CHAPTER 10

Power Semiconductor Drives

10.1 DC Drives

- DC Drive consists of a DC Motor, Power Electronic Converter. i.e. Rectifier (or) chopper.
  Speed Sensing Mechanism – Tachometer,
  Feedback circuit and intelligent device (Micro controller)
- The following dc motors are suitable for speed control applications.
  1. Series motor
  2. Separately excited dc motor

In the speed control applications, load remains same i.e., output current is continuous and assumed to be constant.

$$E_a = \frac{Z\phi NP}{60A} = Z\phi n\left(\frac{P}{A}\right)$$

$$\omega_m = 2\pi n$$

$$E_a = Z\phi\left(\frac{\omega_m}{2\pi}\right)\left(\frac{P}{A}\right) = \left(\frac{Z}{2\pi}\cdot\frac{P}{A}\right)\phi\,\omega_m$$

$$\boxed{E_a = K_a\,\phi\,\omega_m}$$

where,

$$\boxed{K_a = \frac{Z}{2\pi}\left(\frac{P}{A}\right)}$$

$$E_a\cdot I_a(\text{Electrical power}) = \tau_e\,\omega_m(\text{Mechanical power})$$

$$\tau_e = \frac{E_a I_a}{\omega_m}$$

$$\boxed{\tau_e = K_a\,\phi\,I_a}$$

Seperately Excited DC Motor

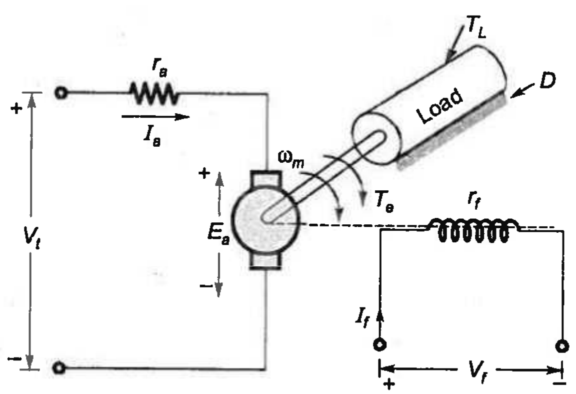


Figure-10.1

$$E_a = K_a \phi \omega_m = (K_a \phi)\omega_m \Rightarrow \boxed{E_a = K_m \omega_m}$$

where, $K_m = K_a\phi$ (V-s/rad)

$$T_e = K_a \phi I_a \Rightarrow \boxed{T_e = K_m I_a}$$

where, units of K_m are N-m/A

Example - 10.1 A 250 V separately excited DC motor has armature resistance of 2.5 ohms. When driving a load at 600 r.p.m. with constant torque, the armature takes 20 A. The motor is controlled by a DC chopper operating with a frequency of 400 Hz and an input voltage of 250 V DC. What should be the value of duty ratio, if it is desired to reduce the speed from 600 r.pm. to 400 rpm? Also find the motor speed at rated current and a duty ratio of 0.5, if the motor is regenerating.

Solution:

For separately excited dc motor,

Armature Resistance = 2.5 Ω

∴ back emf $E_\phi = k_n \phi N$

where $E = V_t - I_a R_a = 250 - 20 \times 2.5 = 200$ V

$$\therefore \quad k_n\phi = \frac{200}{600} = \frac{1}{3}$$

Let (δ) be the duty ratio, then, $V_t = \delta V_i$ [where V_i = input voltage]

$$[\delta V_i - I_a R_a] = k_n \phi \times N'$$

Since torque remains constant,

∴ 'I' should be constant

$$[\delta \times 250 - 20 \times 2.5] = \frac{1}{3} \times 400$$

$$\delta = 0.733$$

At (δ = 0.5), and given, motor is regenerating working as a generator, then

$$N'' = \frac{[\delta V_i + I_a R_a]}{k_n \phi} = 3 \times [125 + 20 \times 2.5] = 525 \text{ rpm}$$

DC Series Motor

$$E_a = K_a \phi \omega_m$$

$$\phi \propto I_a$$

$$\phi = c I_a$$

$$E_a = K_a c I_a \omega_m \Rightarrow \boxed{E_a = K_1 I_a \omega_m}$$

$$T_e = K_a \phi I_a = K_a c I_a \cdot I_a \Rightarrow \boxed{T_e = K_1 I_a^2}$$

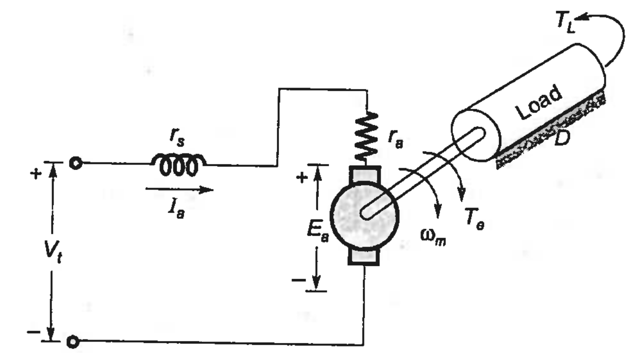
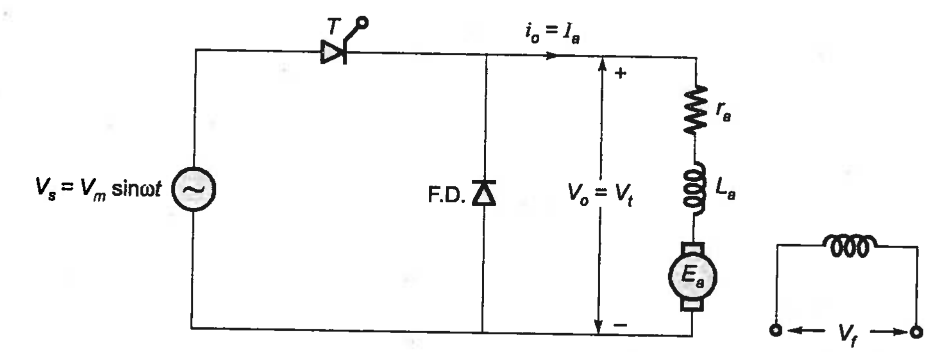


Figure-10.2

K_1 units are [N-m/A²]

1-φ Half wave Rectifier Drive



1 − φ semi converter

Figure-10.3

$$V_0 = V_t = \frac{V_m}{2\pi}(1 + \cos\alpha_1)$$

$$V_f = \frac{V_m}{\pi}(1 + \cos\alpha_2)$$

Rms source current, $I_{sr} = I_{Tr} = I_a \sqrt{\left(\frac{\pi - \alpha_1}{2\pi}\right)}$

$$\text{Input power factor} = \frac{E_a I_a + I_a^2 r_a}{V_s I_{sr}} = \frac{I_a(E_a + I_a r_a)}{V_s \cdot I_{sr}}$$

$$\boxed{\text{Input power factor} = \frac{V_t \cdot I_a}{V_s \cdot I_{sr}}}$$

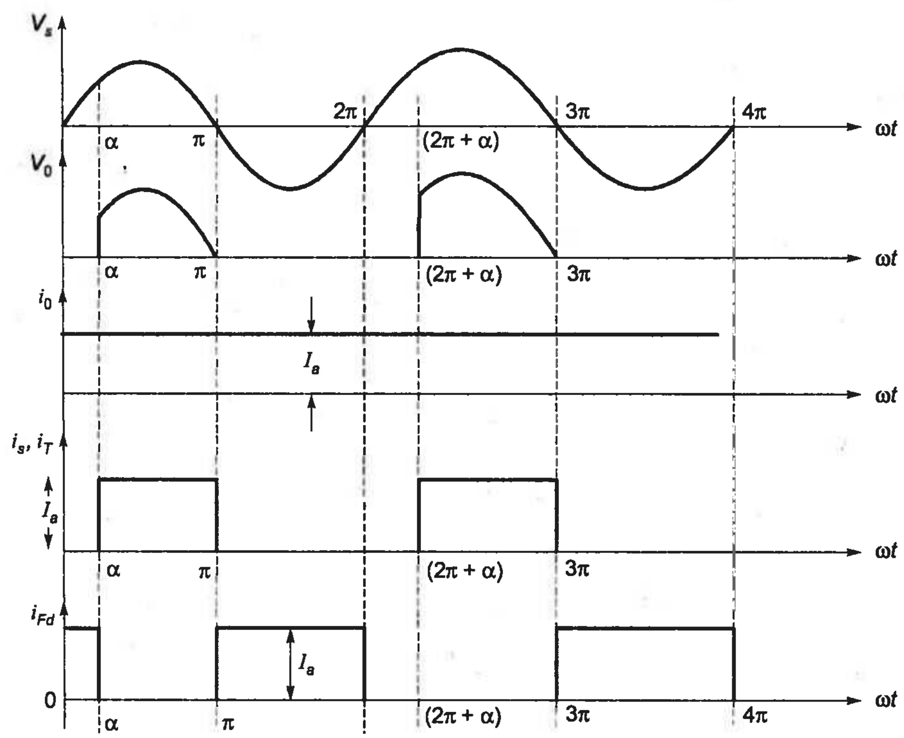


Figure-10.4

1-ϕ Semi Converter Drive

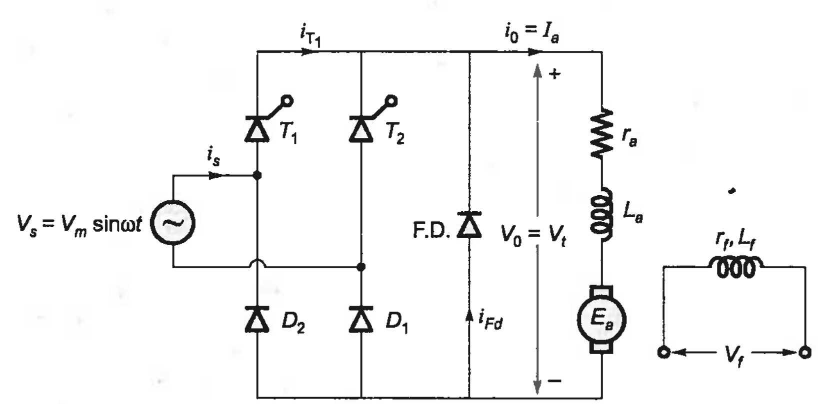


Figure-10.5

For a 1-ϕ semiconverter, average output voltage

$$\boxed{V_0 = V_t = \frac{V_m}{\pi}(1+\cos\alpha)}$$

For field circuit,
$$V_f = \frac{V_m}{\pi}(1+\cos\alpha_1)$$

Rms value of source current,
$$I_{s\,rms} = I_a\sqrt{\left(\frac{\pi-\alpha}{\pi}\right)}$$

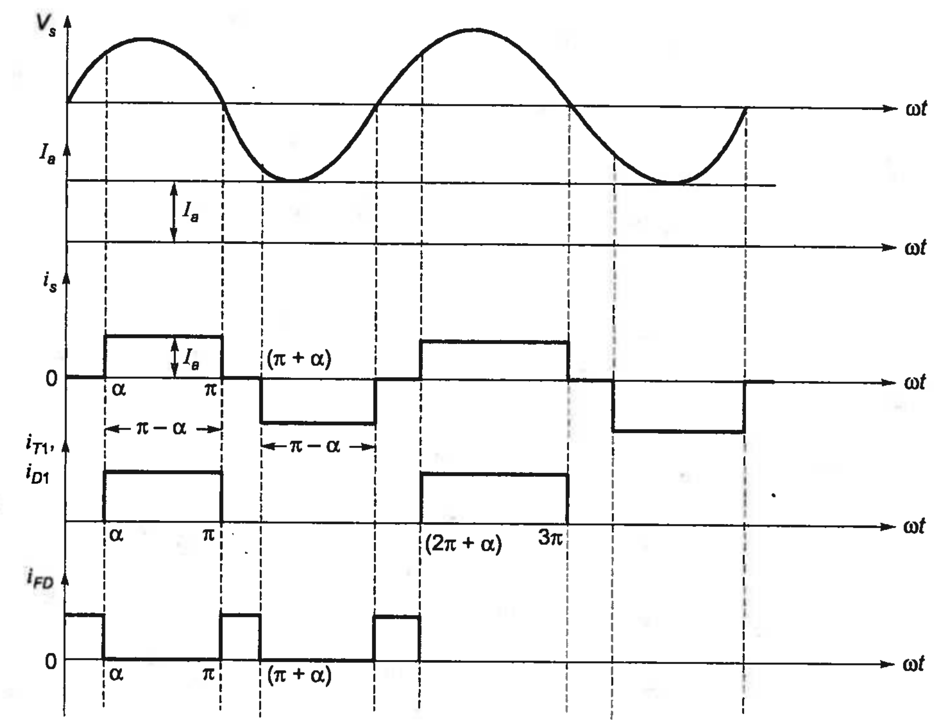


Figure-10.6

Rms value of freewheeling diode current,

$$I_{FD\,rms} = I_a\sqrt{\left[\frac{\alpha}{\pi}\right]}$$

Rms value of thyristor current,

$$I_{T\,rms} = I_a\sqrt{\left(\frac{\pi-\alpha}{2\pi}\right)}$$

$$\text{Input power factor} = \frac{V_t \cdot I_a}{V_s \cdot I_{sr}} = \frac{\sqrt{2}V_s\cdot(1+\cos\alpha)\cdot I_a\sqrt{\pi}}{\pi\cdot V_s\, I_a\sqrt{\pi-\alpha}}$$

$$\boxed{\text{Input pf} = (1+\cos\alpha)\sqrt{\left[\frac{2}{\pi(\pi-\alpha)}\right]}}$$

A 1-ϕ semiconverter is also called 1-ϕ half controlled bridge converter.

Example - 10.2 A single-phase half-controlled rectifier is driving a separately excited dc motor. The dc motor has a back emf constant of 0.25 V/rpm. The armature current is 5 A without any ripple. The armature resistance is 2 Ω. The converter is working from a 230 V, single phase ac source with a firing angle of 30°. Under this operating condition, the speed of the motor will be

(a) 339 rpm
(b) 346 rpm
(c) 366 rpm
(d) 386 rpm

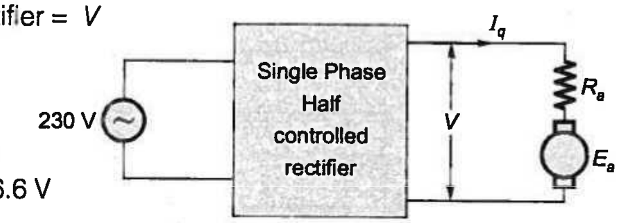
Solution: (b)

Back emf $= E_a = k\phi N$

or $E_a = k_b N$

where, k_b = Back-emf constant = 0.25 V/rpm

Average output voltage of 1-ϕ half controlled rectifier = V



$$V = \frac{V_m}{2\pi}(1+\cos\alpha) = \frac{230\sqrt{2}}{2\pi}(1+\cos 30°)$$

$\Rightarrow$ $V = 96.6$ V

$E_a = V - I_a R_a = 96.6 - 5 \times 2 = 86.6$ V

$$\text{Speed} = N = \frac{E_a}{k_b} = \frac{86.6}{0.25} = 346.4 \text{ V}$$

So, option (a) is closer to 346.4 V.

Example - 10.3 A separately-excited dc motor is supplied from 230 V, 50 Hz source through a single-phase half-wave controlled converter. Its field is fed through 1-phase semiconverter with zero degree firing-angle delay. Motor resistance r_a = 0.7 Ω and motor constant = 0.5 V-sec/rad. For rated load torque of 15 Nm at 1000 rpm and for continuous ripple free currents, determine.

(a) Firing angle delay of the armature converter

(b) rms value of thyristor and freewheeling diode currents

(c) input power factor of the armature converter.

Solution:

(a) Motor constant = 0.5 V-sec/rad = 0.5 Nm/A = K_m

But motor torque, $T_e = K_m I_a$

$\therefore$ Armature current $= \frac{15}{0.5} = 30$ A

Motor emf, $E_a = K_m \cdot \omega_m = 0.5 \times \frac{2\pi \times 1000}{60} = 52.36$ V.

For 1-phase half-wave converter feeding a dc motor.

$$V_t = \frac{V_m}{2\pi}(1+\cos\alpha) = E_a + I_a r_a$$

or

$$V_t = \frac{\sqrt{2}\times 230}{2\pi}(1+\cos\alpha) = 52.36 + 30 \times 0.7 = 73.36 \text{ V}$$

$$\therefore \quad \alpha = \cos^{-1}\left[\frac{73.36 \times 2\pi}{\sqrt{2}\times 230} - 1\right] = 65.349°$$

Thus, firing angle delay of converter 1 is 65.336°

(b) Rms value of thyristor current, is

$$I_{Tr} = I_a\left(\frac{\pi-\alpha}{2\pi}\right)^{1/2} = 30\left(\frac{180-65.349°}{360}\right)^{1/2}$$

$$= 16.930 \text{ A} = I_{sr}$$

Rms value of freewheeling diode current,

$$I_{fd,r} = I_a\left(\frac{\pi+\alpha}{2\pi}\right)^{1/2} = 30\left(\frac{180+65.349°}{360}\right)^{1/2} = 24.766 \text{ A}$$

(c) Input power factor of armature converter $= \frac{V_t I_a}{V_s I_{sr}} = \frac{73.36 \times 30}{230 \times 16.931} = 0.5651$ lag.

Also, input power factor of armature converter

$$= \frac{1+\cos\alpha}{\sqrt{\pi(\pi-\alpha)}} = \frac{1+\cos 65.349°}{\left[\pi(180-65.336°)\frac{\pi}{180}\right]^{1/2}} = 0.56518 \text{ lag.}$$

1-ϕ Fullwave Rectifier Drive

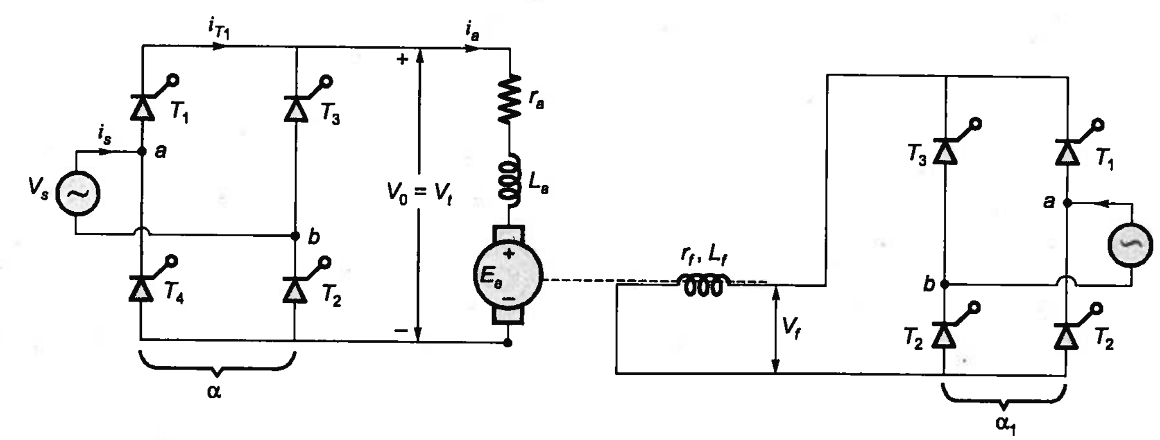


Figure-10.7

- For the armature converter 1,

$$\boxed{V_0 = V_t = \frac{2V_m}{\pi}\cos\alpha} \quad \text{for } 0 < \alpha < \pi.$$

- For the field converter 2, $V_f = \frac{2V_m}{\pi}\cos\alpha_1$ for $0 < \alpha_1 < \pi$

- Rms value of source current, $I_{s\,rms} = \sqrt{\left(I_a^2 \cdot \frac{\pi}{\pi}\right)} = I_a$

- Rms value of thyristor current, $I_{T\,rms} = \sqrt{\left(I_a^2 \cdot \frac{\pi}{2\pi}\right)} = \frac{I_a}{\sqrt{2}}$

- Input supply p.f. $= \frac{V_t \cdot I_a}{V_s \cdot I_{sr}} = \frac{2V_m}{\pi}\cos\alpha \frac{I_a\sqrt{2}}{V_m \cdot I_a}$

$$\boxed{\text{Input p.f.} = \frac{2\sqrt{2}}{\pi}\cos\alpha}$$

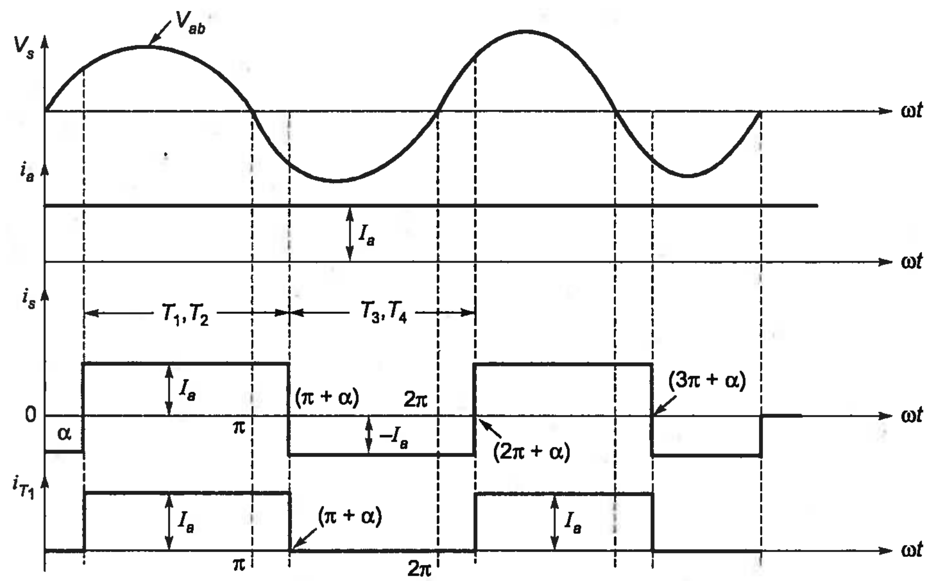
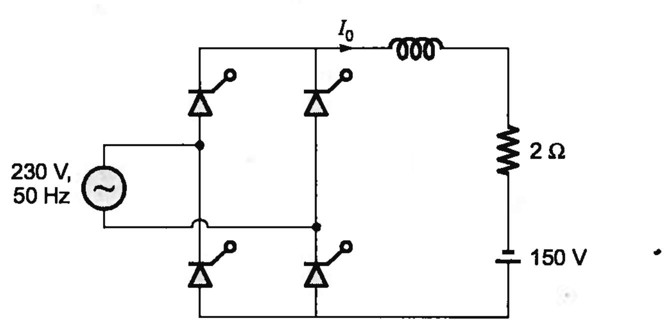


Figure-10.8

Example - 10.4 A single phase fully controlled converter bridge is used for electrical braking of a seprately excited dc motor. The dc motor load is respectively by an equivalent circuit as shown in the figure.



Assume that the load inductance is sufficient to ensure continous and ripple free load current. The firing angle of the bridge for a load current of I_0 = 10 A will be

(a) 44° (b) 51°
(c) 129° (d) 136°

Solution: (c)

Average output voltage of the converter,

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

Load current = I_0 = 10 A
Back emf = E_b = 150 V
Armature resistance = R_a = 2 Ω

Applying KVL,

$$V_0 - 2I_0 + 150 = 0$$

$$\Rightarrow \quad V_0 = -150 + 2 \times 10 = -130 \text{ V}$$

$$\Rightarrow \quad \frac{2V_m}{\pi}\cos\alpha = -130$$

$$\Rightarrow \quad \frac{2\times\sqrt{2}\times 230}{\pi}\cos\alpha = -130 \quad \Rightarrow \quad \alpha = 129°$$

3-ϕ Halfwave Converter Drive (or) Rectifier Drive

$$V_0 = V_t = \frac{3\sqrt{6}}{2\pi}V_{ph}\cos\alpha$$

$$I_{sr} = I_{T\,rms} = I_a\sqrt{\frac{1}{3}}$$

3-ϕ Fullwave Rectifier Drive

$$V_0 = \frac{3\sqrt{6}}{\pi}V_{ph}\cos\alpha$$

$$I_{T\,rms} = I_a\sqrt{\frac{1}{3}}$$

$$I_{s\,rms} = I_a\sqrt{\frac{2}{3}}$$

3-ϕ Semiconverter Drive

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

For $\alpha_1 < 60°$;

$$I_{s\,rms} = I_a\sqrt{\frac{2}{3}}$$

$$I_{T\,rms} = I_a\sqrt{\frac{1}{3}}$$

For $\alpha_1 > 60°$,

$$I_{s\,rms} = I_a\sqrt{\frac{180° - \alpha_1}{180}}$$

$$I_{T\,rms} = I_a\sqrt{\frac{(180° - \alpha_1)}{360°}}$$

Chopper drive: $\boxed{V_0 = \alpha V_s}$

Example - 10.5 A solar cell of 350 V is feeding power to an ac supply of 440 V, 50 Hz through a 3-phase fully controlled bridge converter. A large inductance is connected in the dc circuit to maintain the dc current at 20 A. If the solar cell resistance is 0.5 Ω, then each thyristor will be reverse biased for a period of

(a) 125° (b) 120°
(c) 60° (d) 55°

Solution: (d)

Solar cell emf $E = 350$ V

DC current, $I_{dc} = 20$ A

Solar cell resistance,

$$R_{cell} = 0.5\ \Omega$$

V_0 = Voltage across inverter

$$= -(E - I_{dc}R_{cell}) = -(350 - 20 \times 0.5) = -340 \text{ V}$$

The bridge acts as inverter,

Output voltage of 3-ϕ fully controlled bridge

$$V_0 = \frac{3V_{ml}}{\pi}\cos\alpha$$

$$\frac{3V_{ml}}{\pi}\cos\alpha = -340$$

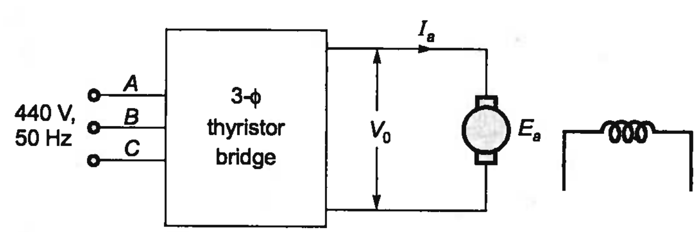
$$\Rightarrow \quad \frac{3\times 440\sqrt{2}\cos\alpha}{\pi} = -340 \quad \Rightarrow \quad \alpha = 125°$$

Therefore, each thyristor will be reverse biased for a period of 55°.

Example - 10.6 A three-phase, 440 V, 50 Hz ac mains fed thyristor bridge is feeding a 440 V dc, 15 kW, 1500 rpm separately excited dc motor with a ripple free continous current in the dc link under all operating conditions. neglecting the losses, the power factor of the ac mains at half the rated speed is

(a) 0.354 (b) 0.372
(c) 0.90 (d) 0.955

Solution: (a)



For a separately excited dc motor

$$\text{Back emf} = E_a = V_0 - I_aR_a$$

Since, losses are neglected R_a can be neglected

So,

$$E_a \approx V_0$$
$$V_0 = E_a = k_a\phi N$$
$$V_0 \propto N$$

At rated voltage V_0 = 440 V and N = 1500 rpm so, at half the rated speed. $\left(\frac{N}{2} = 750\text{rpm}\right)$ output voltage of the bridge (V_0) is 220 V.

If I_a is the average value of armature current rms value of supply current will be

$$I_s = I_a\sqrt{\frac{2}{3}}$$

Power delivered to the motor,

$$P_0 = V_0 I_a$$

Input VA to the thyristor bridge

$$S_{in} = \sqrt{3}V_sI_s$$

$$\text{Input power factor} = \frac{P_0}{S_{in}} = \frac{V_0I_a}{\sqrt{3}V_sI_s} = \frac{220\times I_a}{\sqrt{3}\times 440\times I_a\sqrt{\frac{2}{3}}} = 0.354 \text{ or } 0.3535$$

Example - 10.7 A three-phase semiconverter feeds the armature of separately excited dc motor, supplying a non-zero torque, for steady-state operation, the motor armature current is found to drop to zero at certain instances of time. At such instances, the voltage assumes a value that is

(a) equal is the instantaneous value of the ac phase voltage
(b) equal to the instantaneous value of the motor back emf
(c) arbitrary
(d) zero

Solution: (b)

$$V = E_b + I_aR_a$$
$$I_a = 0,$$
$$V = E_b$$

Example - 10.8 The speed of a separately excited dc motor is controlled by means of a three-phase semiconverter from a three-phase, 415 V, 50 Hz supply. The motor constants are: inductance 10 mH, resistance 0.9 ohm and armature constant 1.5 V/rad/s (Nm/A). Calculate the speed of this motor at a torque of 50 Nm when the converter is fired at 45°, Neglect losses in the converter.

Solution:

Armature constant, K_m = 1.5 V/rad/s or 1.5 Nm/A

Motor torque, $T_e = K_m I_a = 50$ Nm

∴ Motor armature current, $I_a = \frac{50}{1.5} = \frac{100}{3}$ A

The equation for the converter-motor combination is

$$\frac{3V_{ml}}{2\pi}(1+\cos\alpha) = E_a + I_ar_a = K_m\omega_m + I_ar_a$$

$$\frac{3\sqrt{2}\times 415}{2\pi}(1+\cos 45°) = 1.5\times\ \omega_m + \frac{100}{3}\times 0.9$$

$$478.3 = 1.5\times\ \omega_m + 30$$

or, $$\omega_m = \frac{478.3-30}{1.5} = 298.914 \text{ rad/s}$$

or, $$\frac{2\pi N}{60} = \omega_m = 298.914 \text{ rad/s}$$

∴ Motor speed, $$N = \frac{298.867\times 60}{2\pi} = 2854.42 \text{ rpm}$$

Example - 10.9 In a speed controlled dc drive, the load torque is 40 Nm. At time $t = 0$, the operation is under steady state and the speed is 500 rpm. Under this condition at $t = 0^+$, the generated torque is instantly increased to 100 Nm. The inertia of the drive is 0.01 Nm. sec^2 /rad. The friction is negligible.

(a) Write down the differential equation governing the speed of the drive for $t > 0$.
(b) Evaluate the time taken for the speed to reach 1000 rpm.

Solution: (a)

(a) At $t = 0$, steady state exists and therefore, generated torque, $T_e = T_L$, load torque
In general, the dynamic equation for the motor-load combination is generated (or motor) torque = inertia torque + friction torque + load torque

or,
$$T_e = J\frac{d\omega_m}{dt} + D\omega_m + T_L$$

As friction torque is zero, $D\omega_n = 0$. This gives the differential equation, governing the speed of the drive at $t > 0$, as

$$T_e = J\frac{d\omega_m}{dt} + T_L$$

$$100 = 0.01\frac{d\omega_m}{dt} + 40 \qquad ...(i)$$

(b) From equation (*i*),
$$\frac{d\omega_m}{dt} = \frac{60}{0.01} = 6000 \quad \text{or} \quad dt = \frac{d\omega_m}{6000}$$

Its integration gives,
$$t = \frac{1}{6000}\cdot\omega_m + A \qquad ...(ii)$$

Initial speed at $t = 0+$ remains 500 rpm. Therefore

$$\omega_{mo} = \frac{2\pi\times 500}{60} = \frac{100\pi}{6} \text{ rad/sec}$$

From equation (*ii*),
$$0 = \frac{1}{6000}\times\frac{100\pi}{6} + A \quad \text{or} \quad A = \frac{-\pi}{360}$$

$\therefore$
$$t = \frac{\omega_n}{6000} - \frac{\pi}{360}$$

Final speed,
$$\omega_m = \frac{2\pi\times 1000}{60} = \frac{200\pi}{6} \text{ rad/sec}$$

$\therefore$
$$t = \frac{200\pi}{6000\times 6} - \frac{\pi}{360} = \frac{\pi}{360} \text{ sec} = 8.7266 \text{ msec}$$

$\therefore$ Time taken for the speed to reach 1000 rpm = 0.008728 sec.

10.2 AC Drives

Induction motors are the one generally used in AC drives. Various methods of speed control of induction motors are

1. **Pole changing method**
2. **Cascade method of speed control**
3. **Stator voltage control:**
   An AC voltage controller will be employed to control the AC voltage applying to motor.
4. **Stator frequency control:**
   A cyclo converter will be employed to control the frequency of the AC supply applying to the induction motor.
5. **Stator *v/f* control:**
   A cyclo converter will be employed to control the voltage and frequency simultaneously.

Static Rotor Resistance Control

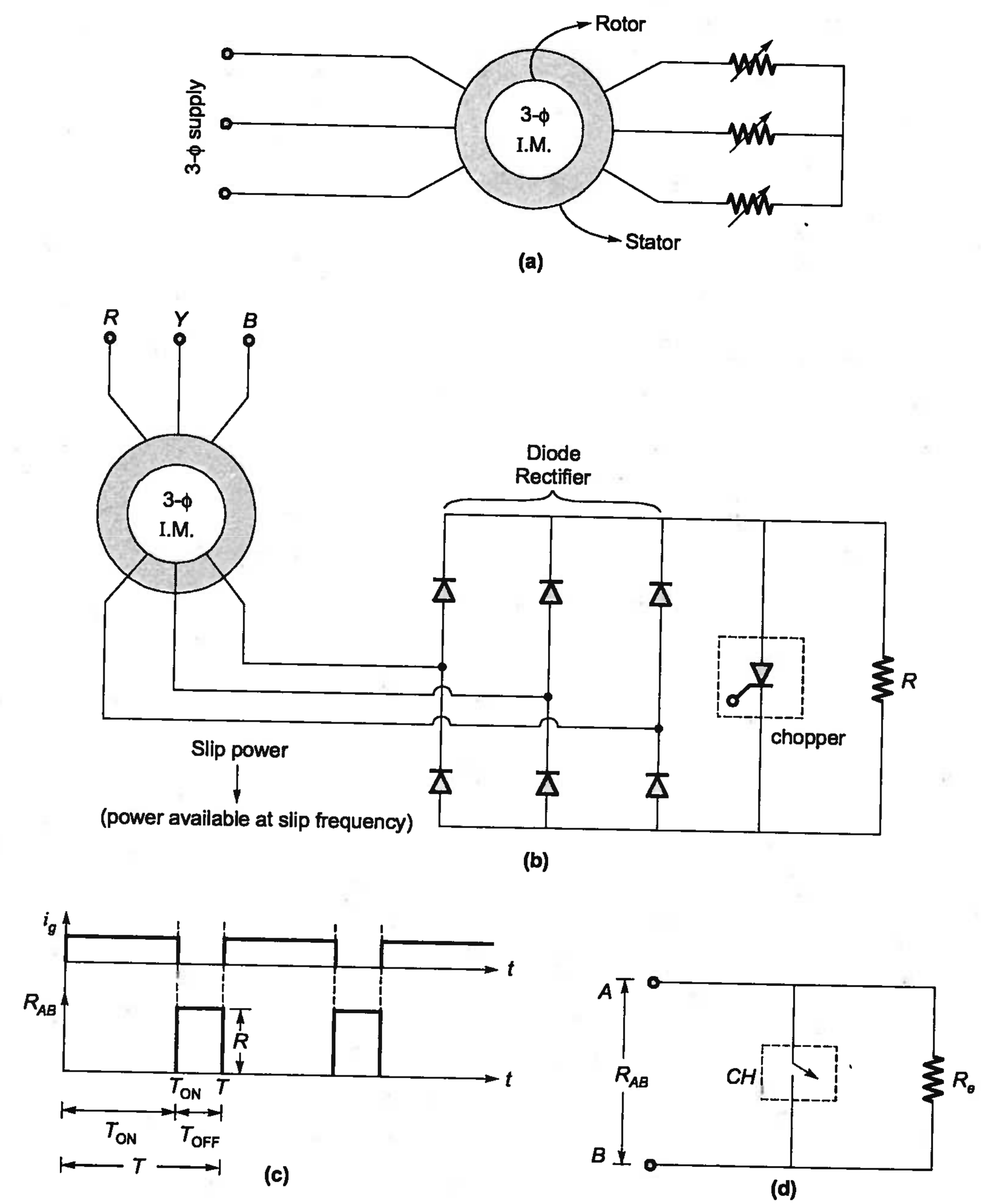


Figure-10.9

- When chopper is switched ON, the resistance is zero and when it is switched OFF, it is '*R*'.
- The effective resistance offered to the rotor circuit can be controlled by varying the duty cycle of the chopper.

$$R_{eff} = R\left(\frac{T_{off}}{T}\right) = \frac{R(1-\alpha)T}{T}$$

$$\boxed{R_{eff} = R(1-\alpha)}$$

Example - 10.10 What is the equivalent external resistance connected in series with the rotor winding?

Solution:

$$\text{Total Cu loss} = SP_g$$

$$3I_2^2R_2 + I_d^2R_e(1+\alpha) = SP_g \quad ...(1)$$

and

$$I_d = \sqrt{\frac{3}{2}}I_2 \quad ...(2)$$

From equation (1) and (2), we get

$$3I_2^2R_2 + \frac{3}{2}I_2^2R_e(1-\alpha) = SP_g \quad [R_e \to \text{External resistance}]$$

$$3I_2^2[R_2 + 0.5R_e(1-\alpha)] = SP_g$$

NOTE

Effective resistance connected in series with the rotor is $0.5\ R_e(1-\alpha)$.

- The physical movement of the resistance is being replaced by electronic control of the duty cycle. Hence is called as 'Static Rotor Resistance Control'.
- In chopper method of speed control, slip power is getting wasted in the external resistance and it leads to poor efficiency of the drive. To recover the slip power, there are two schemes available.
  1. Static Kramer Drive (Sub synchronous speed)
  2. Static Scherbius Drive (Super synchronous speed)

10.3 Static Kramer Drive

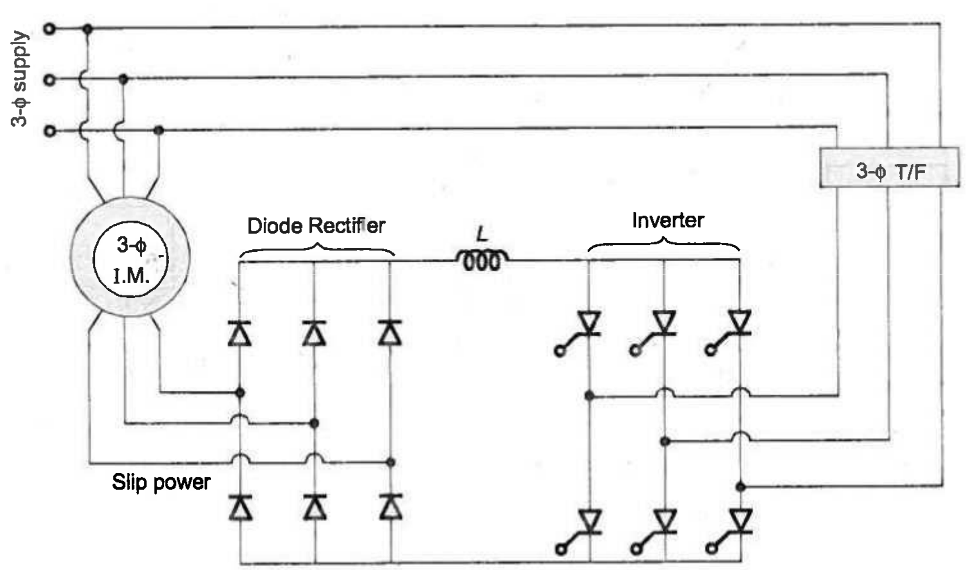


Figure-10.10

- In this method, slip power is getting transferred from rotor circuit to supply lines by adjusting its voltage and frequency values to the line values.
- As the slip power flows from rotor circuit to supply lines it is suitable for only subsynchronous speeds i.e., below the synchronous speed.

10.4 Static Scherbius Drive

There are two configurations to obtain such a drive:

1. DC link scherbius drive
2. Cyclo converter scherbius drive

1. DC Link Scherbius Drive

- It consists of two phase controlled bridges, smoothening inductor and transformer.
- For sub synchronous speed control Phase Controlled Rectifier-I acts as rectifier ($\alpha < 90°$). P.C.R.-II acts as line commutated inverter ($\alpha > 90°$).
- For super synchronous speed control, P.C.R.-II acts as rectifier, P.C.R.-I will act as a line commutated inverter.

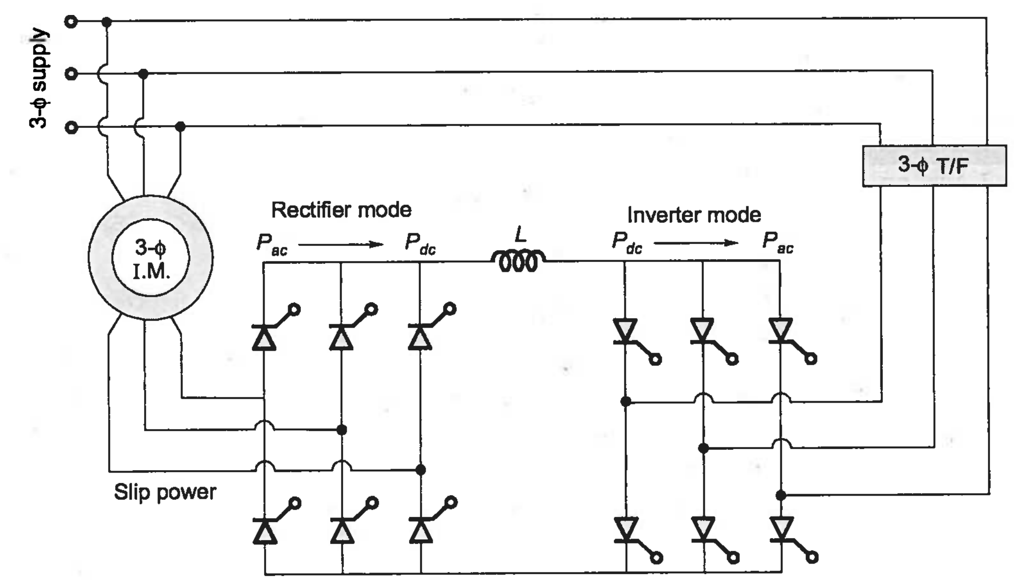


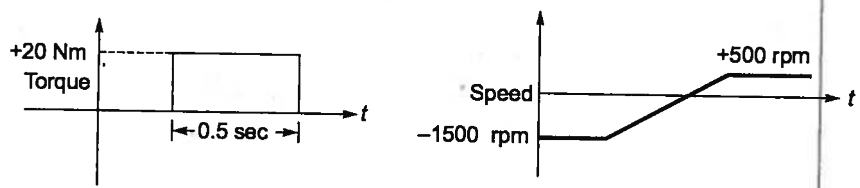
Figure-10.11

Cyclo Converter Scherbius Drive

It consists of a cyclo converter, which allows the power flow in both the directions by adjusting its frequency.

NOTE: Both the above scherbius drives are suitable for sub-synchronous as well as super synchronous speed.

Example - 10.11 A variable speed drive rated for 1500 rpm, 40 Nm is reversing under no load. Figure shows the reversing torque and the speed during the transient. The moment of inertia of the drive is



(a) 0.048 kg m²
(b) 0.064 kg m²
(c) 0.096 kg m²
(d) 0.128 kg m²

Solution: (a)

Speed changes from −1500 rpm to 500 rpm in 0.5 sec.

So angular acceleration,

$$\alpha = \frac{500-(-1500)}{0.5} \times \frac{2\pi}{60} \text{rad/sec}^2 = 418.88 \text{ rad/sec}^2$$

$$\text{Torque} = T = 20 \text{ N-m}$$

$$T = I\alpha$$

Moment of inertia,

$$I = \frac{T}{\alpha} = \frac{20}{418.88} = 0.048 \text{ kgm}^2$$

Example - 10.12 An electric motor, developing a starting torque of 15 Nm, starts with a load torque of 7 Nm on its shaft. If the acceleration at start is 2 rad/sec2, the moment of inertia of the systems must be (neglecting viscous and Coulomb friction)

(a) 0.25 kg m²
(b) 0.25 Nm²
(c) 4 kg m²
(d) 4 Nm²

Solution: (c)

T_S = Starting torque developed by the motor = 15 N-m

T_L = Load torque = 7 N-m

T_a = Accelerating torque

$= T_S - T_L = 15 - 7 = 8$ N-m

α = Acceleration = 2 rad/sec²

$T_a = I\alpha$

$$I = \text{Moment of inertia} = \frac{T_a}{\alpha} = \frac{8}{2} = 4 \text{kg m}^2$$

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