c) E should be negative and I should be positive
(d) E should be and I should be positive

17. Power supply will be fed back to supply lines during ________ braking.
(a) Regenerative
(b) Rheostatic
(c) Reverse current
(d) Mechanical

18. Power will be dissipated as heat during ________ braking.
(a) Regenerative
(b) Rheostatic
(c) Reverse current
(d) Mechanical

19. Either armature or field terminals of a dc motor are reversed in ________ braking.
(a) Regenerative
(b) Rheostatic
(c) Reverse current
(d) Mechanical

20. For applications of high starting torque, motor preferred is ________.
(a) DC shunt
(b) DC series
(c) DC compound
(d) None of these

21. Which motor is not supposed to start without load? ________.
(a) DC shunt
(b) DC series
(c) DC compound
(d) None of these

22. In dual converter fed dc motor, $\alpha_1 + \alpha_2$ is equal to ________.
(a) 0
(b) $\pi/2$
(c) π
(d) 2π

23. SCR commutation is the process of ________.
(a) Opening the SCR
(b) Closing the SCR
(c) Replacing the SCR
(d) Calibrating the SCR
(e) Reverse motoring
(f) reverse braking

24. Most efficient method of braking system is ________.
(a) Regenerative
(b) Rheostatic
(c) Reverse current
(d) Mechanical

25. What is meant by dynamic braking? ________.
(a) Power dissipated in resistance
(b) Power feedback to the source
(c) Reverse the supply terminals
(d) All of these

26. A freewheeling diode is connected across R–L load because ________.
   (a) It prevents infinite voltage across switch which breaks current
   (b) It rectifies current
   (c) It prevents current in opposite direction
   (d) None of these

27. Power electronic equipments have very high efficiencies because ________.
   (a) The devices always operate in active region
   (b) The device never operate in achieve region
   (c) Devices achieve inverse region at high speed and stay at the two states on or off
   (d) Cooling is very efficient

28. In simultaneous control of dual converter, both the rectifiers are controlled together in order to avoid ________.
   (a) AC circulating current between the rectifiers
   (b) DC circulating current between the rectifiers
   (c) Leakage current between the rectifiers
   (d) None of these

29. In a non-simultaneous control of dual converter, ________.
   (a) One rectifier is controlled at a time
   (b) Two rectifiers are controlled at a time
   (c) Both the rectifiers in the circuit one by one

(d) None of these

30. What are the types of control strategies in a dc chopper?
    (a) Time ratio control
    (b) Current limit control
    (c) Both a and b
    (d) None of these.

31. What is meant by dual converter?
    (a) Fourth quadrant operation is possible
    (b) First quadrant operation is possible
    (c) Second quadrant operation is possible
    (d) Third quadrant operation is possible.

32. What is meant by plugging?
    (a) Supply terminals are reverse
    (b) Supply terminals are disconnected
    (c) Power flows from load to source
    (d) All of these.

33. What is meant by regenerative braking?
    (a) Supply terminals are reverse
    (b) Power flows from load to source
    (c) Power flows from source to load
    (d) All of these.

34. What are the braking methods used in a dc motor?
    (a) Plugging
    (b) Dynamic braking
    (c) Regenerative braking
    (d) All of these.

35. What are the three types of electric braking?
    (a) Plugging
    (b) Dynamic braking
    (c) Regenerative
    (d) All of these.

36. Dual converter operates in _________ quadrants.

(a) First and second
(b) Fourth
(c) Second and third
(d) Third and fourth

1. Differentiate between two-quadrant and four-quadrant drives.
2. Describe how a four-quadrant drive can be obtained from a chopper-fed separately excited dc motor.
3. Describe how two 1-phase full converters can be used back to back to form a circulating dual converter. Discuss its operation with the help of voltage waveforms for (a) each converter, (b) load (R–L) and (c) limiting reactor.
4. Describe how circulating current waveforms can be obtained from reactor voltage waveforms in 3-ϕ dual converters.
5. Derive the expressions for a 3-ϕ dual converter fed with limiting reactor in terms of E_a, L_s, α, etc. Sketch the relevant voltage and current waveforms needed for its derivation.
6. An non-circulating current dual converter is connected to a dc motor. Explain its control strategies for selecting its multi-quadrant operation converter with the help of power circuit diagrams.
7. In a 3ϕ dual converter of circulating current type, the input to the dual converter is 3-phase. Draw its voltage and current waveforms, when converter I delay angle is 30°.
8. Define braking. Describe various types of braking. What is the significance of electrical braking?

9. Enumerate the advantages of electrical braking over mechanical braking of dc motor and explain the speed–torque characteristic of dc motor under plugging for the following: (a) separately excited dc motor; (b) series excited dc motor.
10. What is regenerative braking? Describe the regenerative braking fed in separately and series excited dc motor with the help of circuit diagram.
11. Describe the relative merits and demerits of the following types of braking for dc motors: (a) mechanical braking; (b) dynamic braking; and (c) regenerative braking, with a neat diagram.
12. What is a dual converter? Explain the principle of operation of a dual converter in circulating current mode. How is the same used for speed control of dc drive?
13. Draw the circuit diagram and explain the operation of closed-loop speed control with inner-current loop and field weakening.
14. Explain how four-quadrant operation is achieved by dual converters, each of 3ϕ full wave configuration, for separately excited dc motor.
15. Distinguish between circulating current and non-circulating current mode of operation.
16. Draw and explain the torque–speed characteristics for dynamic braking operation of dc series motor. Why does torque become zero at finite speed?

17. With a neat diagram, explain the operation of a dc drive in all four quadrants when fed by a single-phase dual converter, with necessary waveforms and characteristics.
18. What are the advantages of electrical braking over mechanical braking of dc motor?
19. Explain with a proper circuit diagram the speed–torque characteristics of dc motor, under dynamic braking, for the following types:
    (a) Separately excited dc motor
    (b) Series motor.
20. List the advantages offered by dc chopper drives over line-commutated converter-controlled dc drives.
21. Discuss in detail the counter current and dynamic braking operations of dc shunt motors.
22. Derive the expressions for average motor currents I_{max} and I_{min}, and average torque for chopper-fed separately excited dc motor.
23. "Electrical braking of series motor is not as straightforward as that of a separately excited dc motor." Justify.
24. Give a simple circuit for the speed control of a dc shunt circuit motor.
25. Draw and explain the torque–speed characteristics for dynamic braking operation of dc series motor. Why does torque become zero at finite speed?
26. For stator voltage control scheme of a 3-phase induction motor, discuss speed range, regeneration, harmonics, torque pulsating, power factor, cost, efficiency and applications.

26. For stator voltage control scheme of a 3-phase induction motor, discuss speed range, regeneration, harmonics, torque pulsating, power factor, cost, efficiency and applications.

1. Differentiate between two-quadrant and four-quadrant drives.
2. Describe how a four-quadrant drive can be obtained from a chopper-fed separately excited dc motor.
3. Define a dc chopper. Describe the various types of basic chopper configurations with necessary diagrams.
4. Write the voltage equations of type A chopper during T_{on} and T_{off} periods for an RLE load. Hence obtain steady state analysis expressions for maximum and minimum currents considered by the load.
5. Explain the operation of a transistorized chopper drive for a separately excited dc motor in
   (a) Regenerative braking mode
   (b) Dynamic braking mode.
6. Describe different methods of braking and explain the plugging operation of a chopper fed with series excited dc motor with the help of its performance curves.
7. Write a short note on closed loop system fed with dc motor drives. Explain the importance of a closed loop system that is used when chopper control dc drive system is connected.

8. A class A chopper, operating in time ratio control, is supplying the armature of a separately excited dc motor. Show that the motor speed–torque relationship is

$$\omega_m = \frac{\delta \cdot V}{K} - \frac{R_a}{K^2} T_a$$

where

V = Chopper input voltage
R_a = Armature resistance
T_a = Motor torque
K = Torque constant.

9. Explain with a neat circuit diagram the basic principle of operation of a class A type chopper. The chopper is connected to a RLE load. Analyze the same for continuous current mode of operation.

10. Discuss with suitable diagrams the first quadrant and second quadrant choppers.

11. What is a dual converter? Explain the principle of operation of a dual converter in circulating current mode. How is the same used for speed control of dc drive?

12. Deduce the mathematical expression for minimum and maximum currents for a class A chopper operated dc motor with back emf.
13. Draw the circuit diagram and explain the operation of closed loop speed control with inner-current loop and field weakening.
14. Explain the principle of speed control of a dc motor and show how it can be achieved by a chopper.
15. Explain how four-quadrant operation is achieved by dual converters, each of 3ϕ full wave configuration, for a separately excited dc motor.
16. Explain the principle of closed loop control of a dc drive using suitable block diagram.
17. Deduce the mathematical expression for minimum and maximum current for a class A chopper-operated dc motor with back emf.
18. List the advantages offered by dc chopper drives over line-commutated converter-controlled dc drives.
19. Derive the expressions for average motor currents I_{max} and I_{min} and average torque for chopper-fed separately excited dc motor.
20. Discuss first quadrant and second quadrant choppers with its suitable diagrams.

UNIT-III: Control of Induction motors

Variable voltage characteristics-Control of Induction Motor by Ac Voltage Controllers – Waveforms – speed torque characteristics. Variable frequency characteristics-Variable frequency control of induction motor by Voltage source and current source inverter and cycloconverters- PWM control – Comparison of VSI and CSI operations – Speed torque characteristics – numerical problems on induction motor drives – Closed loop operation of induction motor drives (Block Diagram Only)

INTRODUCTION

- Induction motors, particularly squirrel cage IM, have many advantages when compared to DC motors. They are,
  - Ruggedness
  - Lower maintenance requirements
  - Better reliability
  - Low cost, less weight and volume
  - Higher efficiency
  - Also induction motors are able to operate in dirty and explosive environments.
- Because of the above said advantages, induction motors are predominantly used in many
- industrial applications. But induction motors were used only for applications requiring constant
- speed.
- DC motors were used for variable speed applications as their speed control is cheap and
- efficient when compared to induction motors.
- After the advent of power electronic converters, it was able to design variable speed drives
- for induction motors. Because speed control of IM using power electronic converters have become
- cheap and less costly when compared to dc drives.

SPEED CONTROL

- The conventional methods of speed control of induction motors are,
- Stator Side
  - Stator voltage control
  - Variable frequency control
  - Stator current control
  - V/f control
  - Changing the number of poles on stator
- Rotor Side
  - Rotor resistance control
  - Injecting emf in the rotor

STATOR VOLTAGE CONTROL

- Speed of induction motor can be varied in a narrow range by varying the voltage applied to the stator winding.
- Torque developed by 3 phase induction motor is directly proportional to the square of the stator voltage as given by the equation,

$$T_m = \frac{3}{2\pi N_s} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} - - - - - - 1$$

$$N_s = \frac{3}{2\pi T_m} \times \frac{S.E_2^2.R_2}{R_2^2 + (S.X_2)^2} - - - \; - - 2$$

- In low slip region $(S.X_2)^2$ is very small as compared to R_2. So, it can be neglected. So equation 1 becomes,

$$T_m \propto \frac{S.E_2^2}{R_2}$$

- Since rotor resistance R_2 is constant, the torque equation becomes,

$$T_m \propto S.E_2^2$$

Here E_2 is proportional to the supply voltage V_1. Hence,

$$T_m \propto S.V_1^2 ------3$$

- From equation 2, it is clear that any reduction in supply voltage will reduce the motor speed. But from equation 3, it is seen that any reduction in supply voltage will reduce the torque also.
- So in this method of speed control, torque reduces when supply voltage reduces. Hence this method is used in applications where torque demand reduces with reduction in voltage.
- In general, this method can be used for small range of speed variation.
- In this method of speed control, the slip increases at low speeds. Hence the efficiency of the drive reduces.
- Examples: Fans and pump drives.

Stator voltage control using AC voltage controllers

- The variation of motor voltage is obtained by ac voltage controllers. AC voltage controllers
- convert fixed ac to variable ac with same frequency.
- But this method produces harmonics in the output and the power factor is low.
- The harmonic content increases and power factor decreases with decrease in output
- voltage.
- Hence the torque produced by the motor reduces.
- This method is used in applications like fans, pumps and crane drives.
- The circuit for star connected ac voltage controller feeding a 3 phase induction motor is
- shown in Fig. 4.1

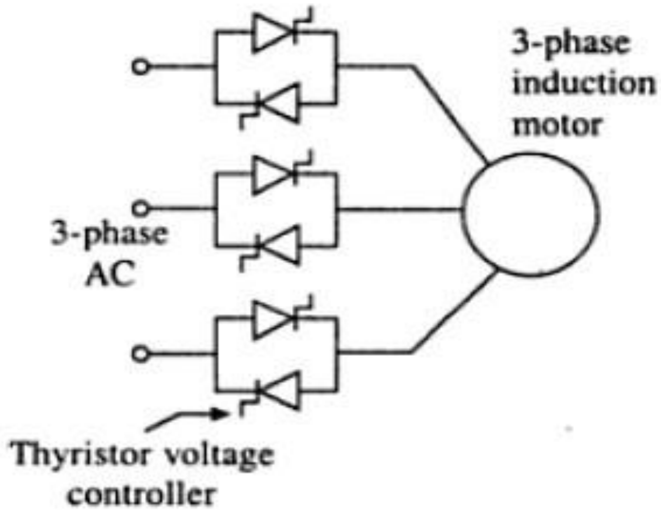


Fig. 4.1 Star connected controller

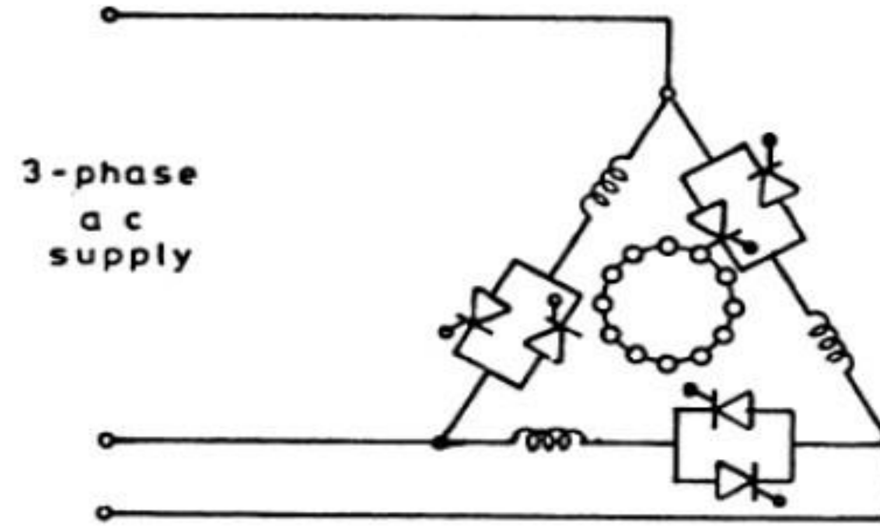


Fig. 4.2 Delta connected controller

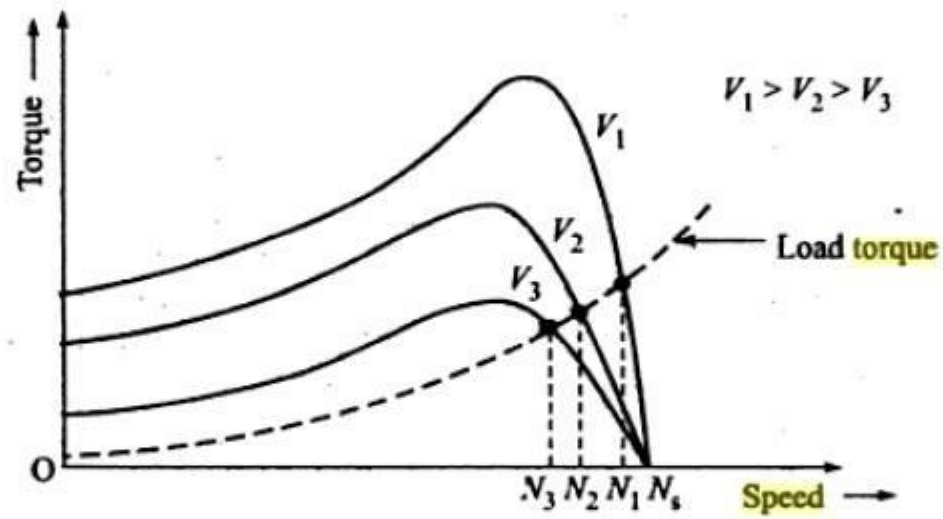


Fig. 4.3 Speed – Torque characteristics with stator voltage control

- By controlling the firing angle of the thyristors connected in each phase, the rms value of stator voltage can be varied.
- As a result of this, the motor torque and the speed of the motor are varied.
- In star connected controller, all the thyristors carry line currents. But in delta controller shown in Fig. 4.2, all the thyristors carry phase current only. Hence low rating thyristors may be employed in delta controller.
- But delta controller produces circulating currents due to third harmonic voltages.
- This may increase power loss across each device.
- The speed range is limited in this method of speed control.
- This method is used for applications where load torque requirement reduces with reduction in speed as shown in Fig. 4.3. When a voltage of V1 is applied, the load load torque required is high and when a voltage V3 is applied. The load torque is low.
- These ac voltage controllers are also used as starters for soft start of motors.
- The power factor of ac voltage circuit is low.
- It can be used for fans and pump drives.

STATOR FREQUENCY CONTROL (OR) FIELD WEAKENING METHOD OF SPEED CONTROL

- In an induction motor, we know that,

$$N_s = \frac{120.f}{P} - - - - - - - - 4$$

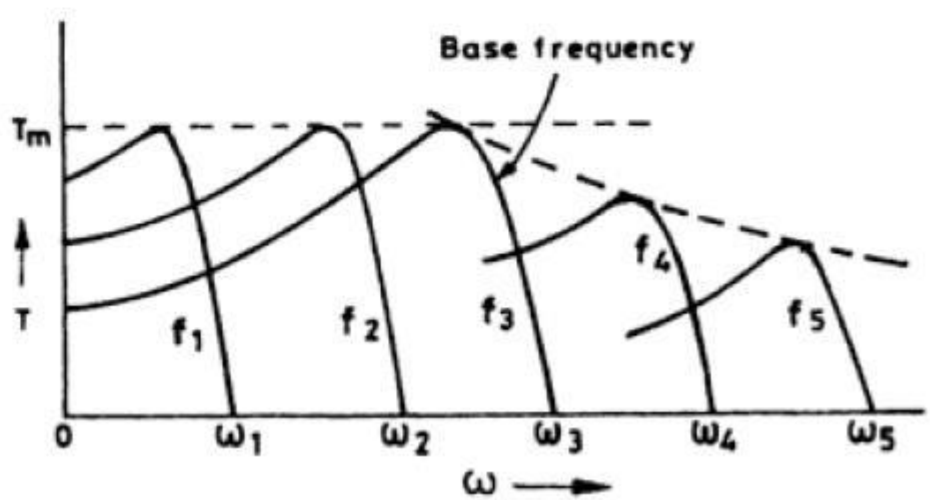
- From the above equation 4, it is clear that changing the supply frequency will change the synchronous speed and hence the rotor speed.
- Emf equation in ac machines is given by,

$$V_1 = 4.44.f.\varphi.K_w.N_1$$

$$\therefore \varphi = \frac{V_1}{4.44.f.K_w.N_1} - - - - - - 5$$

- The above equation 5 states that the flux φ will be constant if V_1 and f are kept constant.

- If frequency is reduced with constant V_1, then the flux φ increases. Hence the core gets saturated.
- This will increase the magnetizing current of the motor. Hence power losses increased and efficiency decreases. It also produces noise.
- If the frequency is increased by keeping the V_1 constant, then flux decreases. This will reduce the maximum torque produced by the motor as shown in Fig. 4.4.
- So this method is rarely used in practice.
- With constant voltage, if the frequency is increased, the air-gap flux reduced. This control is also called as field weakening mode of speed control.



VOLTAGE / FREQUENCY CONTROL (OR) VOLTS / HERTZ CONTROL

- Varying the voltage alone or frequency alone has some disadvantages with regards to the operation of induction motor.
- The maximum torque in an induction motor is given by,

$$T_{max} = \frac{K(V/f)^2}{\frac{R_s}{f} \pm \sqrt{\left[\left(\frac{R_s}{f}\right)^2 + 4\pi^2(L_s + L_r')^2\right]}} -------6$$

- Here K is a constant and Ls & Lr' are the stator and stator referred rotor inductances.
- At high frequencies, the value of (R_s/ f) will be very much less than 2π (Ls+ Lr'). So (R_s/ f) can be neglected and hence the torque equation becomes,

$$T_{max} = \pm \frac{K(V/f)^2}{\sqrt{[4\pi^2(L_s + L_r')^2]}}$$

$$T_{max} = \pm \frac{K(V/f)^2}{2\pi(L_s + L_r')} ------7$$

- From equation 7, it is clear that if the ratio (V / f) is kept constant, the motor can produce a constant maximum torque, T_{max}. i.e constant torque operation.

- At low frequencies (when speed is reduced), the term (Rs / f) will be high and it cannot be neglected in equation 6. Hence the motor torque reduces.
- This is because of the fact that the flux reduces as the frequency is decreased as per equation 5.
- Hence if maximum torque needs to be maintained constant at low speeds, then (V / f) ratio must be increased.
- Near to base speed (or rated speed), the supply voltage will be maximum and it cannot be increased further. Therefore, above base speed, the frequency is changed by keeping supply voltage constant.
- But this will decrease the maximum torque produced by the motor as per the equation 7.

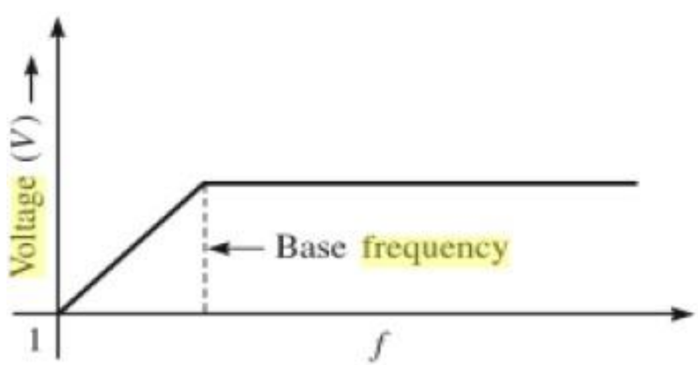


Fig. 4.5. V – f relationship

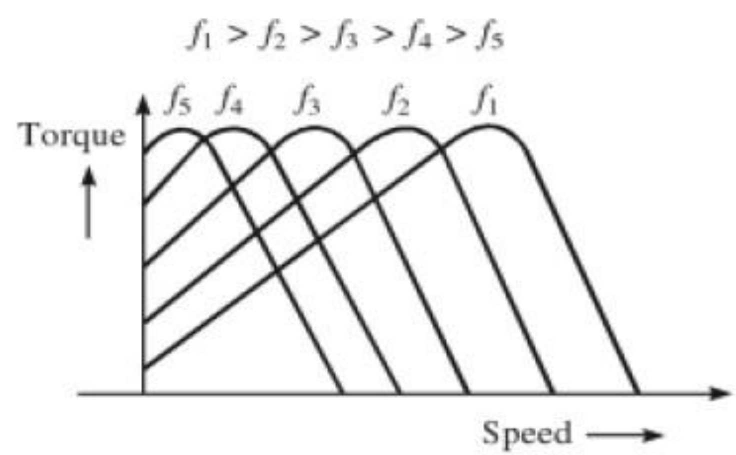


Fig. 4.6. Speed – Torque characteristics

- From the graph of Fig. 4.5, it is clear that
- (V/f) ratio is increased at low frequency to keep maximum torque constant.
- (V/f) ratio is kept constant at high frequencies up to base frequency
- V is kept constant and frequency is varied above base frequency.
- From Fig. 4.6, it is clear that the maximum torque is same at all different speeds.
- This volts / Hertz control offers speed control from standstill up to rated speed of IM.
- This (V/f) control is achieved by using VSI and CSI fed induction motor drives.
- If a six step inverter is used, the frequency alone can be varied at the inverter output and
- the output voltage is controlled by varying the input dc voltage.
- If a PWM inverter is used, both voltage and frequency can be varied inside the inverter
- itself by changing the turn on and off periods of the devices

VOLTAGE SOURCE INVERTER (VSI) FED INDUCTION MOTOR DRIVES

- In voltage source inverters, the input voltage is kept constant.
- The magnitude of output voltage of VSI is independent of the load.
- But the magnitude of output current depends on the type of load.
- A VSI converts the input dc voltage into an ac voltage with variable frequency at its output terminals.
- VSI using normal transistors is shown in Fig. 4.7. Any other self commutated device can be used in place of transistors
- MOSFET is used in low voltage and low power inverters.
- IGBTs and power transistors are used up to medium power levels.
- GTO and IGCT are used for high power levels.
- VSI may be a six step inverter or a PWM
- When VSI is operated as a six step inverter, the transistors are turned ON in the sequence of their numbers with a time interval of T/6 seconds if T is the total time period of one output cycle.
- Frequency of the inverter output is varied by varying the time period (T) of one cycle.
- If the supply is dc, then a variable dc voltage is obtained by connecting a chopper between input dc and the inverter as shown in Fig. 4.8

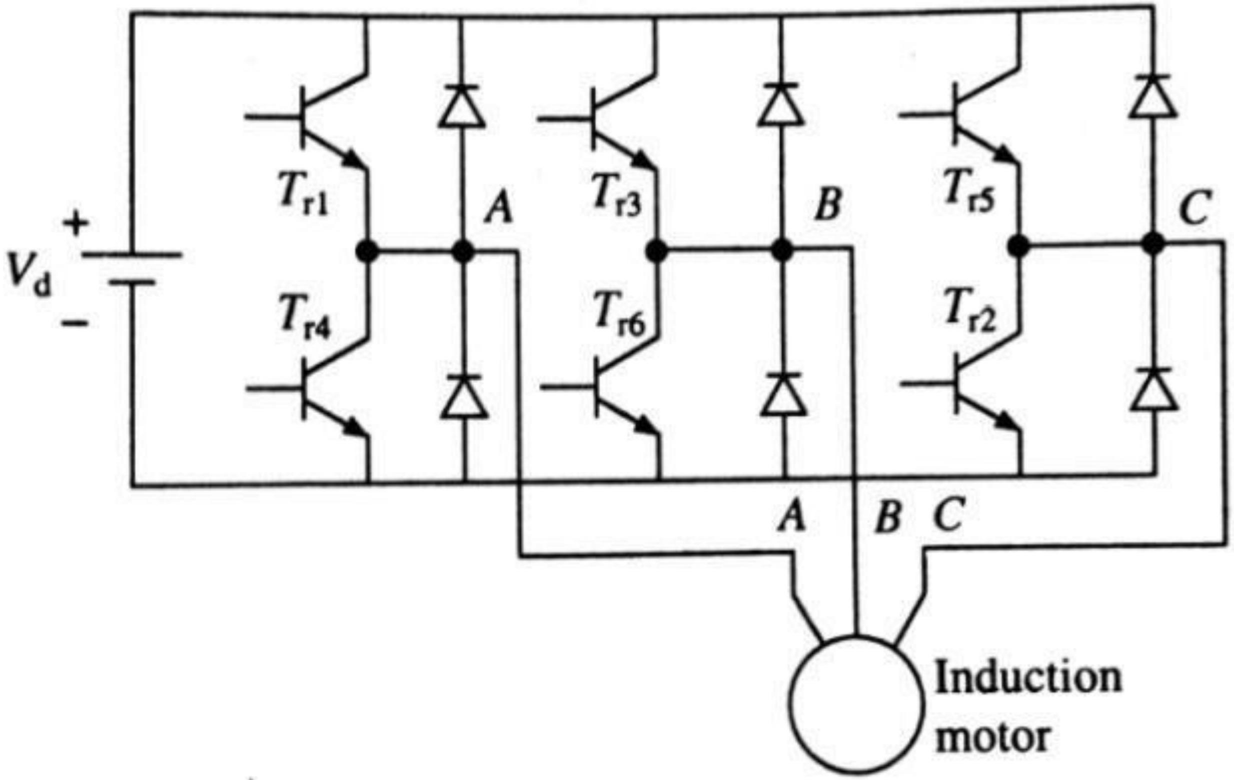


Fig. 4.7 VSI fed Induction Motor

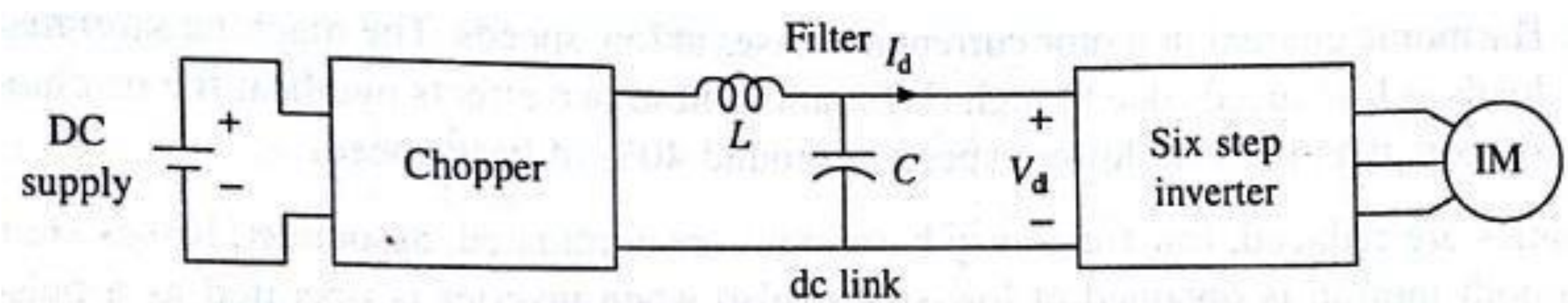


Fig. 4.8

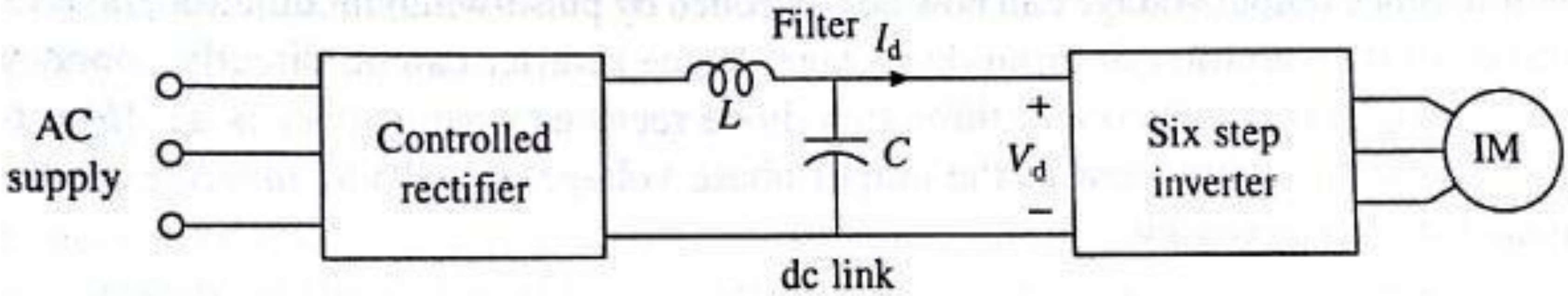


Fig. 4.9

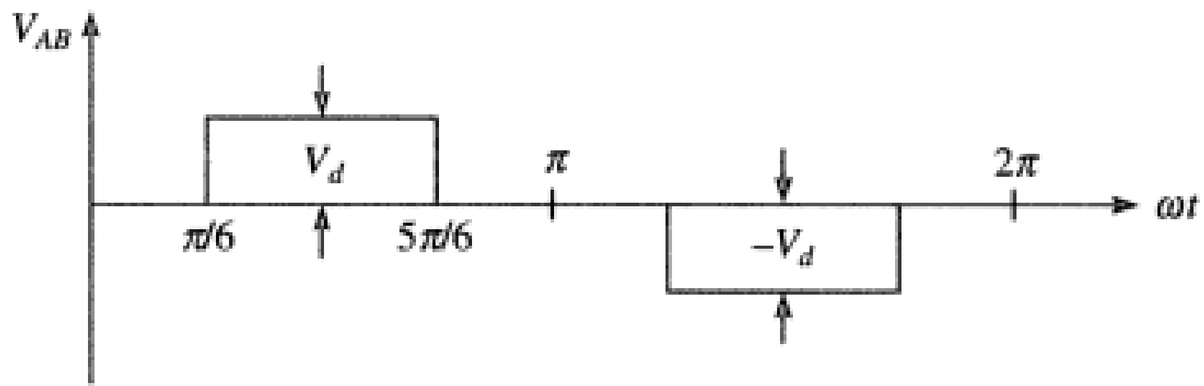


Fig. 4.10

If the input supply is ac, then a variable dc is obtained by connecting a controlled rectifier between the input ac and the inverter as shown in Fig. 4.9. The output voltage waveform of a six step inverter is shown in Fig. 4.10

Disadvantages of six step inverter

- Low frequency harmonics are more and hence the motor losses are increased at all speeds.
- Motor develops pulsating torques due to 5th, 7th, 11th and 13th harmonics.
- Harmonic content increases further when the motor rotates at low speeds. This will
- overheat the machine

- The above said problems are rectified when a PWM inverter is used.
- If a PWM inverter is used as VSI as shown in Fig 4.11, then the input voltage may be a constant dc which is obtained from a simple diode rectifier.
- The output of a PWM inverter is a variable voltage and variable frequency.

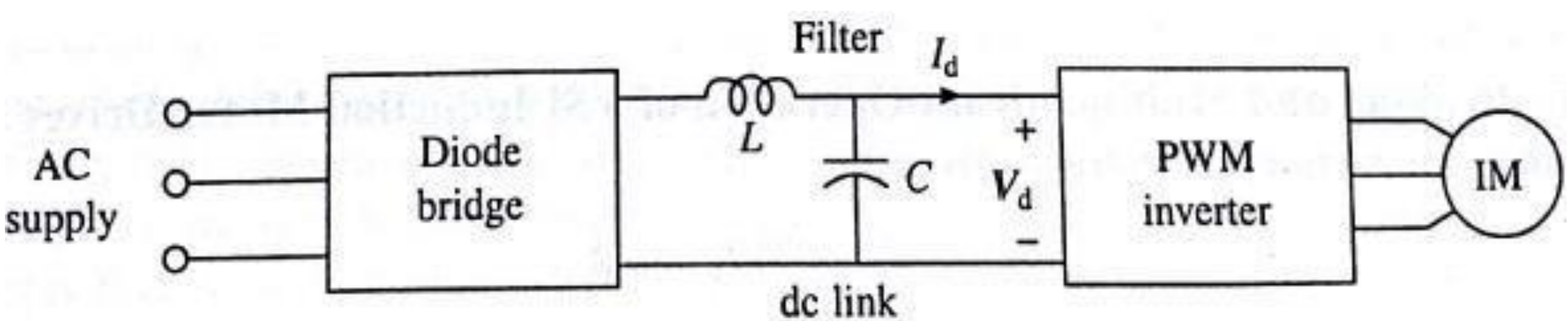


Fig. 4.11

- In a PWM inverter, it is possible to control the output voltage and frequency as well as the harmonic content can be minimized.
- The output voltage waveform of a PWM inverter is shown in Fig. 4.12
- The motors having high leakage inductance are used when a VSI is used to feed the induction motors

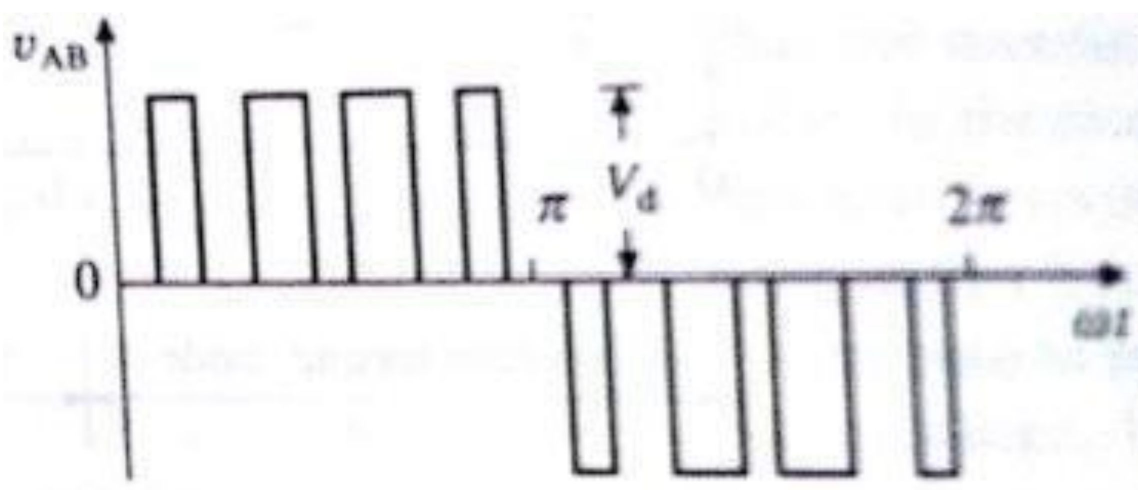


Fig. 4.12

CLOSED LOOP SPEED CONTROL OF INDUCTION MOTOR FED FROM VOLTAGE SOURCE INVERTER

- It employs an inner slip speed loop and an outer speed loop as shown in Fig. 4.13.
- The slip speed loop acts as inner current control loop. It also ensures the motor to operate between synchronous speed and the speed at which maximum torque occurs for all frequencies.
- Thus a high torque will be produced for a small current drawn from supply.
- The drive uses a PWM inverter fed from a dc source. Regenerative braking and four quadrant operation of drive is possible because of the use of PWM inverter.
- The speed error is processed through a speed controller, usually a PI controller, and a slip regulator.

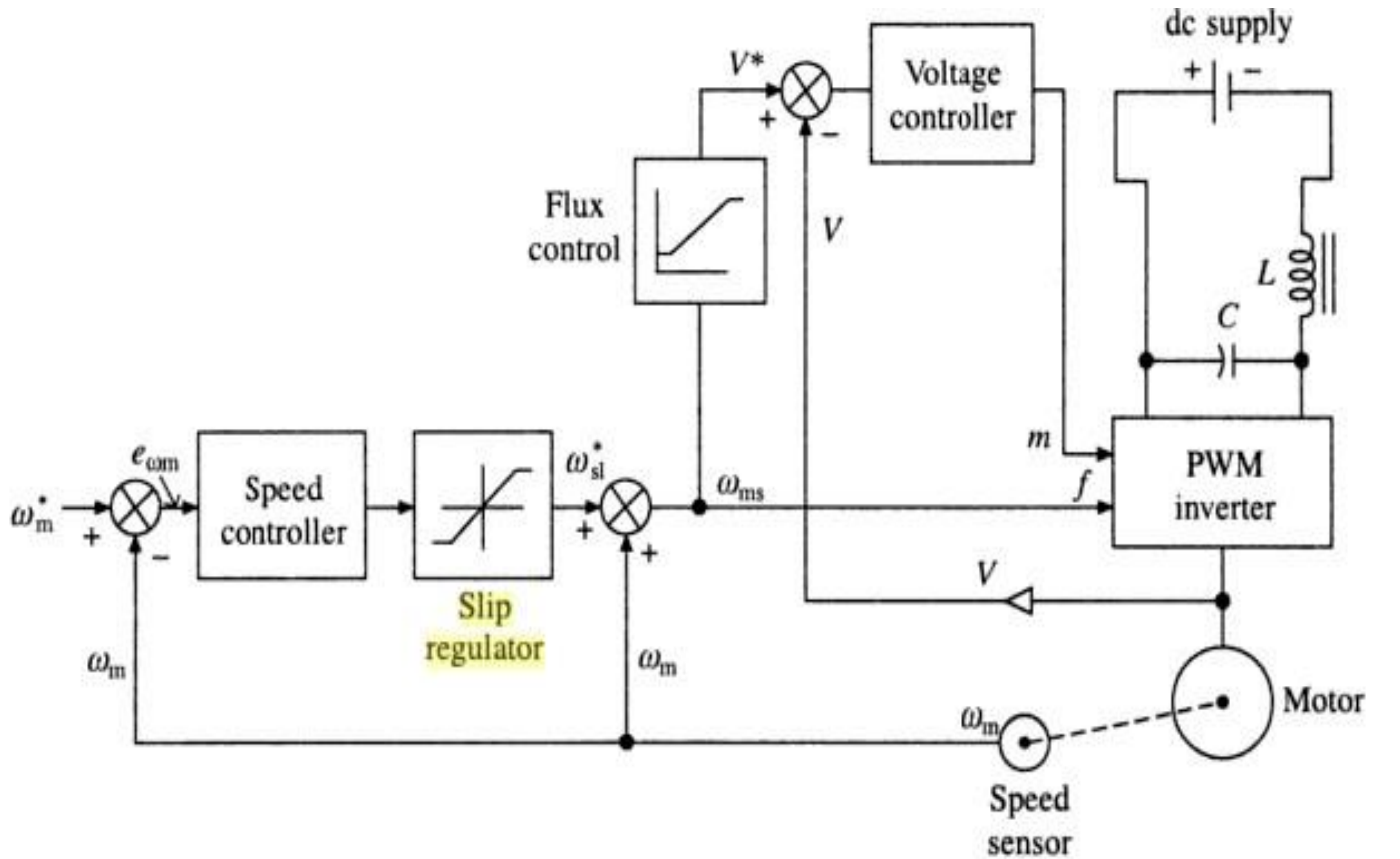


Fig. 4.13 Closed Loop Speed Control of Induction Motor fed from VSI

- *P* controller reduces the steady state error and *I* controller reduces the peak overshoot and settling time so that the response will be faster.
- PI controller gives good steady state accuracy and reduces the noise.
- Slip regulator set the slip speed command ω_{sl}^*. This command controls the inverter current to its maximum allowable value.
- The synchronous speed obtained by adding actual speed ω_m and slip speed ω_{sl}^* determines the frequency of inverter output voltage.
- Reference signal V^* for controlling the output voltage of inverter is generated using a flux control block.
- This reference signal ensures a constant flux operation below base speed and constant voltage operation above base speed.

- **If the motor speed is to be increased**, then the reference speed ω_m^* will be set to the required speed.
- Now the comparator compares the actual speed and reference speed and produces a positive error.
- This will set the slip speed command ω_{sl}^* at its maximum value.
- Hence the motor starts accelerating (i.e speed increases) at the maximum inverter current and hence the speed error decreases.
- When the actual motor speed reaches the reference value, the drive finally settles at that
- **If the motor speed is to be decreased**, then the reference speed ω_m^* will be set to the required speed.
- Now the comparator compares the actual speed and reference speed and produces a negative error.
- This will set the slip speed command ω_{sl}^* at its maximum negative value.
- Hence the motor starts decelerating (i.e speed decreases) at the maximum inverter current and hence the speed error decreases. Here regenerative braking is applied.
- When the actual motor speed reaches the reference value, the drive finally settles at that speed. At this speed, the motor torque equals the load torque.

- For operation below base speed, the ratio (V/f) is kept constant.
- For operation above base speed, the terminal voltage is kept constant and frequency is increased.
- For low frequency operation, the ratio (V/f) is increased to maintain constant flux operation.

- **When a fast response is required**, the drive can be made to accelerate at a current more than the rated current of induction motor.
- But the power electronic switches present in the inverter must be selected such that they can withstand for those high currents. Any device with increased current rating will be more costly. This will increase the cost of total drive system.
- When fast response is not required, current ratings of inverter and rectifier can be chosen to be marginally higher than that of the motor.

CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

- In current source inverters, the input current is constant but adjustable.
- The magnitude of output current of CSI is independent of the load.
- But the magnitude of output voltage depends on the type of load.
- A CSI converts the input dc current into an ac current at its output terminals.
- The output frequency of ac current depends upon the triggering of SCRs.
- Magnitude of output current can be adjusted by controlling the magnitude of dc input current.
- Out of the force commutated CSIs, Auto Sequential Commutated Inverter (ASCI) is the most popular CSI.
- A single phase ASCI is shown in Fig. 4.14

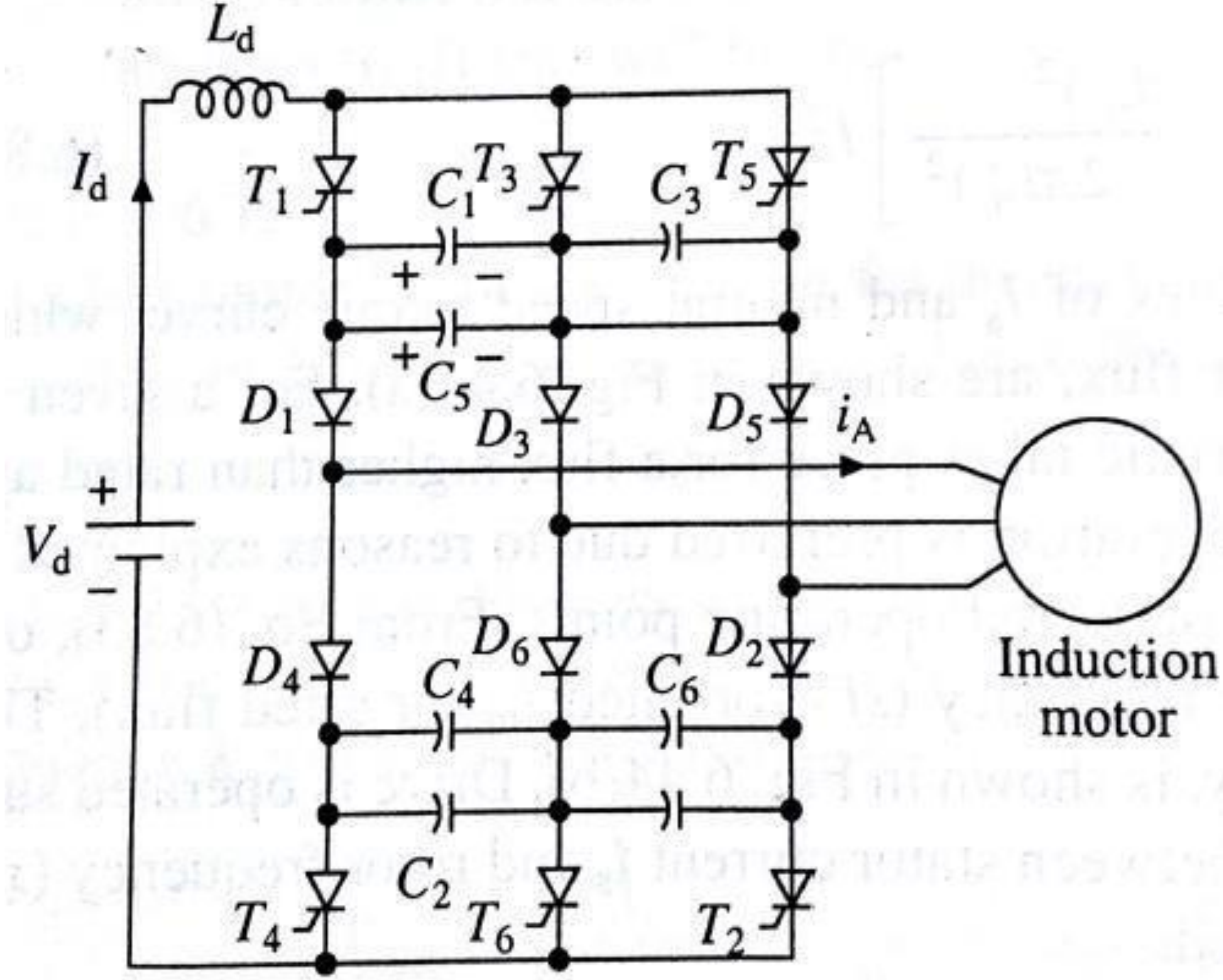


Fig. 4.14 CSI fed Induction Motor Drive

- A large inductance is connected to make this inverter as current source inverter.
- Capacitors C_1 to C_6 are used for commutating the thyristors. These thyristors are fired in sequence with 60^0 intervals.
- Diodes D_1 to D_6 are connected in series with thyristors to prevent the discharge of capacitors through load.
- The inverter output frequency is controlled by adjusting the period ***T*** through triggering
- The fundamental component of motor phase current shown in Fig. 4.15 is,

$$I_s = \frac{\sqrt{6}}{\pi} I_d$$

- For any given speed, the motor torque is controlled by varying the dc current I_d. This I_d can be varied by varying V_d.
- Different types of circuit configurations are shown in Fig. 4.16 and 4.17.
- When the available supply is AC, then a controlled rectifier is connected between the input supply and the inverter as shown in Fig. 4.16

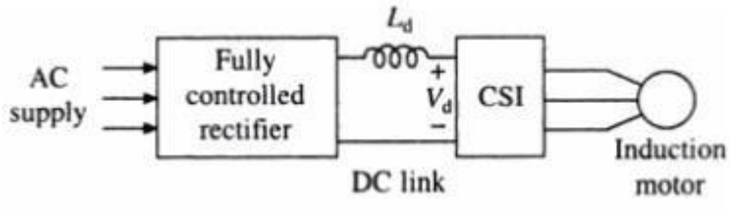


Fig. 4.16

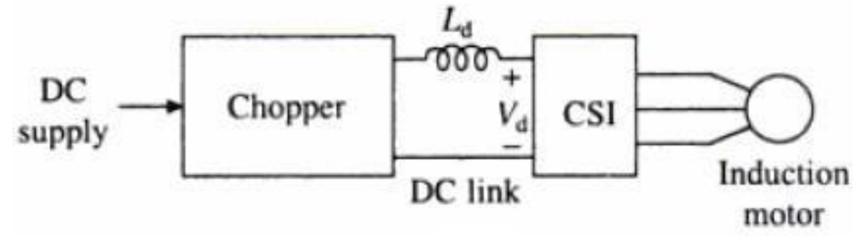


Fig. 4.17

- The output of fully controlled rectifier will be a variable DC which will vary Id. This DC current is converted into AC using a CSI and it is given to the induction motor.
- If the available supply is a fixed DC, then a chopper may be added between the supply and
- the inverter as shown in Fig. 4.17.
- Chopper will give a variable DC voltage Vd which further varies Id. This DC current is converted into AC using a CSI and it is given to the induction motor.
- In VSI, in case of commutation failure, two SCRs in the same leg may conduct. This will short circuit the input supply and hence the current through SCRs will rise to a high value.
- Hence high speed semiconductor fuses are needed to protect the devices and thus making the system costly.
- In case of CSI, no such problem arises even if two devices in same leg conduct. Because the current is controlled by the large inductance connected in series with the source.
- Hence CSI is more reliable than VSI.

- The output current of CSI shown in Fig. 4.15 rises and falls very rapidly.
- This creates ahuge voltage across the leakage inductance of the motor windings. Hence a motor with less leakage inductance is used.
- Using large values of commutation capacitors can reduce these voltage spikes.
- But because of large values of capacitors and inductors, the CSI drive becomes expensive and bulky.
- These types of auto sequentially commutated inverters are used widely in medium and large power current source inverter drives

CLOSED LOOP CONTROL OF CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

- The closed loop CSI shown in Fig. 4.18 consists of an inner slip speed loop and outer speed loop as in the case of VSI.
- This drive operates at constant flux up to base speed. Hence it gives constant torque operation.
- Terminal voltage is kept constant above base speed which gives constant power operation.
- The actual speed ωm is compared with the reference speed ωm
- The speed error is processed through a speed controller (normally a PI controller) and a slip regulator.
- Slip regulator controls the slip speed (Ns – Nr). The sum of rotor speed ωm and slip speed ωsl gives the synchronous speed. This determines the frequency of the inverter output.
- Constant flux operation below base speed is obtained when the slip speed (or rotor frequency) and inverter current Is have the relationship as shown in Fig. 4.19

- This relationship is maintained by flux control block. Flux control block produces a reference signal Id * based on the value of ωsl*.
- This Id * will adjust the dc link current Id through a closed loop to maintain constant flux.
- Both speed and current controllers use PI controllers to get good steady state accuracy.
- If the speed of the drive is to be increased, then the required speed is set as reference speed ωm*.
- Now the speed error is positive and slip speed (Ns – Nr) also positive.
- The drive now accelerates at maximum current in motoring mode. When the motor speed equals the reference speed, the motor continues to rotate at that speed where the motor torque equals load torque.
- If the speed of the drive is to be decreased, then the required speed is set as reference speed ωm*.
- Now the speed error and slip speed (Ns - Nr) are negative.

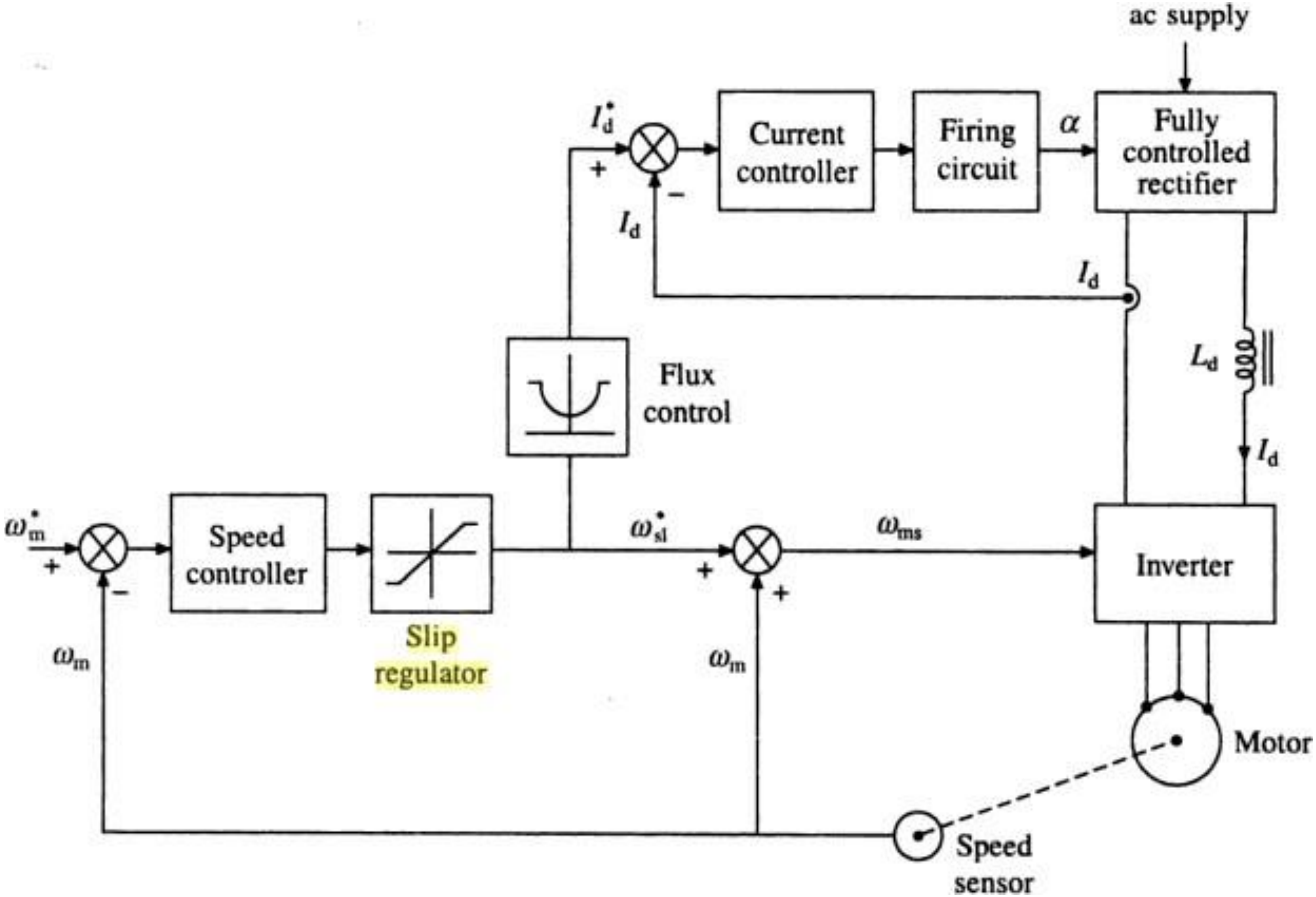
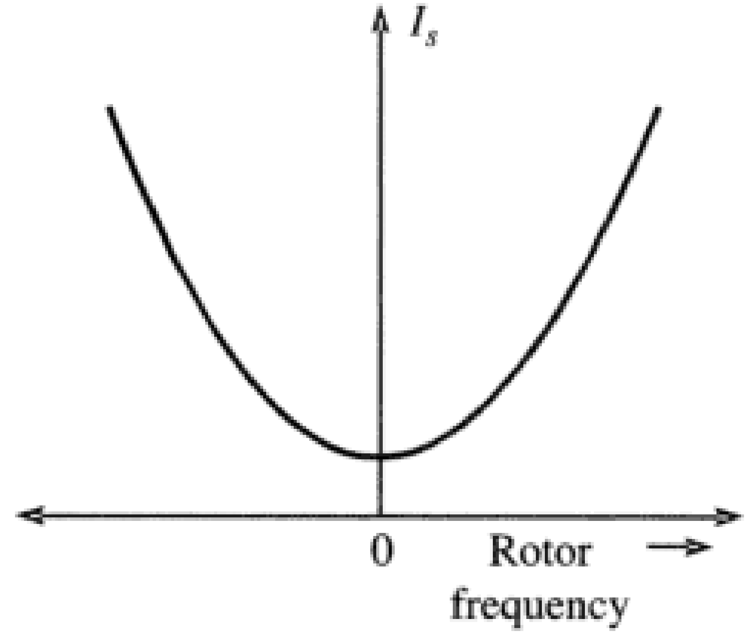


Fig. 4.18 Closed loop CSI fed IM drive



- The drive now decelerates at maximum current in braking mode. When the motor speed equals the reference speed, the motor continues to rotate at that speed where the motor torque equals load torque.
- Above base speed, the terminal voltage is kept constant to get constant power operation.
- Now flux control block and closed loop control of Id become ineffective. Hence Id may
- increase to high value which is not appreciable.
- To control Id, the slip speed limit of slip regulator must increase proportional to inverter frequency.
- This achieved by adding a signal proportional to frequency with the slip regulator output.

Comparison of Current Source Inverter (CSI) & Voltage Source Inverter (VSI) drives

Current Source Inverter (CSI) drives	Voltage Source Inverter (VSI) drives
CSI is more reliable because conduction of two devices in the same leg does not short circuit the input supply.	Conduction of two devices in the same leg due to commutation failure causes short circuit of the input supply. This may raise the current through the devices and damage them.
Raise of current is prevented because of the presence of large inductance in the current source.	It requires expensive high speed semiconductor fuses for controlling the current due to short circuit.
Motor current rise and fall are very fast and that creates high voltage across windings.	No such problem arises here in case of VSI
These high voltage spikes are controlled by having large values of commutating capacitors which may increase the cost and size of the inverter.	Less costly than CSI.

Slow response due to large value of input inductance	**Fast dynamic response is possible if VSI uses PWM inverter. If a six step inverter is used, then response becomes slower like CSI drives.**
Frequency range of CSI is lower than VSI. Hence CSI drive has lower speed range.	Frequency range is wide and hence the speed range is also wide.
CSI requires a separate rectifier and inverter combination. Hence it is not suitable for multi motor drives.	A single rectifier can be used to feed many VSIs. Hence VSI is suitable for multi motor drives.
Regenerative braking is naturally possible in CSI.	An additional full converter is required to achieve regenerative braking.
If input AC supply fails, electric braking is not possible in CSI.	But VSI can use dynamic braking in case input AC supply fails.

UNIT-IV: Rotor side control of Induction motors

Topics

- Static rotor resistance control – Slip power recovery – Static Scherbius drive – Static Kramer Drive – their performance and speed torque characteristics – advantages, applications, problems

SPEED CONTROL OF INDUCTION MOTOR ON ROTOR SIDE

- This method of speed control is applicable only to wound round or slip ring induction motors.
- The portion of air-gap power which is not converted to mechanical energy is called slip power.
- Hence the mechanical power developed is controlled by varying the slip power by some methods. This further controls the speed of the motor.
- Controlling the slip power is done by three different methods.
- Static rotor resistance control
- Emf injection into rotor circuit
  - Static Scherbius drive
  - Static Kramer drive

Rotor resistance control

- In this method of speed control, an external resistance is added with rotor circuit and it is varied to control the speed of the induction motor.
- This method is applicable only to slip ring induction motor.
- From the above equation, it is clear that any increase in R2 will increase slip S.
- Increase in slip means reduction in speed. Hence rotor resistance varies the speed.
- Rotor resistance does not affect the value of maximum torque produced by the motor.
- But it changes the speed at which the maximum torque is produced. It is shown in Fig. 4.20.
- It is clear from Fig. 4.20 that for the same value of motor torque, the speed reduces with an increase in rotor resistance

- From the above equation, it is clear that any increase in R2 will increase slip S.
- Increase in slip means reduction in speed. Hence rotor resistance varies the speed.
- Rotor resistance does not affect the value of maximum torque produced by the motor.
- But it changes the speed at which the maximum torque is produced. It is shown in Fig. 4.20.
- It is clear from Fig. 4.20 that for the same value of motor torque, the speed reduces with an increase in rotor resistance
- In this method of speed control, the motor torque does not change even at low speeds. Also this method is less costly when compared to variable frequency operations.
- Because of its low cost and high torque producing capabilities, this method is used in cranes.
- But major disadvantage of this method is its low efficiency due to additional power losses in the external resistance connected to the rotor.
- These losses occur in the external resistor. So the heat produced around the external resistor does not increase the heat of the motor.

Static Rotor resistance control

- In a three phase slip ring induction motor, a three phase diode rectifier, a chopper and a single resistor is connected as shown in Fig. 4.21

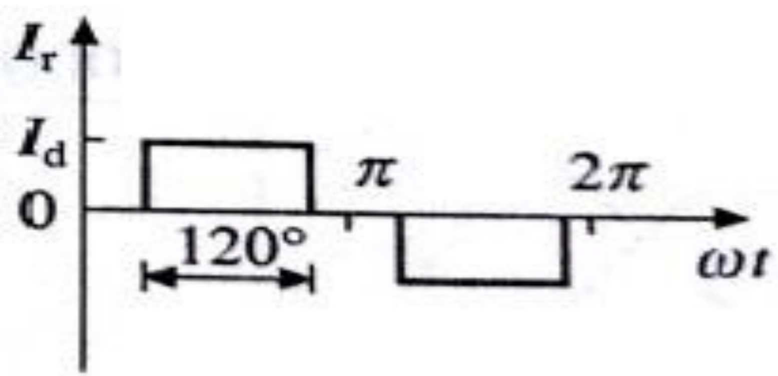


Fig. 4.22

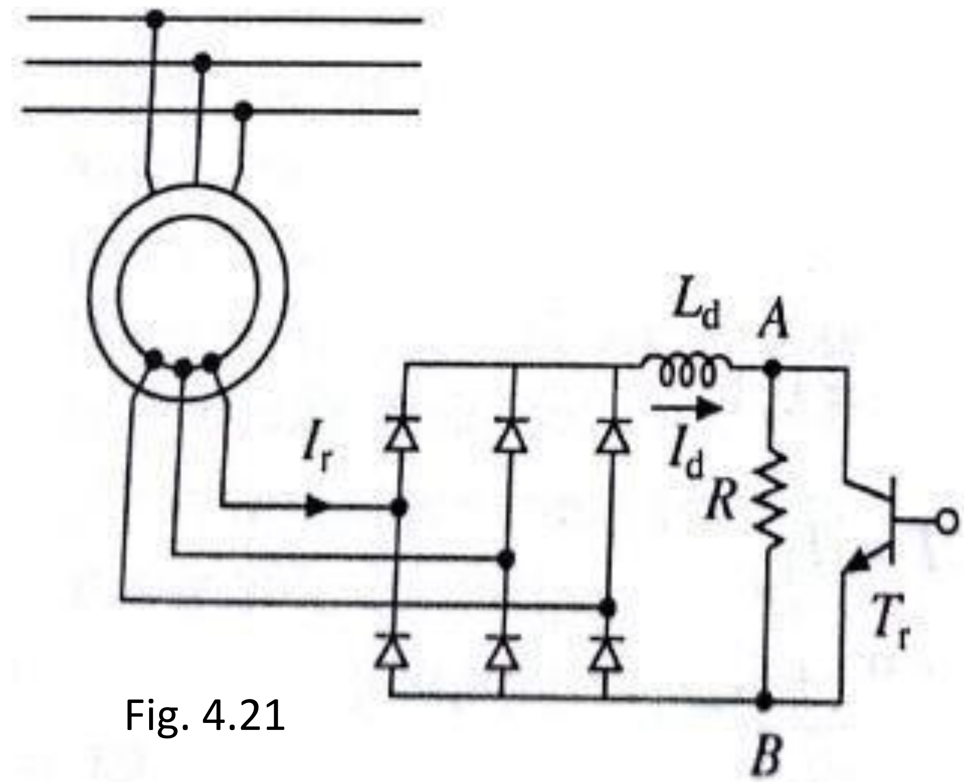


Fig. 4.21

- An inductor L_d is connected to reduce the ripple present in the dc link current.
- The rotor current waveform is shown in Fig. 4.22
- The rms value of rotor current is given by,

$$I_r = \sqrt{\frac{2}{3}} I_d \text{-------} 1$$

- The ac output voltage from rotor windings is rectified using diode bridge and it is fed to the parallel combination of fixed resistor and a transistor.
- The effective value of this resistance connected between the terminals A & B is varied by varying the duty cycle of the transistor.
- The resistance between A & B is zero when transistor is ON. Resistance between A & B is maximum (i.e R) when transistor is off.
- The effective resistance connected between A & B is given by,

$$R_{AB} = (1 - \alpha)R \text{------} 2$$

Where α is the duty cycle.

- Power consumed by R_{AB} is,

$$P_{AB} = I_d^2 R_{AB} = I_d^2 (1-\alpha) R$$

- Power consumed by R_{AB} per phase is,

$$\frac{P_{AB}}{3} = \frac{I_d^2 (1-\alpha) R}{3} ------3$$

- From eqn. 1,

$$I_d = \sqrt{\frac{3}{2}} I_r ------4$$

- Substituting eqn 4 in eqn 3, we get,

$$\frac{P_{AB}}{3} = \frac{I_d^2 (1-\alpha) R}{3} = \frac{\frac{3}{2} \mathrm{I}_r^2 (1-\alpha) R}{3}$$

- Therefore power consumed by R_{AB} per phase is,

$$= 0.5 . \mathrm{I}_r^2 (1-\alpha) . R ----5$$

- From the above equation 5, it is clear that the rotor resistance is increased by 0.5 R(1-α)
- Thus the total resistance in the rotor circuit is,

$$R_{rT} = R_r + 0.5\, R(1-\alpha)$$

- From the above equation, it is clear that rotor resistance is varied from R_r to $(R_r+0.5R)$ when α is varied from 1 to 0.

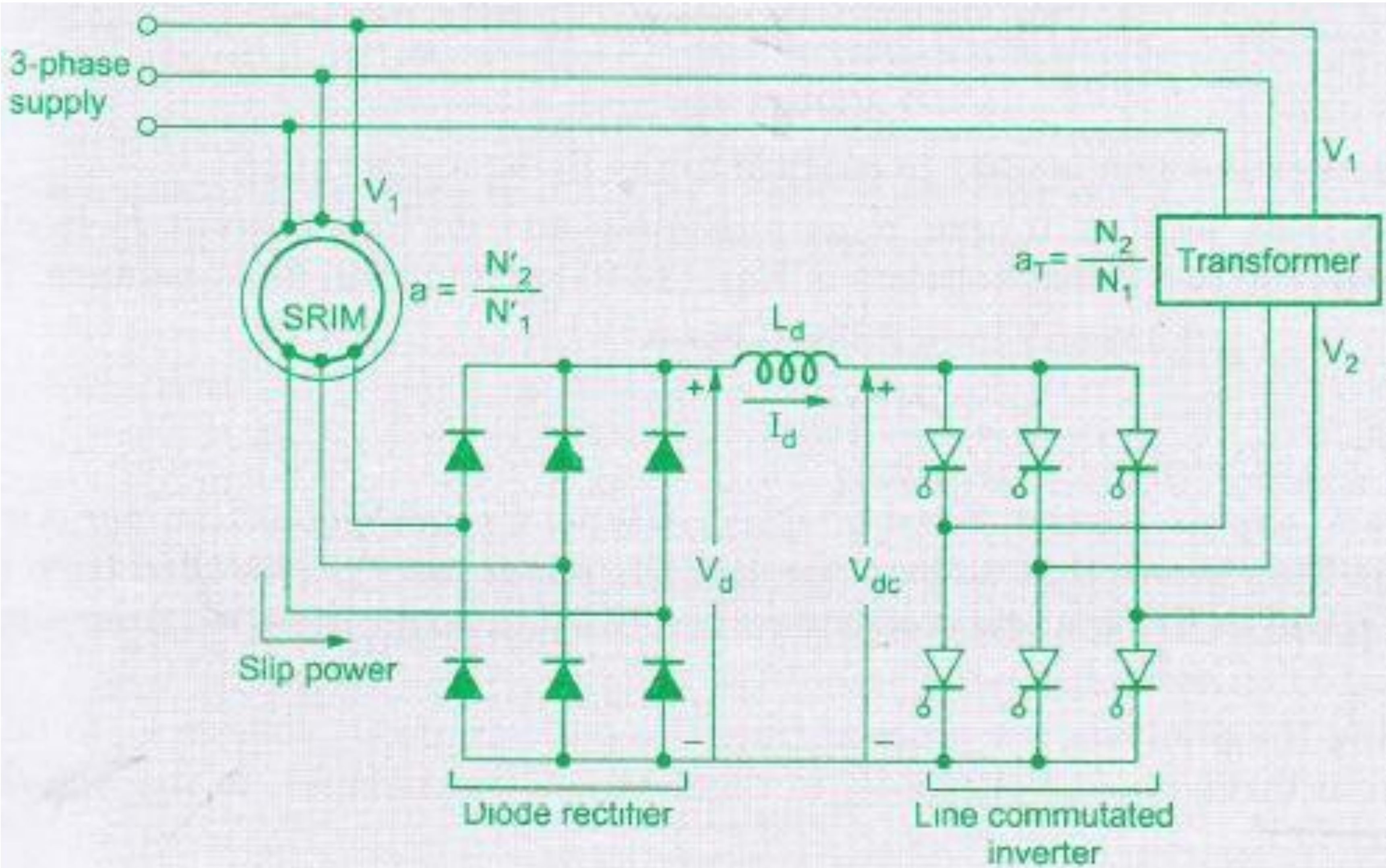
- **Advantages of rotor resistance control method**
- Smooth and stepless control is possible.
- Quick response
- Less maintenance
- Compact size.
- **Disadvantages of rotor resistance control method**
- Increase in rotor resistance leads to increase of power loss in the rotor resistance. This will reduce the system efficiency.

Energy efficient drive (Or) Slip Power Recovery Schemes

- In rotor resistance control method of speed control, the slip power is wasted in the external resistance and hence the efficiency reduces.
- However instead of wasting the slip power in external resistor, it can be recovered and supplied back in order to improve the overall efficiency.
- This scheme of recovering the power is called slip power recovery scheme and this is done by connecting an external source of emf of slip frequency to the rotor circuit.
- The injected emf can either oppose the rotor induced emf or aids the rotor induced emf.
- If it opposes the rotor induced emf, the total rotor resistance increases and hence speed decreases
- If the injected emf aids the main rotor emf the total resistance decreases and hence speed increases.
- Therefore by injecting induced emf in rotor circuit the speed can be easily controlled.

Static Kramer Drive

- In this method of speed control, the slip power flows in only one direction. It flows from the
- rotor back to main supply. Hence the speed can be controlled below synchronous speed only.
- The circuit for static Kramer drive is shown in Fig. 4.23. The slip power from the rotor circuit is converted to dc voltage Vd by diode rectifier.
- The inductor Ld filters the ripples present in the dc voltage Vd.



This dc voltage is then converted to ac voltage at line frequency (50 Hz) using a line commutated inverter and pumped back to ac source.

This drive offers a constant torque operation.

Analysis

This rotor voltage is rectified by diode rectifier. The output voltage of diode rectifier is given by,

$$V_d = \frac{3.V_{ml}}{\pi} - - - - - - -1$$

Here V_{ml} is the maximum value of line voltage supplied to diode rectifier.

$$Rotor\ voltage\ per\ phase\ =\ S.E_2 - - - -2$$

Here E_2 is the per phase rotor emf at standstill and it is given as input to diode rectifier.

S is the slip.

$$Rotor\ line\ voltage, V_l = \sqrt{3}.S.E_2$$

$$Maximum\ value\ of\ rotor\ line\ voltage, V_{ml} = \sqrt{2}.\left(\sqrt{3}.S.E_2\right) = \sqrt{6}.S.E_2 - - - -3$$

$$\therefore V_d = \frac{3.\sqrt{2}\sqrt{3}.S.E_2}{\pi} = \frac{3.\sqrt{6}.S.E_2}{\pi} - - - -4$$

In induction motor, the turns ratio and voltage ratio is given by,

$$\frac{E_2}{V_1} = \frac{N_2}{N_1}; \qquad \boldsymbol{E_2} = \frac{N_2}{N_1}.V_1 = \boldsymbol{a.V_1} - - - -5$$

Substituting equation 5 in equation 4, we get,

$$\boldsymbol{V_d = \frac{3.\sqrt{6}.S.a.V_1}{\pi} = 2.339.(S.a.V_1)} ----6$$

- DC output voltage of a three phase line commutated inverter without transformer is,

$$V_{dc} = -\frac{3.V_{ml}}{\pi}\cos\alpha$$

$$Here\ V_{ml} = \sqrt{2}.\sqrt{3}.V_1$$

$$\therefore V_{dc} = -\frac{3.\sqrt{2}.\sqrt{3}.V_1}{\pi}\cos\alpha = \frac{3.\sqrt{6}.V_1}{\pi}\cos\alpha$$

$$\therefore V_{dc} = -2.339.V_1.\cos\alpha ----7$$

- At no load, $V_d = V_{dc}$. (Eqn 6 = Eqn 7)

$$2.339.(S.a.V_1) = -2.339.V_1.\cos\alpha$$

$$S.a = -\cos\alpha$$

$$S = -\frac{1}{a}\cos\alpha ----8$$

- $For\ a\ = 1,\ slip, S\ = -\ cos\alpha$
- $For\ \alpha = 90^o, then\ Slip, S = 0 \quad (synchronous\ speed) - - - - 9$
- $For\ \alpha = 180^o, then\ Slip, S = 1 \quad (zero\ speed) - - - - 10$
- It is clear from the equations 9 & 10 that, the motor speed can be varied from zero speed to synchronous speed when the firing angle α of line commutated inverter is varied from 180^0 to 90^0.
- In actual practice, the rotor voltage will be less than the supply voltage. Hence a transformer is required to step up the voltage before feeding t back to supply.
- Let the transformer turns ratio be,

$$a_T = \frac{V_2}{V_1}\ and\ hence\ V_2 = a_T.V_1$$

- DC output voltage of a three phase line commutated inverter without transformer is,

$$V_{dc} = -\frac{3.V_{ml}}{\pi}\cos\alpha$$

$$Here\ V_{ml} = \sqrt{2}.\sqrt{3}.a_T.V_1 = \sqrt{6}.a_T.V_1$$

$$\therefore V_{dc} = -\frac{3.\sqrt{6}.a_T.V_1}{\pi}\cos\alpha = -2.339.a_T.V_1.\cos\alpha ----11$$

- At no load, $V_d = V_{dc}$. (Eqn 6 = Eqn 11)

$$2.339.(S.a.V_1) = -2.339.a_T.V_1.\cos\alpha$$

$$S.a = -a_T.\cos\alpha$$

$$S = -\frac{a_T}{a}\cos\alpha ----12$$

Total slip power is given by,

$$3.S.P_g = V_{dc}.I_d$$

$$3.S.\omega_s.T_e = V_{dc}.I_d$$

$$T_e = \frac{V_{dc}.I_d}{3.S.\omega_s} ----13$$

Substituting the values of V_{dc} and S from equations 7 & 8 in equation 13, we get,

$$T_e = \frac{-2.339.V_1.\cos\alpha.I_d}{3.\left(-\frac{1}{a}\cos\alpha\right).\omega_s} = \frac{2.339.a.V_1.I_d}{3.\omega_s} - - - - - 14$$

When a transformer is used, the values of V_{dc} and S will be given by the equations 11 & 12. Hence substituting equations 11 & 12 in equation 13, we get,

$$T_e = \frac{-2.339.a_T.V_1.\cos\alpha.I_d}{3.\left(-\frac{a_T}{a}\cos\alpha\right).\omega_s} = \frac{2.339.a.V_1.I_d}{3.\omega_s} - - - - - 15$$

Looking into the equations 14 & 15, it is clear that Te is same whether a transformer is used in the system or not. Also Te is

Proportional to Id

Proportional to V1

Proportional to the turns ratio, a

Inversely proportional to ωS

The dc link current I_d is given by,

$$I_d = \frac{V_d - V_{dc}}{R_d}$$

$$V_d = V_{dc} + I_d.R_d = 2.339.S.a.V_1$$

$$\therefore Slip, S = \frac{V_{dc} + I_d.R_d}{2.339.a.V_1} = \frac{-2.339.a_T.V_1.\cos\alpha + I_d.R_d}{2.339.a.V_1}$$

$$\therefore Slip, S = \frac{-2.339.a_T.V_1.\cos\alpha}{2.339.a.V_1} + \frac{I_d.R_d}{2.339.a.V_1} = -\frac{a_T}{a}.\cos\alpha + \frac{I_d.R_d}{2.339.a.V_1} ----16$$

Motor speed is given by,

$$\omega_m = \omega_S(1 - S) ----17$$

Substituting the value of S from equation 16 in equation 17, we get,

$$\omega_m = \omega_S\left[1 + \frac{a_T}{a}.\cos\alpha - \frac{I_d.R_d}{2.339.a.V_1}\right] ----18$$

From equation 15, the total torque $3T_e$ is given by,

$$3.T_e = T_L = \frac{2.339.a.V_1.I_d}{\omega_s}$$

$$I_d = \frac{\omega_s.T_L}{2.339.a.V_1} - - - - 19$$

Substituting equation 19 in equation 18, we get,

$$\omega_m = \omega_S\left[1 + \frac{a_T}{a}.\cos\alpha - \left(\frac{\omega_s.T_L}{2.339.a.V_1} \times \frac{R_d}{2.339.a.V_1}\right)\right] = \omega_S\left[1 + \frac{a_T}{a}.\cos\alpha - \frac{\omega_s.R_d.T_L}{(2.339.a.V_1)^2}\right]$$

$$\omega_m = \omega_S \left[1 + \frac{a_T}{a}.\cos\alpha - \frac{\omega_s.R_d.T_L}{(2.339.a.V_1)^2}\right] ----20$$

$$\omega_m = \omega_S \left[1 + \frac{a_T}{a}.\cos\alpha - K.T_L\right] ----21$$

$$where\ K = \frac{\omega_s.R_d}{(2.339.a.V_1)^2}$$

From equation 21, the no load speed of the drive is given by,

$$\omega_m = \omega_S \left[1 + \frac{a_T}{a}.\cos\alpha\right] ----21$$

Using equation 20, the speed – torque characteristics are drawn as shown in Fig. 4.24.

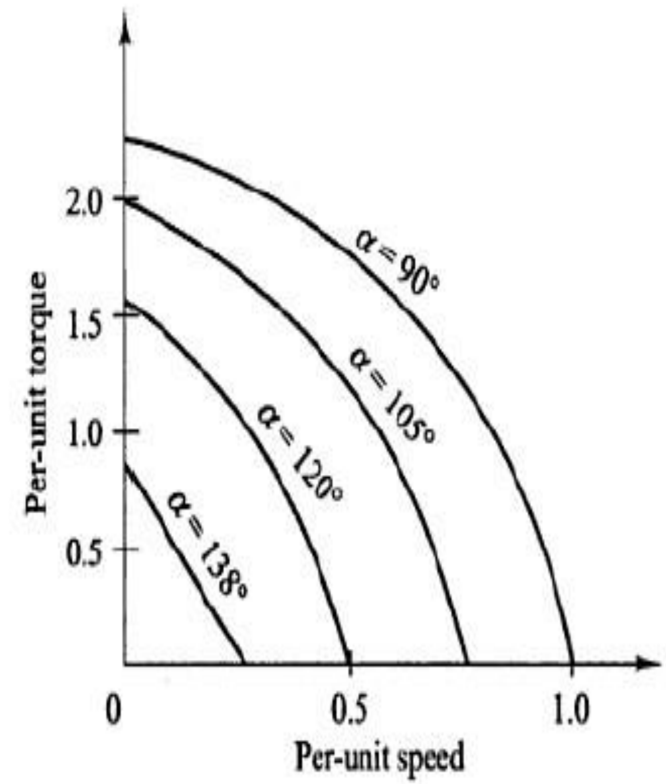


Fig. 4.24 Speed – Torque characteristics

Static Kramer systems are used in large power pumps and compressor type loads where speed control range is less and below synchronous speed.

Static Scherbius Drive

- In static Kramer drive, the speed of slip ring induction motor can be controlled below synchronous speed only.
- For controlling the speed below and above synchronous speed, the static Scherbius drive is used.
- There are two configurations of this drive. They are,
- 1. DC link Scherbius Drive
- 2. Cycloconverter Scherbius Drive

DC link Scherbius Drive

- For controlling the speeds below synchronous speed (Sub Synchronous), the slip power is removed from the rotor circuit and it is fed back into the input AC supply.
- For controlling the speeds above synchronous speed (Super Synchronous), an additional power is fed into the rotor circuit at slip frequency.
- The circuit of dc link Scherbius drive is shown in Fig. 4.25 and it has a slip ring induction motor, two controlled converters, a smoothing inductor and a transformer.
- Smoothing inductor is used to suppress the ripples present in the dc link.

Sub synchronous speed control

- Bridge 1 is operated with a firing angle range of 0 to 90. It means that bridge 1 works as rectifier.
- Bridge 2 is operated with a firing angle range of 90 to 180. It means that bridge 2 works as inverter.
- Now the slip power flows from the rotor circuit to the supply through bridge 1, bridge 2 and transformer.
- Here transformer steps up the rotor voltage to the level of ac input supply.

Sub synchronous speed control

- Bridge 1 is operated with a firing angle range of 90 to 180. It means that bridge 1 works as inverter.
- Bridge 2 is operated with a firing angle range of 0 to 90. It means that bridge 2 works as rectifier.
- Now the slip power flows from the input ac supply to the rotor circuit through transformer, bridge 2 and bridge 1.
- Here transformer steps down the input ac supply to the level of rotor voltage.

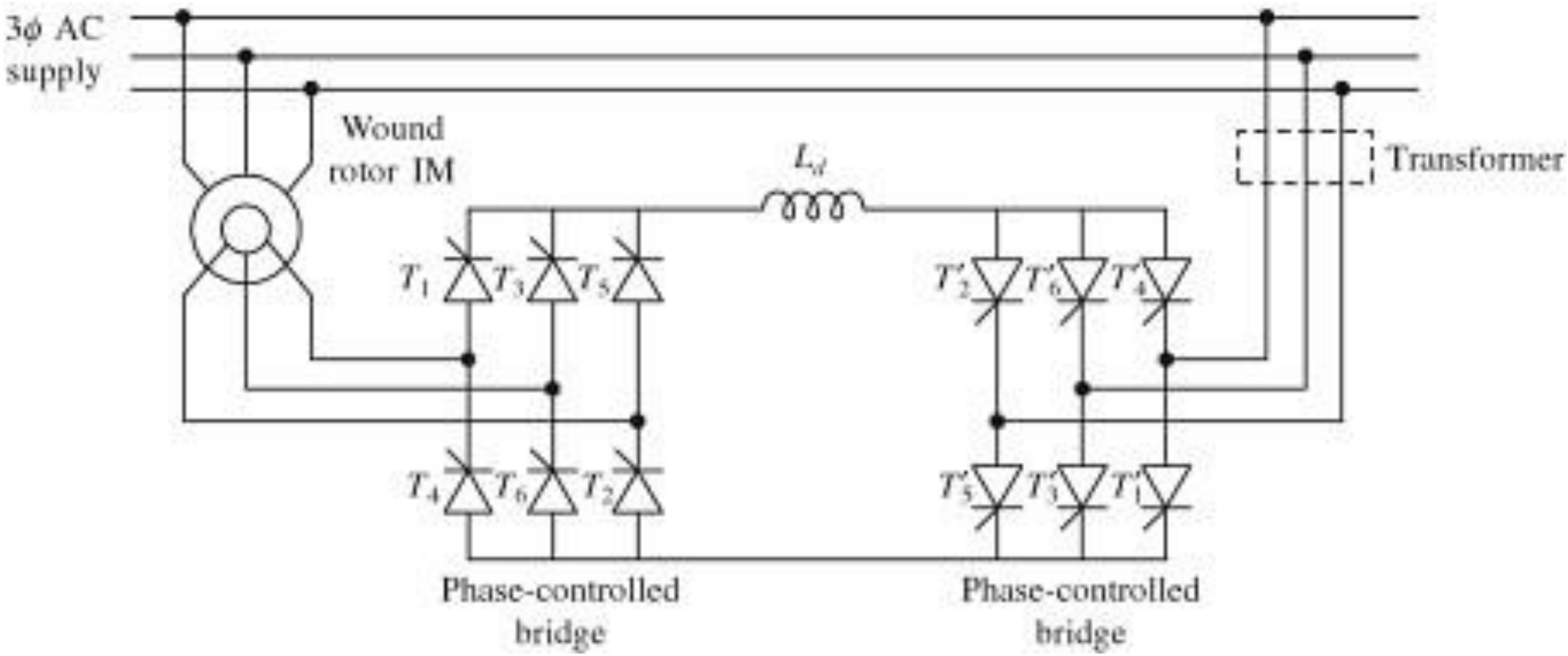


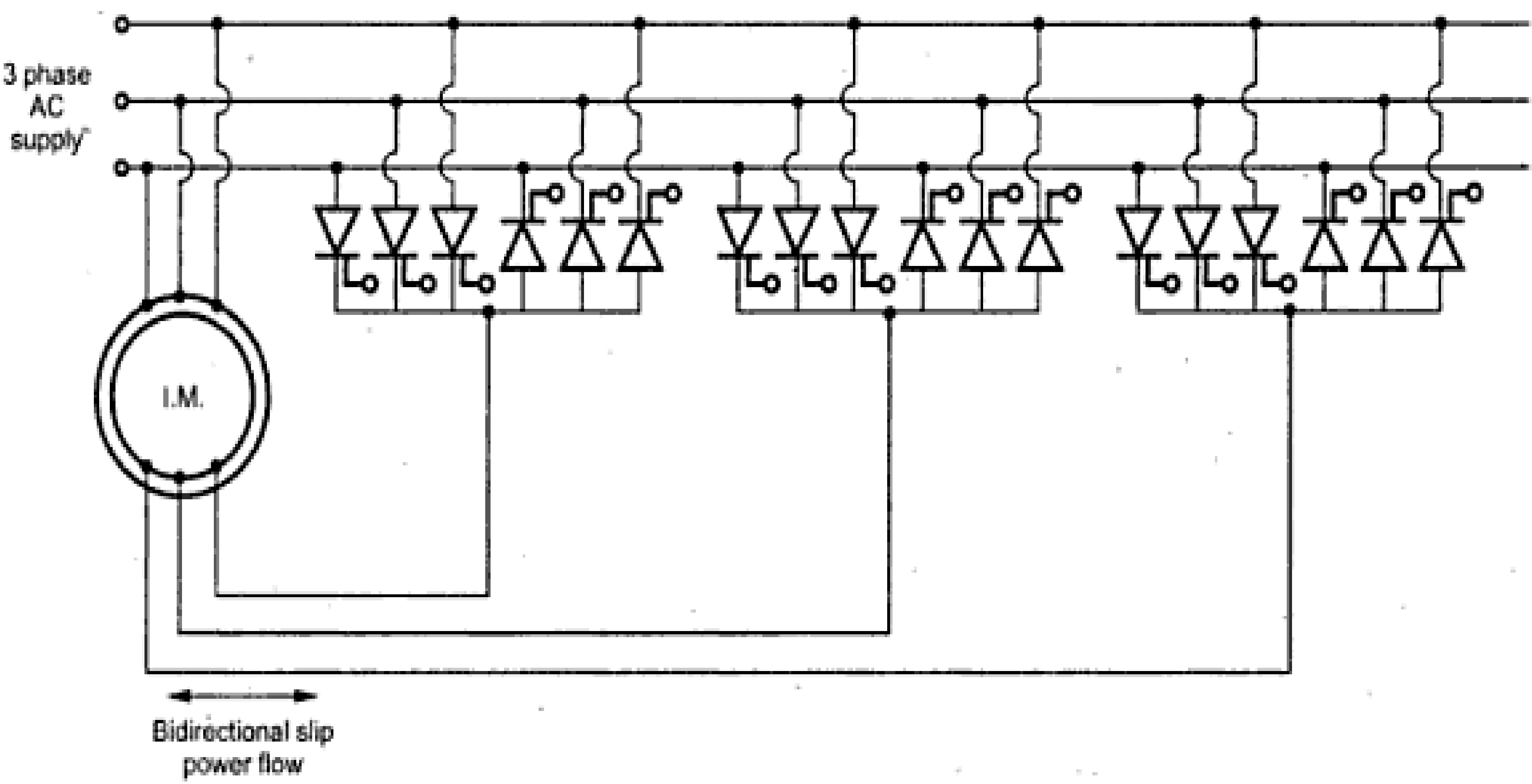
Fig. 4.25 DC Link Static Scherbius Drive

- Rotor voltages at slip frequency are used to commutate the thyristors present in the converters.
- At low speeds, the voltage across rotor will be less and it may not be sufficient to naturally commutate the thyristors.
- This difficulty can be overcome by using forced commutation.
- It means that an additional forced commutation circuitry is necessary for Scherbius drives where both below and above synchronous speeds are possible.
- Also this Scherbius scheme requires 6 thyristors in place of 6 diodes present in Kramer drive.
- Hence the drive becomes costly compared to static Kramer drive.

Cycloconverter Scherbius Drive

- A 3 phase Cycloconverter can be used to control the speed of a 3 phase induction motor.
- Cycloconverter fed induction motors are used in applications such as high power pumps and blower type drives.
- Using a Cycloconverter, it is possible to send power in both the directions and hence speed control below and above synchronous speed is possible.
- Also it allows regenerative braking during which the power is fed back to the supply.
- Like dc link Scherbius drive, this scheme also offers a constant torque operation

Fig. 4.26 Cycloconverter Static Scherbius Drive



Vector control of induction motor

- The control of inverter fed induction motor has given good steady state response. But it gives poor dynamic response.
- The reason for this is that the air-gap flux keeps changing in magnitude and direction.
- This variation needs to be controlled by controlling the magnitude and angle of the stator and rotor currents.
- The variation in angle of the currents results in torque variations which is not good. Also it increases the current drawn by the motor and hence higher rating inverters are needed.
- Separately excited DC motor drives are simpler in control because they separately control the flux.
- Separate control in dc motors is possible because armature current and field current can be independently controlled.
- But in an induction motor, a coordinated control of the magnitude, phase and frequency of the stator current is required. This type of control is much complicated when compared to dc motor control.

- Vector control schemes are classified into two types based on how the field angle is calculated.
- They are,
- 1. Direct vector control
- 2. Indirect vector control
- If the field angle is calculated by using terminal voltages and currents or hall sensors, then it is called direct vector control.
- If the field angle is calculated by using rotor position measurement, then it is called indirect vector control

Algorithm for vector control

- Obtain the field angle (θf)
- Calculate the flux producing component of current (If^*) to produce a flux linkages of λr^*.
- The flux linkages are controlled by controlling the field current If^*. it is similar to dc motor where field flux controls the field current.
- The torque producing component of stator current iT^* is calculated from Te^* and λr^*.
- Controlling iT^* by keeping the λr^* as constant gives an independent control of the torque produced by the motor.
- This is similar to a dc motor where armature current controls the torque independently.
- Calculate the stator current magnitude is^* from the vector sum of iT^* and if^*.
- Calculate the torque angle from the flux and torque producing components of the stator commands.

$$\theta_T = \tan^{-1}\frac{i_T^*}{i_f^*}$$

- Add θ_T and θ_f to obtain the stator current phasor angle, θ_s.
- By using the stator current phasor angle and its magnitude, θ_s and i_s^*, the required stator current commands are found by going through the qd transformation to abc variables.

$$i_{as}^* = i_s^* \sin\theta_s$$

$$i_{bs}^* = i_s^* \sin\left(\theta_s - \frac{2\pi}{3}\right)$$

$$i_{cs}^* = i_s^* \sin\left(\theta_s + \frac{2\pi}{3}\right)$$

- Synthesize these currents by using an inverter. When they are supplied to the stator of the induction motor, the required rotor flux linkages and torque are produced.

UNIT-V: Control of Synchronous Motors

Separate control and self-control of synchronous motors – Operation of self-controlled synchronous motors by VSI, CSI and cyclo converters. Load commutated CSI fed Synchronous Motor – Operation – Waveforms – speed torque characteristics – Applications – Advantages and Numerical Problems – Closed Loop control operation of synchronous motor drives (Block Diagram Only), variable frequency control - Cyclo converter, PWM based VSI & CSI.

Synchronous motor

- A synchronous motor is constructionally same an alternator
- It runs at synchronous speed or it remains stand still
- Speed can be varied by varying supply frequency
  because synchronous speed, $N_s = (120f/p)$
- Due to unavailability of economical variable frequency sources, this method of speed control was not used in past & they were mainly used for constant speed applications
- The development of semiconductor variable frequency sources such as inverter & cycloconverter allowed the use of synchronous motor in variable speed applications
- It is not self starting. It has to be run upto near synchronous speed by some means & it can be synchronised to supply
- Starting methods : a) using an auxiliary motor
  - b) using damper windings

Types of synchronous motors

- Commonly used synchronous motors are
  1. Wound field synchronous motor (Cylindrical & salient pole)
  2. Permanent magnet synchronous motor
  3. Synchronous reluctance motor
  4. Hysteresis motor
- All these motors have a stator with 3 phase winding which is connected to an AC source
- Fractional horse power synchronous reluctance & hysteresis motors employ a 1 phase stator

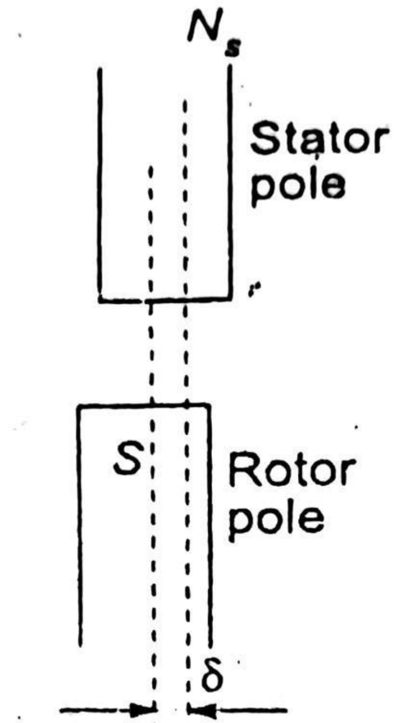
Operation of a wound field synchronous motor

- Rotor is provided with a DC field winding & damper windings Stator contain 3 phase winding & is connected to AC supply which is pulsating in nature & not unidirectional
- - As a result synchronous motor is not self starting
- Normally the motor is made self starting by providing damper windings on rotor
- Due to the presence of damper windings, motor will start as an induction motor
- When speed of motor reaches near synchronous speed, DC excitation is given to rotor
- Now the rotor poles gets locked with rotating magnetic field poles in stator & continue to rotate at synchronous speed

- **Load angle/power angle/torque angle (δ)**

- The rotor poles are locked with stator poles & both run at synchronous speed in same direction

- As load on motor increases, the rotor tends to fall back in phase by some angle
- This angle is known as load angle (δ)
- The value of δ depends upon the load



Pull out torque

The power produced by synchronous motor, $P_m = \frac{3VE}{X_s} Sin\delta$

Where, V = stator supply voltage

E = Field excitation voltage

Torque, $T = \frac{P_m}{\omega_s} = \frac{3VE}{\omega_s X_s} Sin\delta$

For a given value of supply voltage, frequency & field excitation, the torque will be maximum when δ = 90

i.e, $T_{max} = \frac{3VE}{\omega_s X_s}$

The maximum torque is known as *pull out torque*

- Any increase in torque beyond this value will cause the motor to slow down & the synchronism is lost
- This phenomenon is called *pulling out of step*

Variable frequency control of Synchronous motor

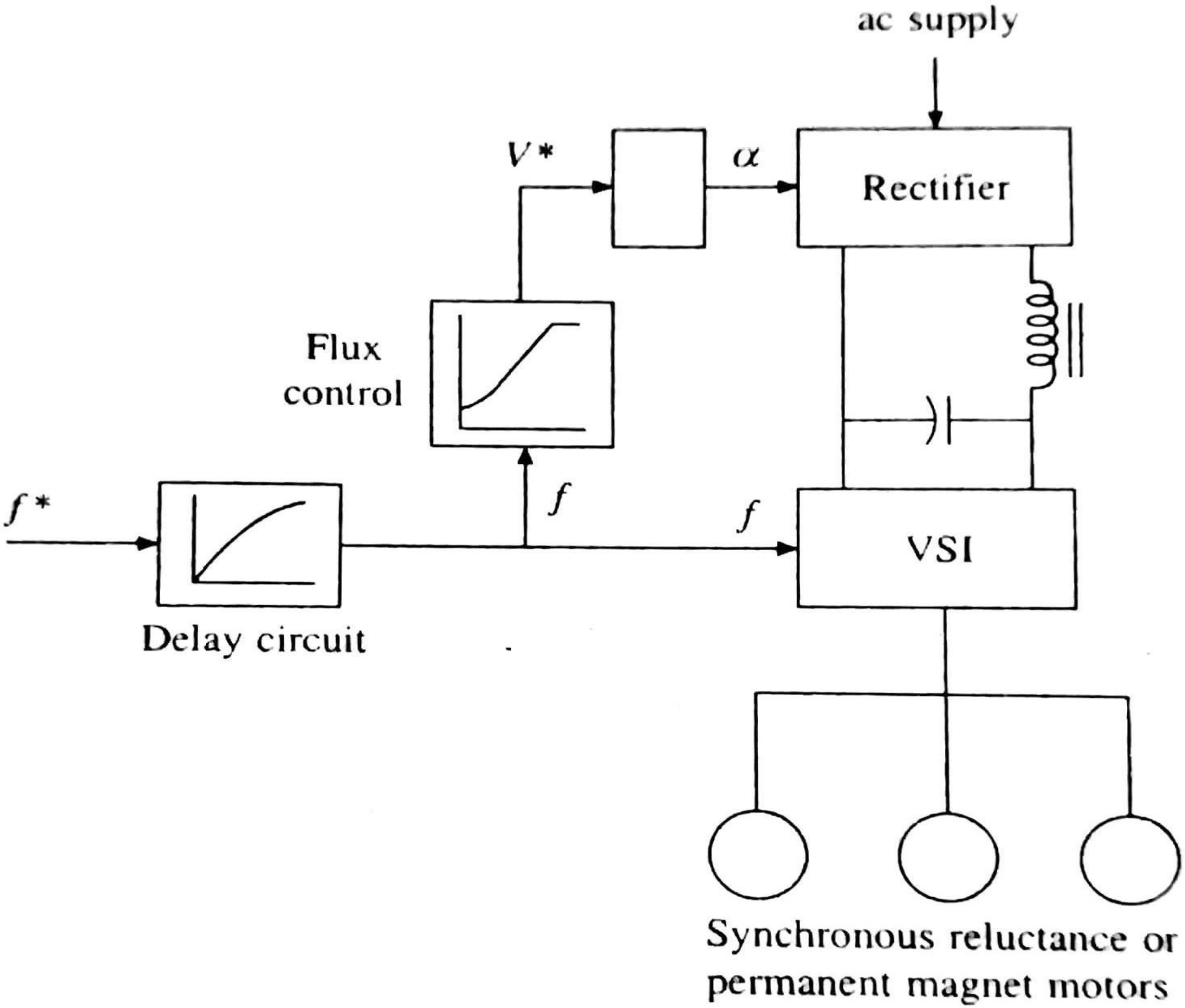
- Synchronous speed α frequency
- So by varying frequency, speed can be controlled
- Like in induction motor, upto base speed, the V/f ratio is kept constant & for speed above base speed, the terminal voltage is maintained at rated value & frequency is varied
- In variable frequency control, synchronous motor may operate in two modes

  a) True synchronous mode /open loop mode

  b) Self controlled mode

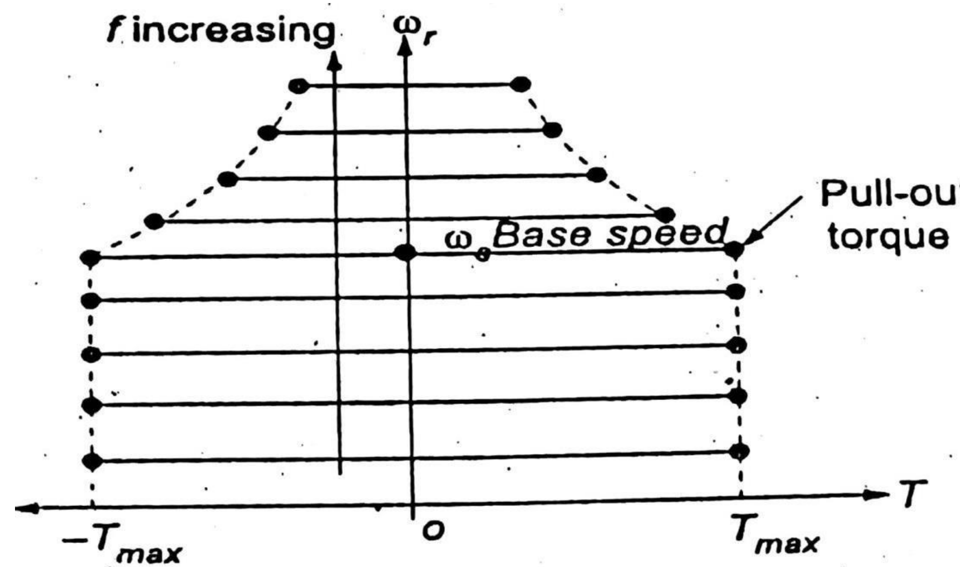
- **a) <u>True synchronous mode</u>**

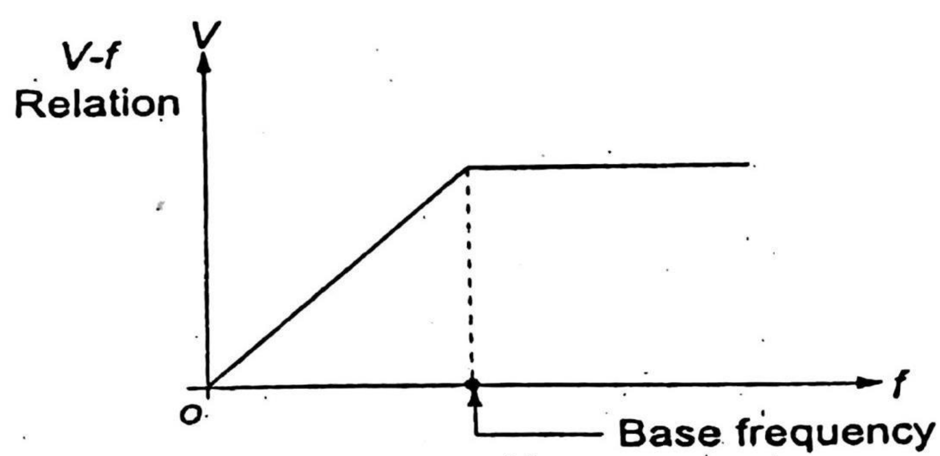
- Here the stator supply frequency is controlled from an independent oscillator
- Frequency from initial value to desired value is varied gradually so that the difference between synchronous speed & actual speed is


ac supply
V*
α
Rectifier
Flux
control
f*
f
f
VSI
Delay circuit
Synchronous reluctance or
permanent magnet motors

- A drive operating in true synchronous mode is shown in previous slide
- Frequency command f* is applied to a VSI through a delay circuit so that rotor speed is able to track the changes in frequency

- A flux control block changes stator voltage with
- frequency to maintain a constant flux below base speed & constant terminal voltage above base speed

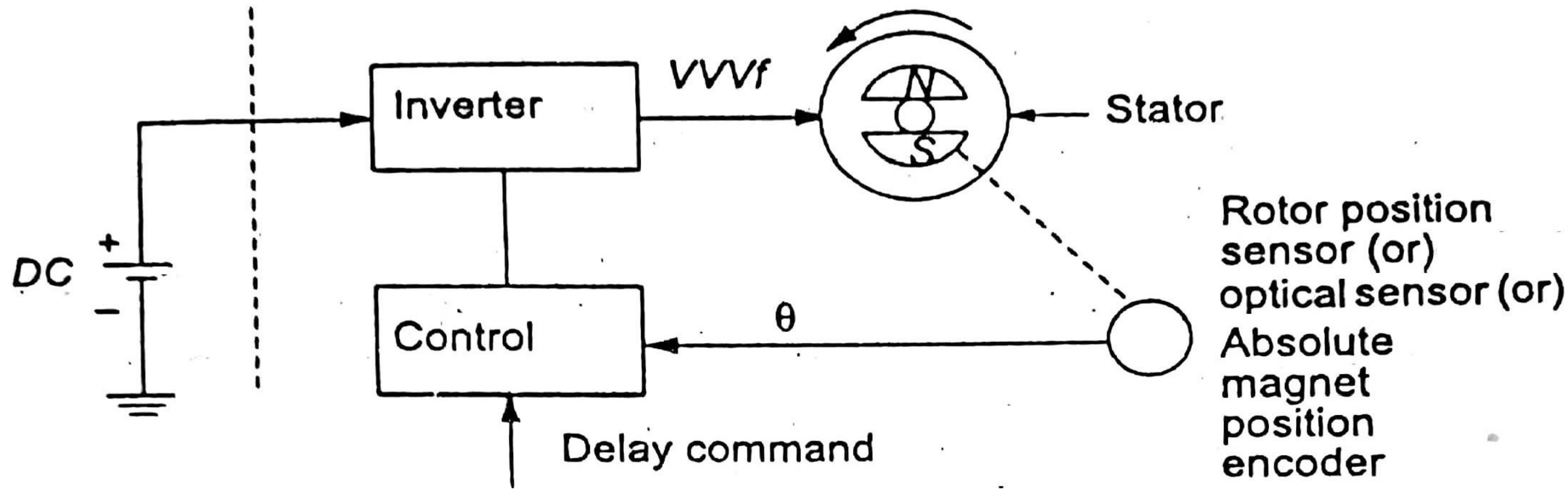




- - Under steady operating conditions, a gradual increase in frequency causes the synchronous speed > actual speed & torque angle δ increasesTo follow this change in frequency, motor accelerates & settles at new speed after hunting oscillations which are damped by damper windings
- A gradual decrease in frequency causes the synchronous speed to become < actual speed & δ become negative
- To follow this change in frequency, the motor decelerates under regenerative braking
- Motor settles down at new speed after hunting oscillations
- The frequency must be changed gradually to allow the rotor to track the changes in revolving field, otherwise the motor may pull out of step
- This method is employed only in multiple synchronous motor drives requiring accurate speed tracking between motors
- E.g, fibre spinning mills, paper mills, textile mills

- **b) Self controlled mode**
- - A machine is said to be in self controlled mode if it gets its variable frequency from an inverter whose thyristors are fired in a sequence, using the information of rotor position or stator voltages
- *i) Rotor position sensor*

- here a rotor position sensor is used, which measures the rotor position w.r.to stator & sends pulses to thyristor
- Hence the frequency of inverter output is decided by rotor speed
- Here the supply frequency is changed so that the synchronous speed is same as rotor speed & hence rotor cannot pull out of slip & hunting oscillations are eliminated
- A self controlled motor has properties of a DC machine both under steady state & dynamic conditions
- There fore it is called a commutator less motor

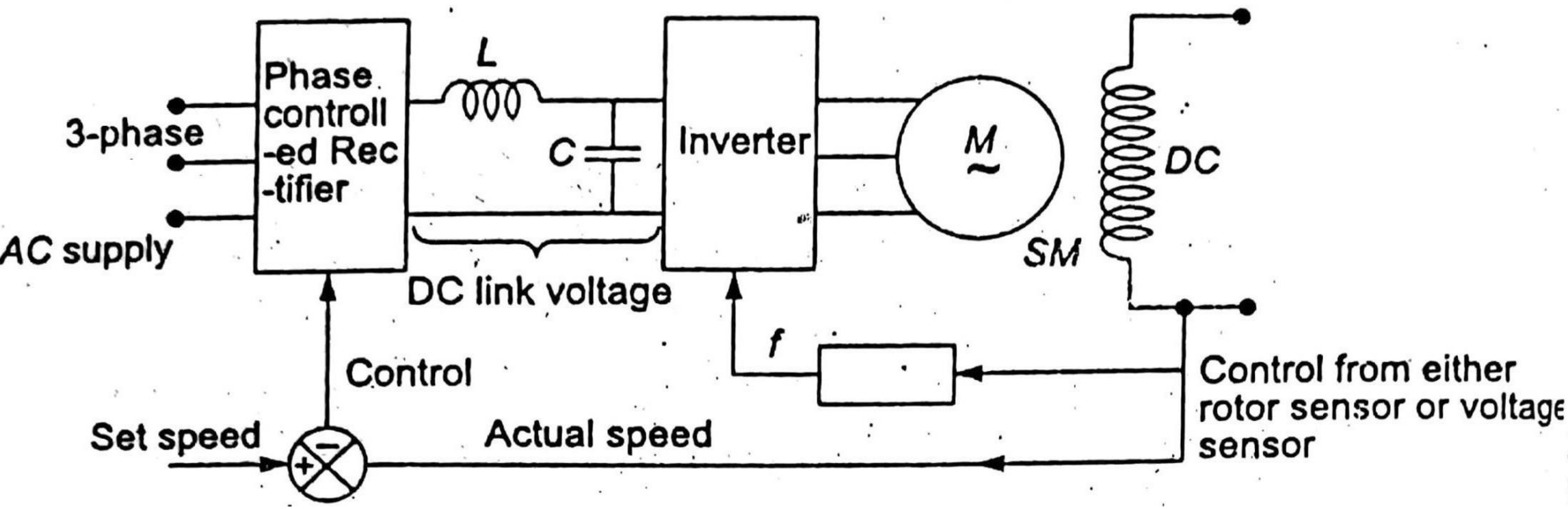


ii) *Stator voltage sensor*

- Here the firing pulses for inverter switches are derived from stator induced voltages (stator induced voltages depends on rotor position)
- The synchronous machine with the inverter can be considered to be similar to a line commutated converter where the firing pulses are synchronised with the line voltage
- Variable speed synchronous motor drives are generally operated in self controlled mode

VSI fed Synchronous Motor Drives

- \- VSI fed synchronous motor drives can be classified as

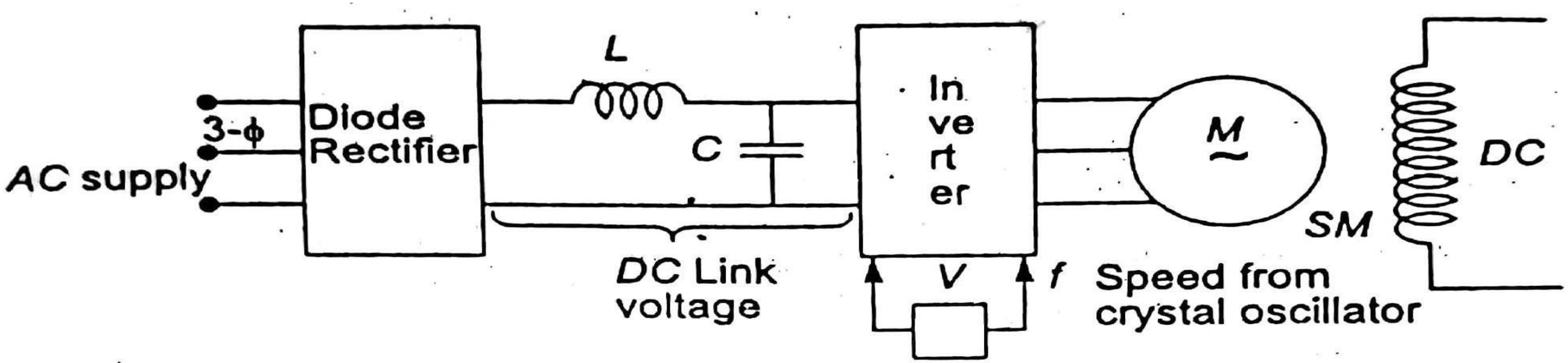


\- Here the output frequency is controlled by the inverter & voltage is controlled by the controlled rectifier

\- If the inverter is PWM inverter, both frequency & voltage can be controlled within the inverter

\- Upto base frequency, V/f ratio is kept constant & above base speed f is varied by keeping V at rated value

- 2. **True synchronous mode where the speed of motor is determined by the external independent oscillator**



- Here the output frequency & voltage is controlled within the PWM inverter
- If the inverter is not PWM controlled, then the voltage is controlled by using a controlled rectifier & frequency is controlled by the inverter

Advantages & drawbacks of True synchronous mode operation

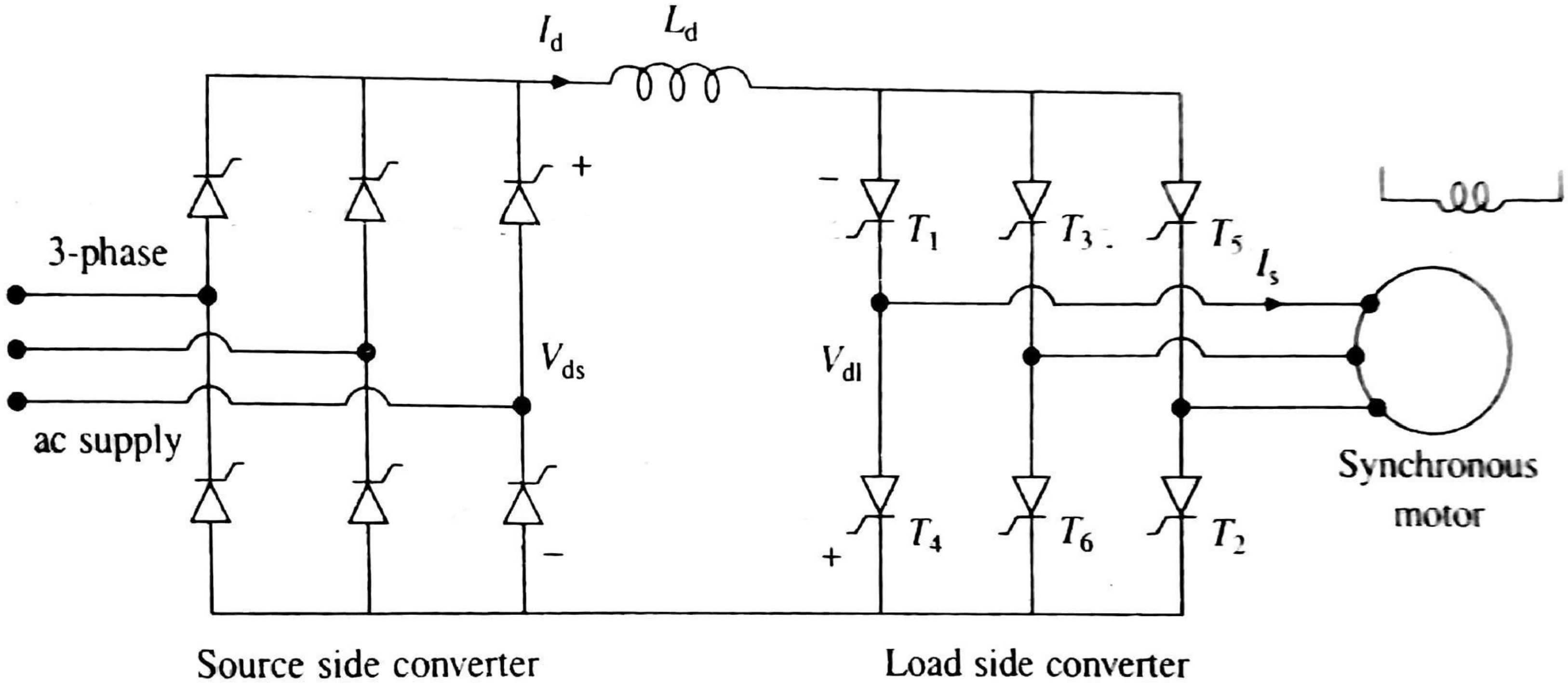
- Multi motor drive is possible
- Involve hunting & stability problems
- Can be implemented by using VSI & CSI
- Power factor can be controlled in a wound field synchronous motor by controlling the field excitation

- **Advantages & drawbacks of Self controlled mode operation**

- Eliminates hunting & stability problems
- Good dynamic response
- Can be implemented by using VSI & CSI
- Load commutation of inverter is possible & no need of forced commutation
- Power factor can be controlled in a wound field synchronous motor by controlling the field excitation

Self controlled synchronous motor drive employing a load commutated thyristor inverter

- A CSI fed synchronous motor drive may employ a load commutated thyristor inverter
- When a synchronous motor is fed from a CSI, it can be operated in self controlled mode or true synchronous mode
- When fed from CSI, synchronous motor is operated at leading power factor so that the inverter will work as a load commutated inverter
- A load commutated inverter fed synchronous motor under self controlled mode is shown in figure
- The source side converter is a 6 pulse line commutated thyristor converter
- For a firing angle range $0<\alpha_s<90$, it works as a line commutated fully controlled rectifier delivering positive V_d & I_d
- For a firing angle range $90<\alpha_s<180$, it works as a line commutated inverter delivering negative V_d & I_d



- When synchronous motor is operated at leading power factor, thyristors of load side converter can be commutated by motor induced voltages in the same way, as thyristors of a line commutated converter are commutated by line voltages
- Commutation of thyristors by induced voltages of load is known as load commutation
- The load side converter will work as an inverter for $90<\alpha_L<180$

- **Motoring operation** – for $0<\alpha_S<90$ & $90<\alpha_L<180$, source side converter works as rectifier & load side converter as inverter causing power to flow from AC source to motor
- **Generating operation** - for $90<\alpha_S<180$ & $0<\alpha_L<90$, load side converter work as rectifier & source side converter as inverter causing power to flow from motor to AC source

- The DC link inductor L_d reduces ripples in the DC link current
- Due to L_d, load side converter works as a CSI
- For operating in self controlled mode, rotating magnetic field speed should be same as rotor speed
- This condition is achieved by making the frequency of load side converter output voltage equal to frequency of voltage induced in the armature
- Normally hall sensors are used to obtain rotor position information
- The difference between CSI fed induction motor drive & synchronous motor drive is that induction motor drive uses forced commutation &