Example 6.1. *A single-phase 230 V, 1 kW heater is connected across 1-phase, 230 V, 50 Hz supply through an SCR. For firing angle delays of 45° and 90°, calculate the power absorbed in the heater element.*

Solution. Heater resistance $R = \frac{(230)^2}{1000}\ \Omega$

From Eq. (6.3), the value of rms voltage for $\alpha = 45°$ is

$$V_{or} = \frac{\sqrt{2}\cdot 230}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{4}\right) + \frac{1}{2}\sin 90°\right]^{1/2} = 155.071\ \text{V}$$

$\therefore$ Power absorbed by heater element for $\alpha = 45°$ is

$$\frac{V_{or}^2}{R} = \left(\frac{155.071}{230}\right)^2 \times 1000 = 454.57\ \text{watts}$$

For $\alpha = 90°$, rms voltage is

$$V_{or} = \frac{\sqrt{2}\cdot 230}{2\sqrt{\pi}}\left[\left(\pi - \frac{\pi}{2}\right) + 0\right]^{1/2} = 115\ \text{V}$$

$\therefore$ Power absorbed for $\alpha = 90°$ is

$$\frac{V_{or}^2}{R} = \left(\frac{115}{230}\right)^2 \times 1000 = 250\ \text{watts.}$$

Example 6.2. *A dc battery is charged through a resistor R as shown in Fig. 6.5 (a). Derive an expression for the average value of charging current in terms of V_m, E, R etc. on the assumption that SCR is fired continuously.*

(a) For an ac source voltage of 230 V, 50 Hz, find the value of average charging current for $R = 8\ \Omega$ and $E = 150$ V.

(b) Find the power supplied to battery and that dissipated in the resistor.

(c) Calculate the supply pf.

Solution. For the circuit of Fig. 6.5 (*a*), the voltage equation is

$$V_m \sin \omega t = E + i_0 R$$

or

$$i_0 = \frac{V_m \sin \omega t - E}{R}$$

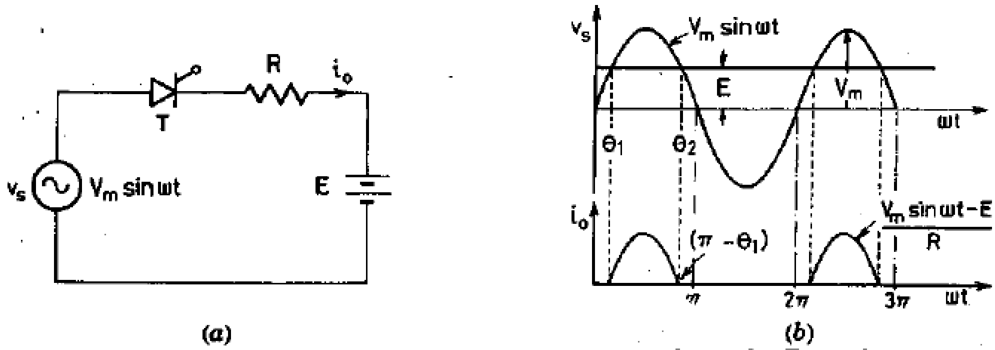


Fig. 6.5. (*a*) Power circuit diagram (*b*) various waveforms for Example 6.2.

It is seen from Fig. 6.5 that SCR is turned on when $V_m \sin \theta_1 = E$ and is turned off when $V_m \sin \theta_2 = E$, where $\theta_2 = \pi - \theta_1$. The battery charging requires only the average current I_0 given by

$$I_0 = \frac{1}{2\pi R}\left[\int_{\theta_1}^{\pi - \theta_1} (V_m \sin \omega t - E)\, d(\omega t)\right]$$

$$= \frac{1}{2\pi R}\,[2V_m \cos\theta_1 - E(\pi - 2\theta_1)]$$

(*a*) Here $\quad \theta_1 = \sin^{-1}\frac{150}{\sqrt{2}\cdot 230} = 27.466°$

$$\therefore \qquad I_0 = \frac{1}{2\pi\cdot 8}\left[2\cdot\sqrt{2}\cdot 230\cos 27.466° - 150\left(\pi - \frac{2\times 27.496\times\pi}{180}\right)\right] = 4.9676\text{ A.}$$

(*b*) Power supplied to battery $= EI_0 = 150 \times 4.9676 = 745.14$ W.

For finding the power dissipated in R, rms value of charging current must by obtained From Eq. (6.23),

$$I_{or} = \left[\frac{1}{2\pi\cdot 64}\left\{(150^2 + 230^2)\left(\pi - 2\times 27.466\frac{\pi}{180}\right) + (230)^2 \sin 2\times 27.466 - 4\cdot\sqrt{2}\cdot 230\cdot 150\cos 27.466°\right\}\right]^{1/2} = 9.2955\text{ A.}$$

$\therefore$ Power dissipated in resistor $= (9.2955)^2 \times 8 = 691.25$ Watts.

(*c*) From Eq. (6.25), supply pf $= \frac{691.25 + 745.14}{230\times 9.2955} = 0.672$ lagging.

Example 6.3. *A 230 V, 50 Hz, one-pulse SCR controlled converter is triggered at a firing angle of 40° and the load current extinguishes at an angle of 210°. Find the circuit turn off time, average output voltage and the average load current for*

(*a*) *$R = 5\ \Omega$ and $L = 2$mH.*

(*b*) *$R = 5\ \Omega$, $L = 2$ mH and $E = 110$ V.*

Solution. (*a*) For this part, refer to Fig. 6.2. It is seen from this figure that circuit turn off time t_c

$$= \frac{2\pi - \beta}{\omega} = \frac{(360 - 210)\,\pi}{180\times 2\pi\times 50} = 8.333\text{ m-sec}$$

From Eq. (6.8), average output voltage

$$V_0 = \frac{\sqrt{2}\cdot 230}{2\pi}\,[\cos 40° - \cos 210°] = 84.477\text{ V}$$

Average load current $\quad I_0 = \frac{V_0}{R} = \frac{84.477}{5} = 16.8954$ A.

(*b*) Fig. 6.4 shows that circuit turn-off time is again 8.333 m-sec. From Eq. (6.18), average load current

$$I_0 = \frac{1}{2\pi\cdot 5}\left[\sqrt{2}\cdot 230\,(\cos 40° - \cos 210°) - 110\,(210 - 40)\frac{\pi}{180}\right] = 6.5064\text{ A.}$$

$\therefore$ Average load voltage, $V_0 = E + I_0R = 110 + 6.5064\times 5 = 149.04$ V.

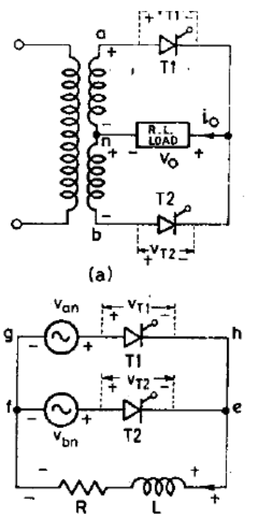


Fig. 6.8. Single-phase full-wave mid-point converter (*a*) circuit diagram (*b*) equivalent circuit

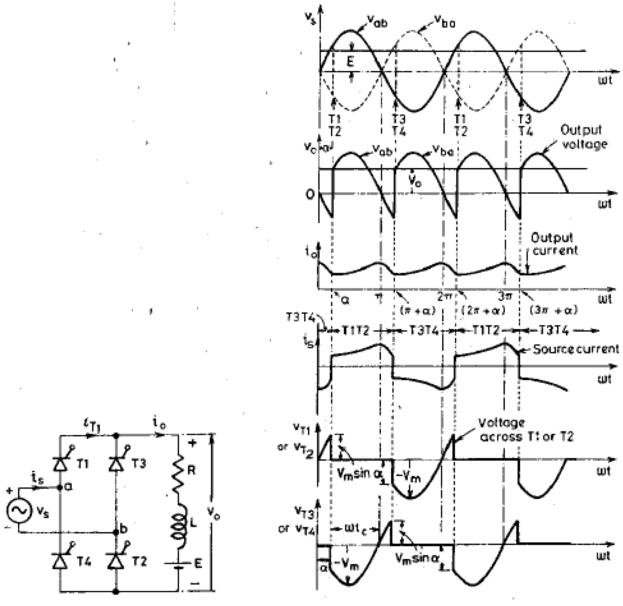


Fig. 6.10. (*a*) Single-phase full converter bridge with RLE load
(*b*) voltage and current waveforms for continuous load current.

Example 6.4. *SCRs with peak forward voltage rating of 1000 V and average on-state current rating of 40 A are used in single-phase mid-point converter and single-phase bridge converter. Find the power that these two converters can handle. Use a factor of safety of 2.5.*

Solution. Maximum voltage across SCR in single-phase mid-point converter is $2V_m$, Fig. 6.8. Therefore, this converter can be designed for a maximum voltage of $\frac{1000}{2 \times 2.5} = 200$ V.

$\therefore$ Maximum average power that mid-point converter can handle

$$= \left(\frac{2\,V_m}{\pi} \cos \alpha \right) I_{TAV} = \frac{2 \times 200}{\pi} \times 40 \, \frac{1}{1000} = 5.093 \text{ kW}$$

SCR in a single-phase bridge converter is subjected to a maximum voltage of V_m, Fig. 6.10. Therefore, maximum voltage for which this converter can be designed is

$$\frac{1000}{2.5} = 400 \text{ V}$$

$\therefore$ Maximum average power rating of bridge converter

$$= \frac{2 \times 400}{1000 \times \pi} \times 40 = 10.186 \text{ kW.}$$

Example 6.19. *A 3-phase full converter bridge is connected to supply voltage of 230 V per phase and a frequency of 50 Hz. The source inductance is 4 mH. The load current on dc side is constant at 20 A. If the load consists of a dc voltage source of 400 V having an internal resistance of 1 Ω, then calculate :*

(a) firing angle delay and

(b) overlap angle in degrees.

Solution. (*a*) Converter output voltage

$$= E + I_0 R = 400 + 20 \times 1 = 420 \text{ V.}$$

From Eq. (6.48),
$$420 = \frac{3\sqrt{6} \cdot 230}{\pi} \cos \alpha - \frac{3(2\pi \times 50)4}{1000 \times \pi} \times 20$$

or
$$\alpha = 34.382°$$

$\therefore$ Firing angle delay is 34.382°

(*b*) From Eq. (6.48),
$$420 = \frac{3\sqrt{6} \times 230}{\pi} \cos (\alpha + \mu) + \frac{3\,(2\pi \times 50)\,4}{1000 \times \pi} \times 20$$

or
$$\alpha + \mu = \cos^{-1} \frac{396 \times \pi}{3\sqrt{6} \times 230} = 42.602°$$

$\therefore$
$$\mu = 42.602 - 34.382 = 8.22°$$

$\therefore$ Overlap angle in degrees = 8.22°.

Example 6.20. *A 3-phase dual converter, operating in the circulating-current mode, has the following data :*

$$i_{cp} = \frac{\sqrt{3}\, V_{ml}}{\omega L}\,[1 - \sin \alpha_1] \qquad \text{...(6.59)}$$

Per phase supply voltage $= 230$ V, $f = 50$ *Hz*, $\alpha_1 = 60°$, *current limiting reactor,* $L = 15$ *mH. Calculate the peak value of circulating current.*

Solution. The peak value of circulating current, for firing angle $\alpha_1 = 60°$, is given by Eq. (6.59).

$$\therefore \qquad i_{cp} = \frac{\sqrt{3}\cdot\sqrt{6}\cdot 230}{2\pi \times 50 \times 15 \times 10^{-3}}\,[1 - \sin 60°] = 27.7425 \text{ A}.$$

6.9. SOME WORKED EXAMPLES

In this article, some typical problems on phase controlled rectifiers are solved.

Example 6.21. *A single-phase full converter is supplied from 230 V, 50 Hz source. The load consists of R = 10 Ω and a large inductance so as to render the load current constant. For a firing angle delay of 30°, determine (a) average output voltage (b) average output current (c) average and rms values of thyristor currents and (d) the power factor.*

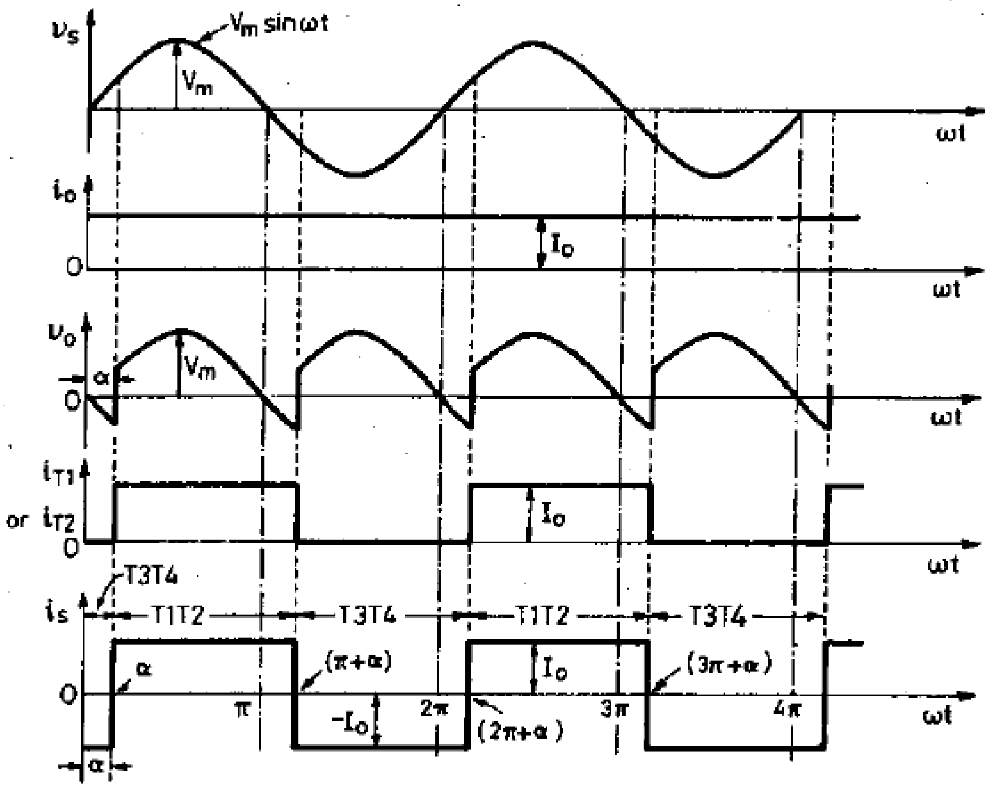


Fig. 6.41. Pertaining to Example 6.21.

Solution. The waveforms for source voltage v_s, load current i_0, load voltage v_0, thyristor current i_{T1} (or i_{T2}) and source current i_s (refer to Fig. 6.10) are drawn in Fig. 6.41.

(*a*) For a single-phase full converter, average output voltage V_0, Eq. (6.28), is given by

$$V_0 = \frac{2V_m}{\pi}\cos\alpha = \frac{2\sqrt{2}\times 230}{\pi}\cos 30° = 179.303\text{ V}$$

(*b*) Average output current, $I_0 = \frac{V_0}{R} = \frac{179.303}{10} = 17.93$ A

(*c*) It is seen from the waveform of thyristor current i_{T1} (or i_{T2}) that its average value is given by

$$I_{T\cdot a} = I_0 \cdot \frac{\pi}{2\pi} = \frac{I_0}{2} = \frac{17.93}{2} = 8.965\text{ A}$$

Rms value of thyristor current is

$$I_{T\cdot r} = \sqrt{I_0^2 \cdot \pi \times \frac{1}{2\pi}} = \frac{I_0}{\sqrt{2}} = \frac{17.93}{\sqrt{2}} = 12.68\text{ A}$$

(*d*) Rms value of source current, $I_s = \sqrt{I_0^2 \cdot \frac{\pi}{\pi}} = I_0 = 17.93$ A

Load power $= V_0 I_0 = 179.3 \times 17.93$ W

Input power $= V_s I_s \cos\phi$

For no loss in the power converter,

$$V_s I_s \cos\phi = V_0 I_0$$

$\therefore$ Power factor, $\cos\phi = \frac{179.3\times 17.93}{230\times 17.93} = 0.7796$ lag

In general, for a 1-phase full converter with ripple free load current as in this example and with no device drops,

$$\text{input power} = \text{load power}$$

or

$$V_s I_s \cos\phi = V_0 I_0$$

$\therefore$ Input

$$pf = \frac{2V_m}{\pi}\cos\alpha \cdot I_0 \times \frac{1}{V_s \cdot I_0}$$

$$= \frac{2\sqrt{2}\,V_s}{\pi}\cos\alpha \cdot \frac{1}{V_s} = \frac{2\sqrt{2}}{\pi}\cos\alpha$$

For this example, input $pf = \frac{2\sqrt{2}}{\pi}\cos 30° = 0.7796$ lag.

Example 6.22. In Example 6.21, if source has an inductance of 1.5 mH, then determine (*a*) average output voltage (*b*) the angle of overlap and (*c*) the power factor.

Solution. (*a*) From Eq. (6.46), average output voltage is

$$V_0 = \frac{2V_m}{\pi}\cos\alpha - \frac{\omega_0 L_s}{\pi} I_0$$

$$= \frac{2\sqrt{2}\times 230}{\pi}\cos 30° - \frac{2\pi\times 50\times 1.5\times 10^{-3}}{\pi}\times 17.93$$

$$= 176.614\text{ V}$$

(*b*) From Eq. (6.44),

$$I_0 = \frac{V_m}{\omega L_s}[\cos\alpha - \cos(\alpha+\mu)]$$

or

$$17.93 = \frac{\sqrt{2}\times 230\times 10^3}{2\pi\times 50\times 1.5}[\cos 30 - \cos(30+\mu)]$$

Its simplification gives overlap angle,

$$\mu = 32.855 - 30 = 2.855°$$

(*c*) Power factor

$$= \frac{V_0 I_0}{V_s I_s} = \frac{176.614\times 17.93}{230\times 17.93} = 0.7679\text{ lag.}$$

Example 6.23. *A 3-phase fully-controlled bridge converter with 415 V supply, 0.04 Ω resistance per phase and 0.25 Ω reactance per phase is operating in the inverting mode at a firing advance angle of 35°. Calculate the mean generator voltage when the current is level at 80 A. The thyristor voltage drop is 1.5 V.* [I.A.S., 1994]

Solution. Power circuit diagram of a 3-phase full converter reveals that source resistance r_s will lead to a voltage drop of $2 I_0 r_s$. Two thyristors, one from positive group and another from negative group, conduct together, therefore there will be a constant thyristor voltage drop of $2 V_T$. The source reactance leads to overlap and its effect is taken care of by Eq. (6.48). By taking into consideration these voltage drops, the average, or mean, output voltage V_0 in a 3-phase full converter is given by

$$V_0 = \frac{3 V_{ml}}{\pi} \cos \alpha - 2 I_0 r_s - 2 V_T - \frac{3 \omega L_s}{\pi} I_0$$

In case 3-phase full converter is working in the inverting mode, then the load emf E or V_g (mean generator voltage in this example) can be obtained from the relation :

$$\frac{3 V_{ml}}{\pi} \cos \alpha = -E + 2 I_0 r_s + 2V_T + \frac{3\omega L_s}{\pi} I_0$$

$$\therefore \quad \frac{3\sqrt{2} \times 415}{\pi} \cos (180 - 35) = -E + 2 \times 80 \times 0.04 + 2 \times 1.5 + \frac{3 \times 0.25}{\pi} \times 80$$

or $$E = 459.022 + 6.4 + 3 + 19.1 = 487.522 \text{ V}$$

$\therefore$ Mean generator voltage $= E = 487.522$ V.

Example 6.24. *In Example 6.23, in case load consists of RLE, with R = 0.2 Ω, inductance large enough to make load current level at 80 A and emf E, then find the mean value of E for (i) firing angle of 35° and (ii) firing advance angle of 35°.*

Solution. (*i*) When firing angle is 35°, 3-phase full converter is in the rectifying mode. Therefore, from Example 6.23,

$$V_0 = E + I_0 R = \frac{3 V_{ml}}{\pi} \cos \alpha - 2 I_0 r_s - 2V_T - \frac{3 \omega L_s}{\pi} I_0$$

or $$\frac{3 V_{ml}}{\pi} \cos \alpha = E + I_0 R + 2 I_0 r_s + 2V_T + \frac{3 \omega L_s}{\pi} I_0$$

$$\therefore \quad \frac{3\sqrt{2} \times 415}{\pi} \cos 35° = E + 80 \times 0.2 + 2 \times 80 \times 0.04 + 2 \times 1.5 + \frac{3 \times 0.25}{\pi} \times 80$$

or $$E = 414.522 \text{ V}.$$

(*ii*) For firing advance angle of 35°, the full converter is in the inverting mode. From Example 6.23,

$$\frac{3 V_{ml}}{\pi} \cos \alpha = -E + I_0 R + 2 I_0 r_s + 2V_T + \frac{3 \omega L_s}{\pi} I_0$$

or $$E = 459.22 + 16 + 6.4 + 3 + 19.1 = 503.522 \text{ V}.$$

Example 6.25. *Fig. 6.42 (a) shows a battery charging circuit using SCRs. The input voltage from neutral to any line is 230 V (rms) and firing angle for thyristors is 30°. Find the average current flowing through the battery.*

Derive the expression used.

Solution. For the parameters given in this example, the waveform of load current is drawn in Fig. 6.42 (*b*). When thyristor A_1 is gated at $\alpha = 30°$, it begins conduction at $\omega t = 30 + \alpha = 60°$. After its turn-on, when $V_{mp} \sin \beta = 150$ V, thyristor A_1 gets turned off at $\omega t = \beta$. Note that here β is more than 90° as is seen from Fig. 6.42 (*b*). Equation governing the conduction period in Fig. 6.42 is

$$V_m \sin \omega t - E = i_0 R$$

Here $\sqrt{2} \cdot 230 \sin \beta = 150$ V. This gives $\beta = 27.47°$ or $152.53°$. As $\beta > 90°$, therefore $\beta = 152.53°$. This gives the value of average battery current I_0 as under :

$$I_0 = \frac{3}{2\pi \times 5}\left[\sqrt{2} \cdot 230 (\cos 60° - \cos 152.53°) - 150\left(152.53 - 30 - 30) \times \frac{\pi}{180}\right)\right]$$

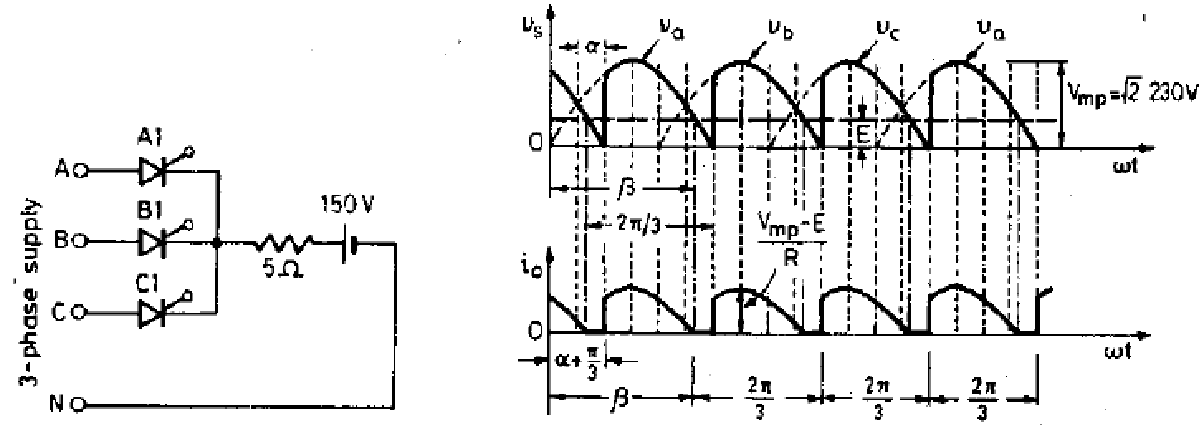
$$= \frac{3}{10\pi} [208.91928] = 19.95 \text{ A}.$$

between the limits of $\left(\frac{\pi}{6}+\alpha\right)$ and $\beta > 90°$. Thus, average output current is given by

$$I_0 = \frac{3}{2\pi}\int_{\alpha+\frac{\pi}{6}}^{\beta} \frac{V_{mp}\sin\omega t - E}{R}\cdot d(\omega t)$$

$$= \frac{3}{2\pi R}\left[V_{mp}\left|\cos\omega t\right|_{\beta}^{\alpha+\pi/6} - E(\beta-\alpha-30°)\right]$$

$$= \frac{3}{2\pi R}\left[V_{mp}\left[\cos(\alpha+30)-\cos\beta\right] - E(\beta-\alpha-30°)\right]$$



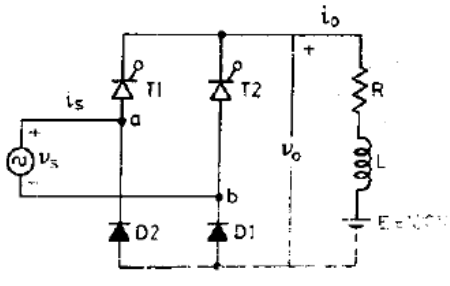
(a) (b)

Fig. 6.42. (a) 3-phase half-wave battery charging circuit and (b) its relevant waveforms, Example 6.25.

Example 6.26. *A single-phase semiconverter, using two thyristors and two diodes as shown in Fig. 6.43 (a), is supplied from 230 V, 50 Hz source. The load consists of $R = 10\ \Omega$, $E = 100$ V and a large inductance so as to render the load current level. For a firing delay angle of 30°, determine (a) average output voltage (b) average output current (c) average and rms values of thyristor currents (d) average and rms values of diode currents (e) input power factor and (f) circuit turn-off time.*

Solution. The waveforms for voltages and currents are sketched in Fig. 6.43 (b).

When forward-biased thyristor T1 is triggered at firing angle α, T1D2 start conducting the constant current I_0. Soon after $\omega t = \pi$, as supply voltage tends to go negative, diode D2 gets forward biased through D1. Therefore, from $\omega t = \pi$, load current begins to freewheel through T1D2. Thyristor T2 gets forward biased after $\omega t = \pi$. At $\omega t = \pi + \alpha$, when T2 is turned



(a)

Fig. 6.43. Pertaining to Example 6.26.

on, current I_0 begins to flow through T2D2 as shown. Soon after $\omega t = 2\pi$, as supply voltage tends to go positive, diode D1 gets forward biased through D2. As a result, current flows through T2D1 till T1 is turned on at $\omega t = 2\pi + \alpha$ and so on.

The waveform of output voltage v_0 shows that average value of output voltage is given by

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

(a) Average value of output voltage

$$V_0 = \frac{\sqrt{2}\cdot 230}{\pi}(1+\cos 30°) = 193.172 \text{ V}$$

(b)
$$V_0 = E + I_0 R$$
$$193.172 = 100 + I_0 \times 10$$

Average value of output current

$$I_0 = \frac{93.172}{10} = 9.32 \text{ A}$$

(c) It is seen from the waveforms of thyristor current i_{T1} and diode current i_{D1} that both conduct for π radians for any value of firing delay angle. On account of this, the circuit of Fig. 6.43 (a) is sometimes called *symmetrical configuration* for a single-phase semiconverter.

Average value of thyristor current

$$I_{TA} = I_0 \frac{\pi}{2\pi} = \frac{I_0}{2} = \frac{9.32}{2} = 4.66 \text{ A}$$

Rms value of thyristor current

$$I_{Tr} = \sqrt{I_0^2 \frac{\pi}{2\pi}} = \frac{I_0}{\sqrt{2}} = \frac{9.32}{\sqrt{2}} = 6.591 \text{ A}$$

(d) Average and rms value of diode currents are the same as those for a thyristor as discussed in (c) above.

∴ Average value of diode current = 4.66 A

Rms value of diode current = 6.591 A

(e) Rms value of source current

$$I_{sr} = \sqrt{I_0^2 \frac{\pi-\alpha}{\pi}} = I_0\sqrt{\frac{\pi-\alpha}{\pi}}$$
$$= 9.32\sqrt{\frac{\pi-(\pi/6)}{\pi}} = 8.508 \text{ A}$$

Rms value of load current $I_{or} = I_0 = 9.32$ A.

Power delivered to load $= E\,I_0 + I_{or}^2 \times R = 100 \times 9.32 + 9.32^2 \times 10$

Also $230 \times 8.508 \times \cos\phi =$ Power delivered to load

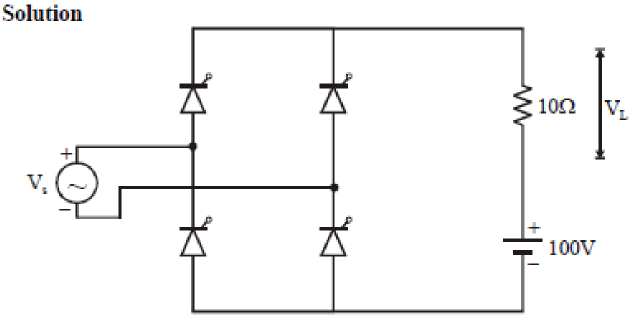
∴ Input $pf = \dfrac{932 + 9.32^2 \times 10}{230 \times 8.508} = 0.9202$ lag

(f) It is seen from the waveform of v_{T1} that circuit turn-off time is

$$t_c = \frac{\pi-\alpha}{\omega} = \frac{\pi - \frac{\pi}{6}}{2\pi\times 50} \times 1000 \text{ ms} = 8.33 \text{ ms.}$$

7. The figure shows a battery charging circuit using SCRs. The input voltage to the circuit is 230 V RMS. Find the charging current for a firing angle of 45^0. If any one of the SCR is open circuited, what is the charging current?

Solution



With the usual notations

$$V_S = V_m \sin \omega t$$

$$V_S = \sqrt{2} \times 230 \sin \omega t$$

$V_m \sin \gamma = V_B$, the battery voltage

$$\sqrt{2} \times 230 \sin \gamma = 100$$

Therefore $\gamma = \sin^{-1}\left(\dfrac{100}{\sqrt{2} \times 230}\right)$

$\gamma = 17.9^0$ or 0.312 radians

$$\beta = (\pi - \gamma) = (\pi - 0.312)$$

$\beta = 2.829$ radians

Average value of voltage across load resistance

$$= \frac{2}{2\pi}\left[\int_{\alpha}^{\beta} (V_m \sin \omega t - V_B)\, d(\omega t)\right]$$

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

$$= \frac{1}{\pi}\left[V_m(\cos \alpha - \cos \beta) - V_B(\beta - \alpha)\right]$$

$$= \frac{1}{\pi}\left[230 \times \sqrt{2}\left(\cos\frac{\pi}{4} - \cos 2.829\right) - 100\left(2.829 - \frac{\pi}{4}\right)\right]$$

$$= \frac{1}{\pi}\left[230 \times \sqrt{2}\,(0.707 + 0.9517) - 204.36\right]$$

$= 106.68$ Volts

Charging current $= \dfrac{\text{Voltage across resistance}}{R}$

$= \dfrac{106.68}{10} = 10.668$ Amps

If one of the SCRs is open circuited, the circuit behaves like a half wave rectifier. The average voltage across the resistance and the charging current will be half of that of a full wave rectifier.

Therefore Charging Current $= \dfrac{10.668}{2} = 5.334$ Amps

There are two different modes of operation of a three phase dual converter system.

- Circulating current free (non circulating) mode of operation
- Circulating current mode of operation

CIRCULATING CURRENT FREE (NON-CIRCULATING) MODE OF OPERATION

In this mode of operation only one converter is switched on at a time when the converter number 1 is switched on and the gate signals are applied to the thyristors the average output voltage and the average load current are controlled by adjusting the trigger angle α_1 and the gating signals of converter 1 thyristors.

The load current flows in the downward direction giving a positive average load current when the converter 1 is switched on. For $\alpha_1 < 90^0$ the converter 1 operates in the rectification mode V_{dc} is positive, I_{dc} is positive and hence the average load power P_{dc} is positive.

The converter 1 converts the input ac supply and feeds a dc power to the load. Power flows from the ac supply to the load during the rectification mode. When the trigger angle α_1 is increased above 90^0, V_{dc} becomes negative where as I_{dc} is positive because the thyristors of converter 1 conduct in only one direction and reversal of load current through thyristors of converter 1 is not possible.

For $\alpha_1 > 90^0$ converter 1 operates in the inversion mode & the load energy is supplied back to the ac supply. The thyristors are switched-off when the load current decreases to zero & after a short delay time of about 10 to 20 milliseconds, the converter 2 can be switched on by releasing the gate control signals to the thyristors of converter 2.

We obtain a reverse or negative load current when the converter 2 is switched ON. The average or dc output voltage and the average load current are controlled by adjusting the trigger angle α_2 of the gate trigger pulses supplied to the thyristors of converter 2. When α_2 is less than 90^0, converter 2 operates in the rectification mode and converts the input ac supply in to dc output power which is fed to the load.

When α_2 is less than 90^0 for converter 2, V_{dc} is negative & I_{dc} is negative, converter 2 operates as a controlled rectifier & power flows from the ac source to the load circuit. When α_2 is increased above 90^0, the converter 2 operates in the inversion mode with V_{dc} positive and I_{dc} negative and hence P_{dc} is negative, which means that power flows from the load circuit to the input ac supply. The power flow from the load circuit to the input ac source is possible if the load circuit has a dc source of appropriate polarity. When the load current falls to zero the thyristors of converter 2 turn-off and the converter 2 can be turned off.

CIRCULATING CURRENT MODE OF OPERATION

Both the converters are switched on at the same time in the mode of operation. One converter operates in the rectification mode while the other operates in the inversion mode. Trigger angles α_1 & α_2 are adjusted such that $(\alpha_1 + \alpha_2) = 180^0$

When $\alpha_1 < 90^0$, converter 1 operates as a controlled rectifier. When α_2 is made greater than 90^0, converter 2 operates in the inversion mode. V_{dc}, I_{dc}, P_{dc} are positive.

When $\alpha_2 < 90^0$, converter 2 operates as a controlled rectifier. When α_1 is made greater than 90^0, converter 1 operates as an Inverter. V_{dc} and I_{dc} are negative while P_{dc} is positive.

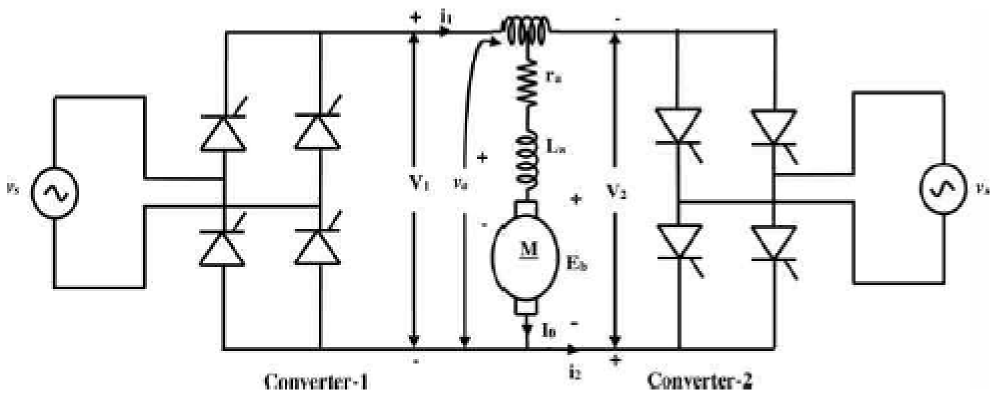


FIGURE 5.23
Power circuit of a dual converter with single-phase converters.

https://www.engineeringbookspdf.com/elementary-concepts-of-power-electronic-drives-by-k-sundareswaran/

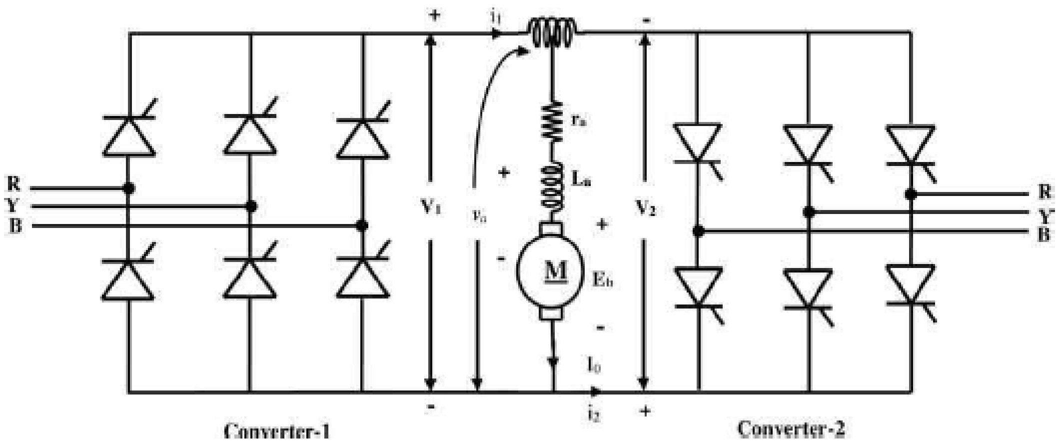


FIGURE 5.24
Power circuit of a dual converter for three-phase operation.

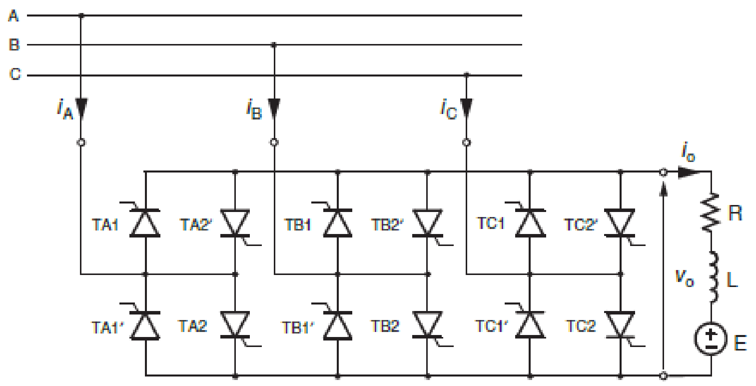


Figure 4.32 Six-pulse circulating current-free dual converter.

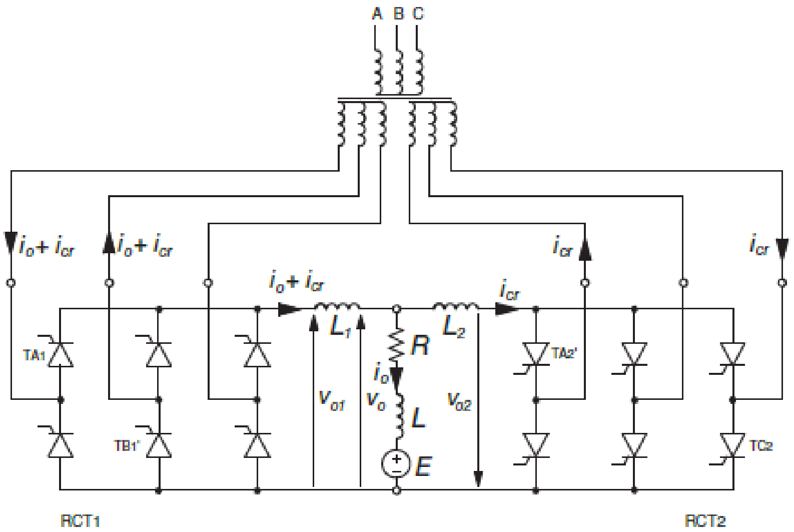


Figure 4.33 Six-pulse circulating current-conducting dual converter supplied from two separate ac sources.

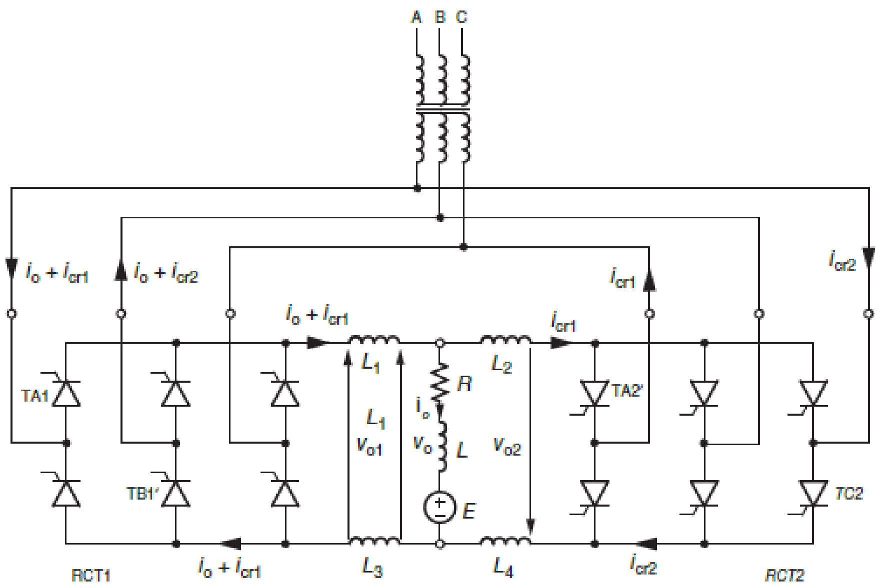


Figure 4.37 Six-pulse circulating current-conducting dual converter supplied from a single ac source.

An extension to four-quadrant operation of controlled rectifiers is possible by installing an electromechanical cross-switch at the output, which allows for a negative load current. Dual converters represent a more convenient and robust solution. A dual converter consists of two rectifiers connected in antiparallel. Circulating

current-free dual converters are simpler but operationally inferior to the circulating current-conducting ones.

A reactor coil is inserted between the converters to avoid short circuit of converter voltages. Converter 1 provides first- and fourth-quadrant operation, while converter 2 is used to operate the motor in the second and third quadrants. The output voltage and current

of converter 1 are indicated as V_1 and I_1, respectively; notations V_2 and I_2 are used for converter 2. For the circuit topology, the average value and polarity of V_1 and V_2 should be the same. For the indicated polarity of V_1 and V_2, we can write,

$$V_1 = -V_2$$
$$V_1 + V_2 = 0$$

If α_1 and α_2 represent firing angles of converter 1 and converter 2, respectively, then

$$V_1 = K_1 \cos\alpha_1 \text{ and } V_2 = K_1 \cos\alpha_2$$

In the above, $K_1 = \frac{2V_m}{\pi}$ for single-phase converters, and $K_1 = \frac{3V_{Lm}}{\pi}$ for three-phase converters.

$$\therefore K_1 \cos\alpha_1 + K_1 \cos\alpha_2 = 0$$
$$\cos\alpha_1 + \cos\alpha_2 = 0$$
$$2\cos\left(\frac{\alpha_1+\alpha_2}{2}\right)\cos\left(\frac{\alpha_1-\alpha_2}{2}\right) = 0$$

The solution of the above equation yields

$$\frac{\alpha_1+\alpha_2}{2} = \frac{\pi}{2} \quad \text{or} \quad \frac{\alpha_1-\alpha_2}{2} = \frac{\pi}{2}$$
$$\alpha_1 + \alpha_2 = \pi \quad \text{or} \quad \alpha_1 - \alpha_2 = \pi$$
$$\alpha_1 = \pi - \alpha_2 \quad \text{or} \quad \alpha_1 = \pi + \alpha_2$$

Because the maximum value of α_1 or α_2 is π, the feasible solution is

$$\alpha_1 = \pi - \alpha_2 \tag{5.41}$$

3.19 SPEED REVERSAL AND REGENERATIVE BRAKING OF SEDC MOTOR DRIVES

As shown in equation (3.23), fully controlled converters have average output voltage give by

$V_{av} = (p\ E_m/\pi)\sin(\pi/p)\cos\alpha$

This means that the increasing firing angle delay will reverse the output voltage at $\alpha > 90°$ (see Fig. 3.32). The ability to reverse the converter voltage gives a means for speed reversal of the motor.

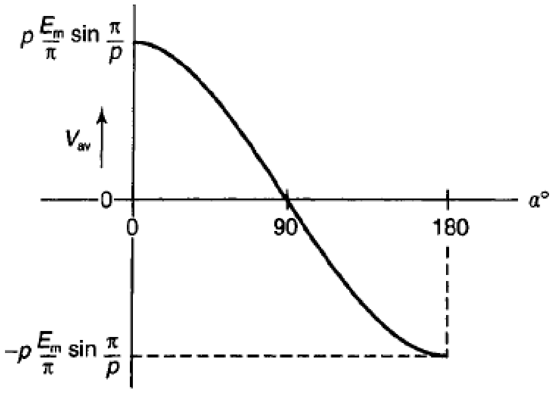


Figure 3.32

The d.c. separately excited motor requires either armature current or field current reversal to drive the motor in the reverse direction. In practice, field inductance is much larger than armature inductance and so field reversal is slower. The armature current can be reversed using either a contactor or two anti-parallel fully controlled bridges, as shown in Figs 3.33(a) and (b). Only one bridge is operated at any one time; the other bridge is inhibited.

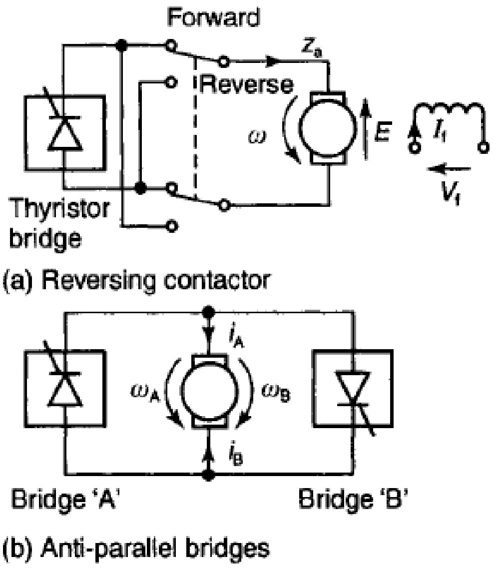
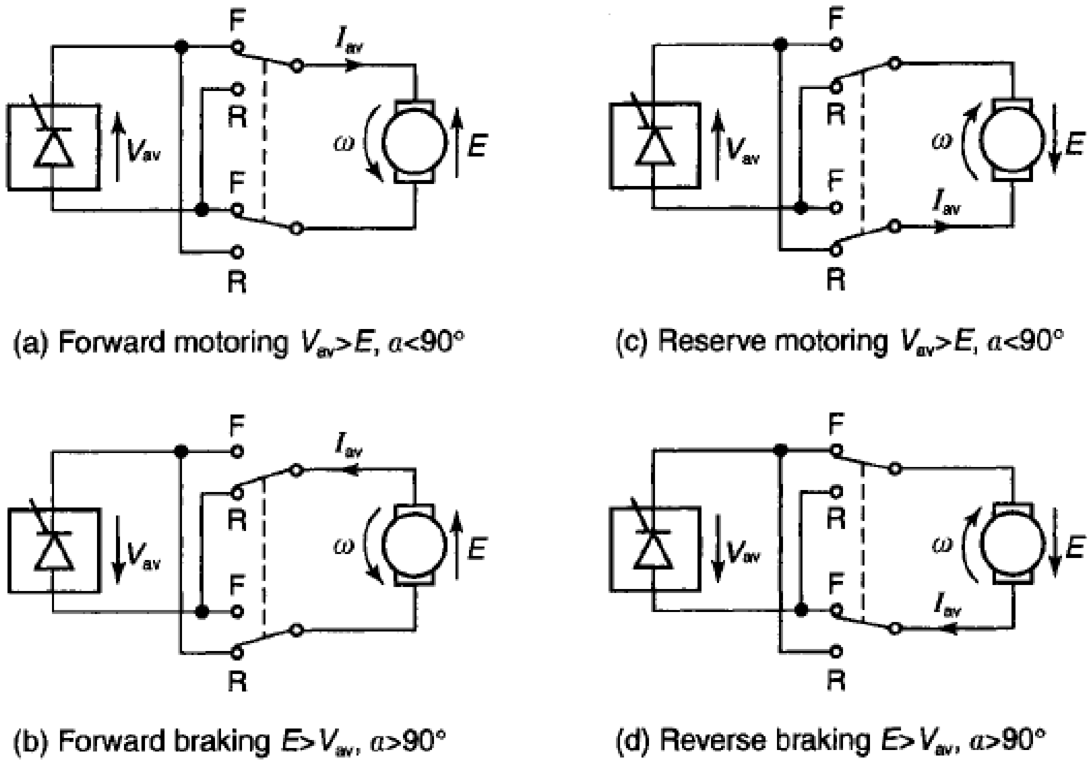


Figure 3.33

For reversal of speed and regenerative braking, the sequence of operations is shown in Figs 3.34(a)–(d). Assume the drive is in the forward motoring condition as shown in Fig. 3.34(a), and the requirement is to reverse the direction of rotation. The firing angle is increased to reduce the armature current to zero. The contactor can then be safely operated as indicated in Fig. 3.34(b). The firing angle is further increased until the generated voltage exceeds the converter voltage; regenerative braking comes into operation; energy is extracted from the armature and fed back to the supply; the motor brakes and generated voltage and speed both fall to zero. The armature voltage is brought back to the normal rectifying mode by phase angle control and speed builds up in the reverse direction to the required value, as shown in Fig. 3.34(c).

To return to the forward direction of speed, the firing angle is increased until armature current is again zero. The contactor is operated as in Fig. 3.34(d), generated voltage exceeds converter voltage, regenerative braking occurs, and armature speed falls to zero. As shown in Fig. 3.34(a), speed is built up in the forward direction by phase angle control.



(a) Forward motoring $V_{av}>E$, $\alpha<90°$

(c) Reserve motoring $V_{av}>E$, $\alpha<90°$

(b) Forward braking $E>V_{av}$, $\alpha>90°$

(d) Reverse braking $E>V_{av}$, $\alpha>90°$

Figure 3.34

Example 3.11

A separately excited d.c. motor is driven from a three-phase fully controlled converter with a contactor for speed reversal. The line voltage is 440 V at 50 Hz. The motor armature resistance is 0.12 Ω and the armature voltage constant k_v = 2.0 V/rad/s at rated field current.

(a) Determine the firing angle delay necessary, at rated field current, for an armature current of 40 A at a speed of 1500 rev/min.

(b) The contactor is operated after delay angle control is used to bring the armature current to zero, at the start of the sequence for speed reversal. Assuming that initially the generated armature voltage remains constant, what delay angle is required to set the armature current back to 40 A for regenerative braking and what power is available for regeneration?

Solution

(a) $E = \omega k_v$

$= (1500 \times 2\pi/60)2.0 = 314.2\text{V}$

$V_{av} = E + I_{av}R_A$

$= 314.2 + (40 \times 0.12) = 319\text{V}$

$V_{av} = (3E_{lm}/\pi) \cos \alpha$

$= (3 \times 440 \sqrt{2}/\pi) \cos \alpha = 594 \cos \alpha$

$\therefore 594 \cos \alpha = 319$

$\cos \alpha = 319/594 = 0.537$

$\alpha = 57.5°$

(b) $E - I_{av}R_a = -V_{av}$

$314.2 - (40 \times 0.12) = -V_{av} = -594 \cos \alpha$

$594 \cos \alpha = -309.4$

$\cos \alpha = -0.52$

$\alpha = 121.3°$

Regenerative braking power, P, is given by

$P = V_{av} I_{av} = 309.4 \times 40 = 12.4\text{kW}$

Braking torque $= P/\omega = 12400/(1500 \times 2\pi/60) = 79$ Nm

7. A three-phase, full-wave converter with an armature contactor, or two anti-parallel bridges. Assume the use of an armature contactor. Firing angle is increased to bring armature current to zero, contactor is operated and firing angle increased, converter voltage is reversed, armature voltage exceeds converter voltage and energy is returned to the supply. Speed falls to zero as motor brakes. Firing angle is now reduced to below 90° for rectifier operation, and speed builds up in the reverse direction.

7. $V_{av} = (3\sqrt{3}\, E_{pm}/2\pi)\cos\alpha = (3\sqrt{2} \times 415/2\pi)\cos\alpha = 280.1 \cos\alpha$
$I_{av} = T/k_v = 400/0.8 = 500\text{A}$
$E = k_v\, \omega = 0.8 \times 1000 \times 2\pi/60 = 83.8\text{V}$
$V_{av} = E + I_{av}R$, i.e. $280.1 \cos\alpha = 83.8 + (500 \times 0.02) = 93.8$
$\therefore \cos\alpha = 93.8/280.1 = 0.335$
$\alpha = 70.4°$

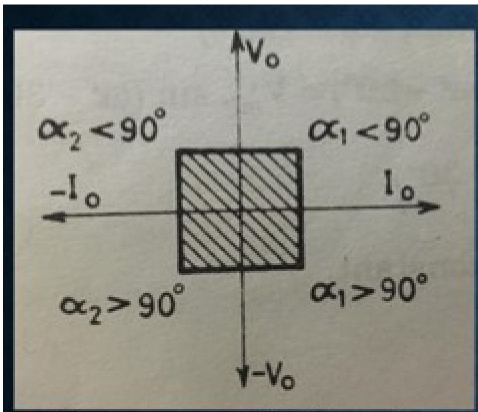
TEK FAZ- PARALEL ÇİFT DÖNÜŞTÜRÜCÜ

Şimdiye kadar gösterilen dönüştürücülerde mevcut yön, tristörün tek yönlü iletken özelliğinden dolayı kabul edilir. Yarı kontrollü dönüştürücüde hem V_0 (yük voltajı) hem de I_0 (yük akımı) geri dönüşümlü değildir. Bu yüzden dönüştürücünün çalışması sadece yalnızca pozitif yük voltajı ve yükün pozitif akımına sınırlandırılır. Bu durumda sadece tek bölgede çalışmak mümkündür. Bu tür dönüştürücülere tek bölgeli dönüştürücüler denir.

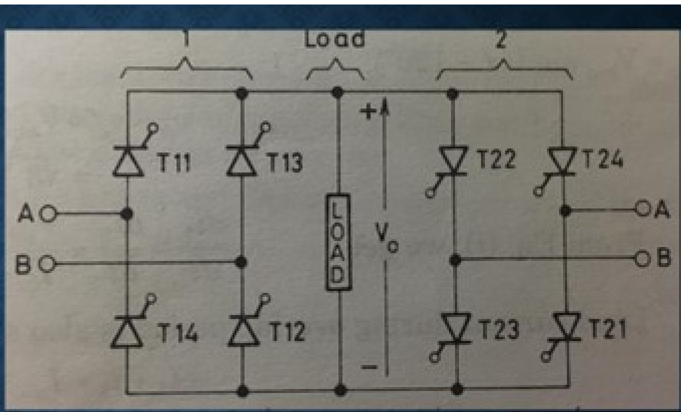
Tam kontrollü bir dönüştürücüde ise uygun bir dönüştürücü kontrolü ile yük voltajı rezerve edilebilir ve yükten güç akışı mümkündür. Bununla birlikte akımın yönü aynı kalır. Böylece, dönüştürücü I ve IV bölgede çalıştırılabilir. Bu tür dönüştürücülere iki bölgeli dönüştürücü denir.

İki tam kontrollü dönüştürücü arka arkaya bağlanırsa, bu düzenlemeye çift dönüştürücü denir. Böylece paralel çift dönüştürücüler, Şekil 1'de gösterildiği gibi V_0-I_0 düzleminin dört çeyreğinin tamamında da çalışabilmektedir. Bu tür dönüştürücüler iki modda çalışır;

- Dolaşımsız akım tipi
- Dolaşımdaki akım tipi



Şekil 1. Dönüştürücünün dört bölgesi çalışması



Şekil 2. Çift Dönüştürücü Devresi

Dolaşımsız Akım Tipi

Bu durumda, bir seferde sadece bir dönüştürücü çalışır, çünkü her köprü bir tam dönüştürücüdür. Dönüştürücü-I , I ve IV bölgede bölgede çalışır. Yük akımının yönü tersine çevrildiğinde, dönüştürücü-I'in kapı sinyalleri kesilerek tristörler kesime götürülür. Yük akımı sıfıra düştüğünde yaklaşık 10-20 ms'lik bir boşluk veya gecikme süresinden sonra, dönüştürücü-II'nin tristörlerine kapı sinyalleri verilerek tristörler iletime geçer., böylece yük akımının yönü tersine döner. Ortalama çıkış gerilimi, tam kontrollü dönüştürücüler ile aynıdır.

$$V_{o1} = \frac{2V_m}{\pi} \cos a_1$$

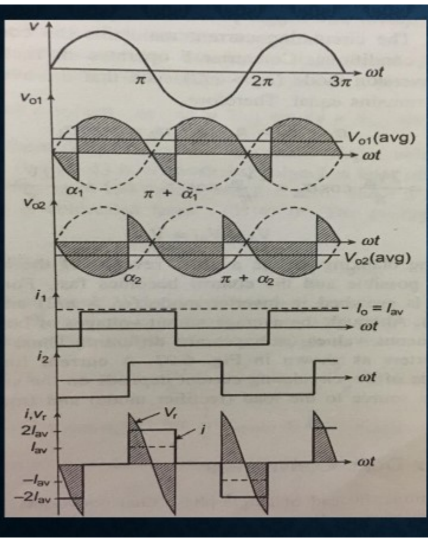
$$V_{o2} = \frac{2V_m}{\pi} \cos a_2$$

Dolaşımdaki Akım Tipi

Çıkış geriliminin ve akımının hızlı bir şekilde değiştirilmesi gerektiğinden (boşluk süresi olmadan), sirkülasyon akımı kontrol tipi kullanılır. Bu modda her iki köprü de aynı anda hareket eder. Her iki dönüştürücüde her zaman iletime açık olduğundan, işlemin bir bölgeden diğerine değiştirilmesi oldukça hızlıdır. Kapı sinyalleri, yük akımının mevcut olup olmadığına bakılmaksızın tüm tristörlere verilir. Sirkülasyon akımı, yük koşullarından bağımsız olarak her iki dönüştürücünün iletimini korur. Dönüştürücü-I ($a_1 < \pi/2$) aralığında doğrultucu modunda çalışır ve dönüştürücü-II ($a_2 > \pi/2$) aralığında inverter modunda çalışır. Öyle ki her dönüştürücünün yük boyunca ortalama çıkış gerilimi eşit kalır. Bu nedenle,

$$a_1 + a_2 = \pi \quad or \quad a_2 = \pi - a_1 \qquad V_{o2} = \frac{2V_m}{\pi}\cos a_2 = \frac{2V_m}{\pi}\cos(\pi - a_1) = -\frac{2V_m}{\pi}\cos a_1$$

$$i_r = \frac{2V_m}{\omega L}(\cos\omega t - \cos a_1) \qquad V_o = V_{o1} = V_{o2}$$



Boşluk periyodunun olmaması nedeniyle, yük voltajının ve yük akımının hızlı bir şekilde ters çevrilmesi mümkündür ve kontrol hızlı bir şekilde gerçekleşir. Akım yönünü ters çevirmek için, dönüştürücü-I inverter modunda ($a_1 > \pi/2$) ve dönüştürücü-II doğrultucu modunda ($a_2 < \pi/2$) değiştirilir. Her iki dönüştürücünün ortalama çıkış voltajları her zaman eşit olmasına rağmen anlık voltaj değerleri farklıdır. Böylece, iki dönüştürücü arasında bir dolaşım akımı akmaktadır. Bu yüzden bir akım sınırlayıcı reaktör bağlanmaktadır. Dolaşım akımının büyüklüğü anahtarlama açısına bağlıdır. Herhangi bir zamanda, kaynaktan yüke ve yükten kaynağa güç akışı mümkündür.

Örnek 1

Tek fazlı bir çift dönüştürücü 230 V, 50 Hz tek fazlı sistem ile beslenmektedir. Dönüştürücü 15 ohm büyüklüğünde bir yükü beslemektedir. Dönüştürücülerin tetikleme açıları $a_1 = 60$ ve $a_2 = 120$'dir. Endüktans 50 mH dir. Dönüştürücü-I'in tepe akımının değerini ve sirkülasyon akımının tepe değerini bulunuz.

ÖRNEK 1

$V_m = \sqrt{2} \cdot 230 = 325{,}2\ V \qquad a_1 = 60° \quad a_2 = 120° \quad \omega = 100\pi$

$\omega L = 100\pi \cdot (50 \cdot 10^{-3}) = 15{,}71\ ohm$

$i_r = \frac{2 \cdot 325{,}2}{15{,}71}(\cos\omega t - \cos 60°)$

Sirkülasyon akımının tepe değeri = $i_r = \frac{2 \cdot 325{,}2}{15{,}71}(1 - 0{,}5) = 20{,}7\ A$

Yük akımının tepe değeri = $\frac{V_m}{R} = \frac{325{,}2\ V}{15\ ohm} = 21{,}68\ A$

Dönüştürücü I'in tepe akımı = yük akımının tepe değeri + sirkülasyon akımının tepe değeri

Dönüştürücü I'in tepe akımı $= 21{,}68\ A + 20{,}7\ A = 42{,}38\ A$

Örnek 2

Tek fazlı sirkülasyon akımı modunda çalışan çift dönüştürücü 230 V, tek fazlı 50 Hz AC kaynak ile besleniyor. Dönüştürücülerin tetikleme açıları $a_1 = 30$ ve $a_2 = 150$'dir. Yük direnci 10 ohm'dur. Tepe sirkülasyon akımı 10.2 A ise;

a) Akım sınırlama reaktörünün endüktansını,

b) Dönüştürücü-I'in tepe akımını bulunuz.

<u>ÖRNEK 2</u>

$V_m = \sqrt{2} \cdot 230 = 325{,}2\ V \quad a_1 = 30° \quad a_2 = 150° \quad \omega = 100\pi$

$i_r = \frac{2 \cdot 325{,}2}{100\pi \cdot L}(\cos \omega t - \cos 30°) = 10{,}2\ A \quad L = 0{,}0272\ H$

Yük akımının tepe değeri $= \frac{325{,}2\ V}{10} = 32{,}52\ A$

Dönüştürücü I'in tepe akımı $= 32{,}52\ A + 10{,}2\ A = 42{,}72\ A$

Örnek 3

Tek fazlı sirkülasyon akım modunda çalışan çift dönüştürücü 230 V, tek fazlı 50 Hz AC kaynak ile besleniyor. Yük tamamen dirençten oluşmaktadır. Dönüştürücü-I'in tepe akımı 39.7 A'dir. Dönüştürücülerin tetikleme açıları $a_1 = 45$ ve $a_2 = 135$'dir. Tepe sirkülasyon akımı 11.5 A ise;

a) Akım sınırlama reaktörünün endüktansını,

b) Yük direncini bulunuz.

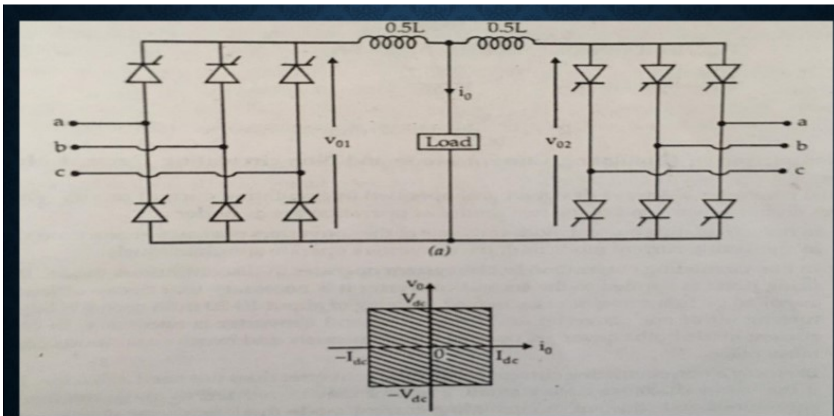
<u>ÖRNEK 3</u>

$V_m = \sqrt{2} \cdot 230 = 325{,}2\ V \quad a_1 = 45° \quad a_2 = 135° \quad \omega = 100\pi$

$i_r = \frac{2 \cdot 325{,}2}{100\pi \cdot L}(\cos \omega t - \cos 45°) = 11{,}5\ A \quad L = 0{,}0542\ H$

Yük akımının tepe değeri $= 39{,}7\ A - 11{,}5\ A = 28{,}2\ A = \frac{V_m}{R} = \frac{325{,}2}{R}$

$R = 11{,}532\ ohm$



Şekil 3. Üç fazlı Çift Dönüştürücü Devresi ve Dört Bölgeli Çalışma Bölgesi

ÜÇ FAZLI ÇİFT DÖNÜŞTÜRÜCÜLER

Yüksek güç uygulamaları için, tek fazlı çift dönüştürücüler yerine, üç fazlı çift dönüştürücüler kullanılır. Çift dönüştürücü olarak performansı, tek fazlı karşılığı ile aynıdır. Bununla birlikte düşük THD, dengeli üç fazlı giriş hattı akımı vb. gibi ek faydaları mevcuttur. Üç fazlı çift dönüştürücüler, yaklaşık 2000 kW'a kadar olan güçlerdeki değişken hızlı sürücüler için oldukça uygundur. Anti-paralel bağlı iki adet üç fazlı tam kontrollü köprü dönüştürücüden oluşur. Dolaşım akımı akışını sınırlamak için reaktör (L) Şekil 3'te gösterildiği gibi bağlanır. Dolaşan akım yük boyunca akmaz. Sirkülasyon akım modunda her iki dönüştürücü aynı anda çalışabilir, böylece Şekil 3'te gösterildiği gibi dört bölgede de çalışır. Bir dönüştürücü doğrultucu modda çalışırken diğeri inverter modunda çalışmaktadır. İki dönüştürücünün tetikleme açıları a_1 ve a_2 ise, $a_1 + a_2 = \pi$ olacak şekilde çalışır.

$$V_r = 3V_m \cos(at - 30°)$$

$$i_r = \frac{3V_m}{\omega L}[(\sin \omega t - 30°) - \sin a_1]$$

Örnek 4

3 fazlı bir çift dönüştürücü, 400 V 50 Hz 3 fazlı bir kaynak ile besleniyor. Akım sınırlama reaktörünün endüktansı 60 mH'dir. Sirkülasyon akımını $\omega t = 0°, 30°\ ve\ 90°$ için bulunuz. a_1 açısının sıfır derece olduğunu varsayın. Ayrıca maksimum sirkülasyon akımının değerini bulunuz.

ÖRNEK 4

$$V_m = \frac{400\sqrt{2}}{\sqrt{3}} = 326{,}56\ V$$

$$\omega L = 2\pi \cdot 50 \cdot (60 \cdot 10^{-3}) = 18{,}85\ ohm$$

$$i_r = \frac{3 \cdot V_m}{\omega \cdot L}(\sin(\omega t - 30°) - \sin a_1)$$

$\boldsymbol{\omega t = 0°\ ve\ a_1 = 0°\ için}$;

$$i_r = \frac{3 \cdot 326{,}56}{18{,}85}(\sin(0° - 30°) - \sin 0°) = -25{,}987\ A$$

$\boldsymbol{\omega t = 30°\ ve\ a_1 = 0°\ için}$;

$$i_r = \frac{3 \cdot 326{,}56}{18{,}85}(\sin(30° - 30°) - \sin 0°) = 0\ A$$

$\boldsymbol{\omega t = 90°\ ve\ a_1 = 0°\ için}$;

$$i_r = \frac{3 \cdot 326{,}56}{18{,}85}(\sin(90° - 30°) - \sin 0°) = 45\ A$$

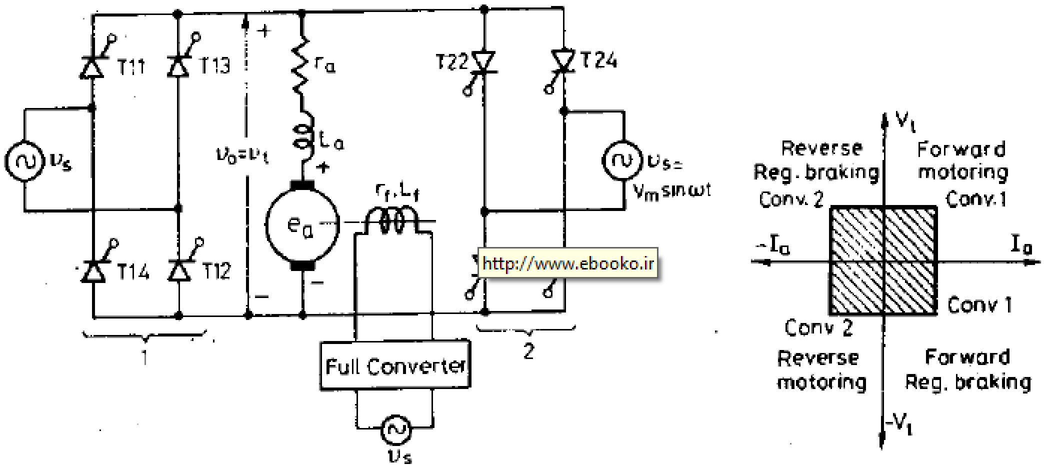
$\boldsymbol{\omega t = 120°\ ve\ a_1 = 0°\ için}$;

$$i_r = \frac{3 \cdot 326{,}56}{18{,}85}(\sin(120° - 30°) - \sin 0°) = 51{,}97\ A$$

$\omega t = 120°$ değeri için sirkülasyon akımı max değerini alır.

12.3.4. Single-phase Dual Converter Drives

A single-phase dual converter, obtained by connecting two full-converters in anti-parallel, is shown feeding a separately- excited dc motor in Fig. 12.10 (*a*). Its use is limited to about 15 kW dc drives. It offers four-quadrant operation, Fig. 12.10 (*b*). For working in first and



(*a*) (*b*)

Fig. 12.10 (*a*) Single-phase dual converter feeding a separately-excited dc motor (*b*) four-quadrant diagram.

fourth quadrants, converter 1 is in operation. For operation in second and third quadrants, converter 2 is energised. Four-quadrant operation demands that field winding of the motor is energised from a single-phase, or three-phase, full converter.

For converter 1 in operation, $V_t = \dfrac{2V_m}{\pi} \cos \alpha_1$ for $0 \le \alpha_1 \le \pi$

For converter 2 in operation, $V_t = \dfrac{2V_m}{\pi} \cos \alpha_2$ for $0 \le \alpha_2 \le \pi$

where $\alpha_1 + \alpha_2 = \pi$

For field converter, $V_f = \dfrac{2V_m}{\pi} \cos \alpha_3$ for $0 \le \alpha_3 \le \pi$

Note that in Fig. 12.10,

(*i*) Converter 1 with $\alpha_1 < 90°$ operates the motor in forward motoring mode in quadrant 1.

(*ii*) Converter 1 with $\alpha_1 > 90°$ and with field excitation reversed operates the motor in forward regenerative braking mode in quadrant 4.

(*iii*) Converter 2 with $\alpha_2 < 90°$ operates the motor in reverse motoring mode in quadrant 3.

(*iv*) Converter 2 with $\alpha_2 > 90°$ and with field excitation reversed operates the motor in reverse regenerative braking mode in quadrant 2.

12.4.4. Three-phase Dual Converter Drives

The schematic diagram for a 3-phase dual converter dc drive is shown in Fig. 12.19. Converter 1 allows motor control in I and IV quadrants whereas with converter 2, the operation in II and III quadrants is obtained. The applications of dual converter are limited to about 2 MW-drives. For reversing the polarity of motor generated emf for regeneration purposes, field circuit must be energised from single-phase or three-phase full converter.

When converter 1, or 2, is in operation, average output voltage is

$$V_0 = V_t = \frac{3V_{ml}}{\pi} \cos \alpha_1 \quad \text{for } 0 \le \alpha_1 \le \pi \qquad ...(12.30)$$

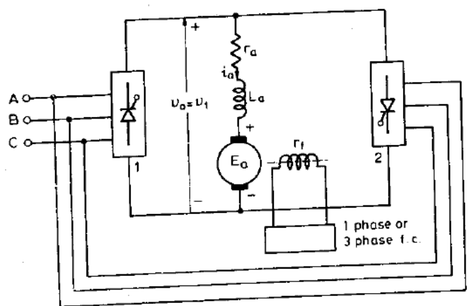


Fig. 12.19. Three-phase dual converter controlled separately-excited dc motor.

With a 3-phase full converter in the field circuit,

$$V_f = \frac{3V_{ml}}{\pi} \cos \alpha_f \qquad \text{for } 0 \le \alpha_f \le \pi \qquad ...(12.31)$$

In case circulating current-type dual converter of Fig. 6.39 is used, then as per Eq. (6.53),

$$\alpha_1 + \alpha_2 = 180°$$

12.5.4. Four-quadrant Chopper Drives

In four-quadrant dc chopper drives, a motor can be made to work in forward-motoring mode (first quadrant), forward regenerative braking mode (second quadrant), reverse motoring mode (third quadrant) and reverse regenerative-braking mode (fourth quadrant). The circuit shown in Fig. 12.24 (*a*) offers four-quadrant operation of a separately-excited dc motor. This circuit consists of four choppers, four diodes and a separately-excited dc motor. Its operation in the four quadrants can be explained as under :

Forward motoring mode. During this mode or first-quadrant operation, choppers CH2, CH3 are kept off. CH4 is kept on whereas *CH1 is operated*. When CH1, CH4 are on, motor voltage is positive and positive armature current rises. When CH1 is turned off, positive armature current free-wheels and decreases as it flows through CH4, D2. In this manner, controlled motor operation in first quadrant is obtained.

Forward regenerative-braking mode. A dc motor can work in the regenerative-braking mode only if motor generated emf is made to exceed the dc source voltage. For obtaining this mode, CH1, CH3 and CH4 are kept off whereas *CH2 is operated*. When CH2 is turned on, negative armature current rises through CH2, D4, E_a, L_a, r_a. When CH2 is turned off, diodes D1, D2 are turned on and the motor acting as a generator returns energy to the dc source. This results in forward regenerative-braking mode in the second-quadrant.

Reverse motoring mode. This operating mode is opposite to forward motoring mode. Choppers CH1, CH4 are kept off, CH2 is kept on whereas *CH3 is operated*. When CH3 and CH2 are on, armature gets connected to source voltage V_s so that both armature voltage V_t and armature current i_a are negative. As armature current is reversed, motor torque is reversed and consequently motoring mode in third quadrant is obtained. When CH3 is turned off, negative armature current freewheels through CH2, D4, E_a, L_a, r_a; armature current decreases and thus speed control is obtained in third quadrant. Note that during this mode, polarity of E_a is opposite to that shown in Fig. 12.24 (*a*).

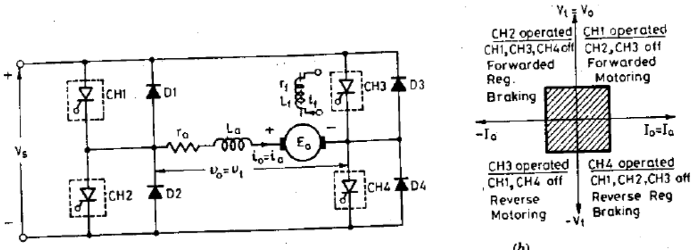


Fig. 12.24. Four-quadrant dc chopper drive (*a*) circuit diagram and (*b*) four-quadrant diagram.

Reverse Regenerative-braking mode. As in forward braking mode, reverse regenerative-braking mode is feasible only if motor generated emf is made to exceed the dc source voltage. For this operating mode, CH1, CH2 and CH3 are kept off whereas *CH4 is operated.* When CH4 is turned on, positive armature current i_a rises through CH4, D2, r_a, L_a, E_a. When CH4 is turned off, diodes D2, D3 begin to conduct and motor acting as a generator returns energy to the dc source. This leads to reverse regenerative-braking operation of the dc separately-excited motor in fourth quadrant.

Note that in Fig. 12,24 (a), the numbering of choppers is done to agree with the quadrants in which these are operated. For example, CH1 is operated for first quadrant, ..., CH4 for fourth quadrant etc.

8.5.5 Four-Quadrant Chopper (or Class E Chopper)

Figure 8.25(a) shows the basic power circuit of Type E chopper. From Fig. 8.25, it is observed that the four-quadrant chopper system can be considered as the parallel combination of two Type C choppers. In this chopper configuration, with motor load, the sense of rotation can be reversed without reversing the polarity of excitation. In Fig. 8.25, CH_1, CH_4 D_2 and D_3 constitute one Type C chopper and CH_2, CH_3, D_1 and D_4 form another Type C chopper circuit. Figure 8.25(b) shows Class-E with R–L load.

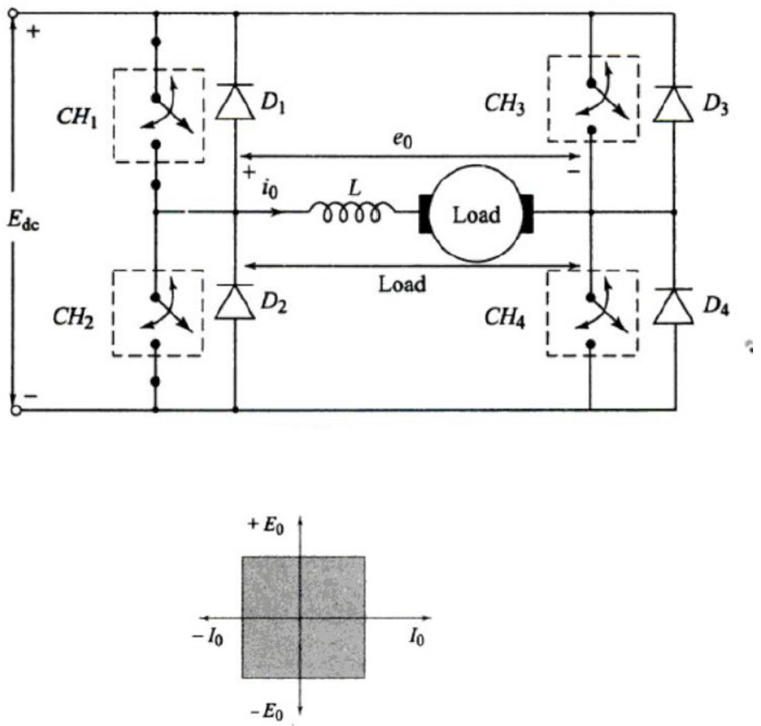


Fig. 8.25(a) *Type E chopper circuit and characteristic*

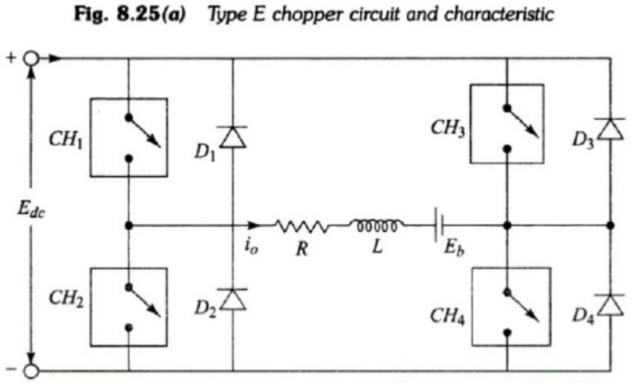


Fig. 8.25(b) *Class E chopper with R–L load*

If chopper CH_4 is turned on continuously, the antiparallel connected pair of devices CH_4 and D_4 constitute a short-circuit. Chopper CH_3 may not be turned on at the same time as CH_4 because that would short circuit source E_{dc}.

With CH_4 continuously on, and CH_3 always off, operation of choppers CH_1 and CH_2 will make E_0 positive and I_0 reversible, and operation in the first and second quadrants is possible. On the other hand, with CH_2 continuously on and CH_1 always off, operation of CH_3 and CH_4 will make E_0 negative and I_0 reversible, and operation in the third and fourth quadrants is possible.

The operation of the four-quadrant chopper circuit is explained in detail as follows:

When choppers CH_1 and CH_4 are turned-on, current flows through the path, $E_{dc+} - CH_1$ – load – $CH_4 - E_{dc-}$. Since both E_0 and I_0 are positive, we get the first quadrant operation. When both the choppers CH_1 and CH_4 are turned-off, load dissipates its energy through the path load–$D_3 - E_{dc+} - E_{dc-} - D_2$ – load. In this case, E_0 is negative while I_0 is positive, and fourth-quadrant operation is possible.

When choppers CH_2 and CH_3 are turned-on, current flows through the path, $E_{dc+} - CH_3$ – load – $CH_2 - E_{dc-}$. Since both E_0 and I_0 are negative, we get the third-quadrant operation. When both choppers CH_2 and CH_3 are turned-off, load dissipates its energy through the path load– $D_1 - E_{dc+} - E_{dc-} - D_2$ – load. In this case, E_0 is positive and I_0 is negative, and second-quadrant operation is possible.

This four-quadrant chopper circuit consists of two bridges, forward bridge and reverse bridge. Chopper bridge CH_1 to CH_4 is the forward bridge which permits energy flow from source to load. Diode bridge D_1 to D_4 is the reverse bridge which permits the energy flow from load-to-source. This four-quadrant chopper configuration can be used for a reversible regenerative d.c. drive.

2.12.4 Four quadrant Chopper or Type E Chopper

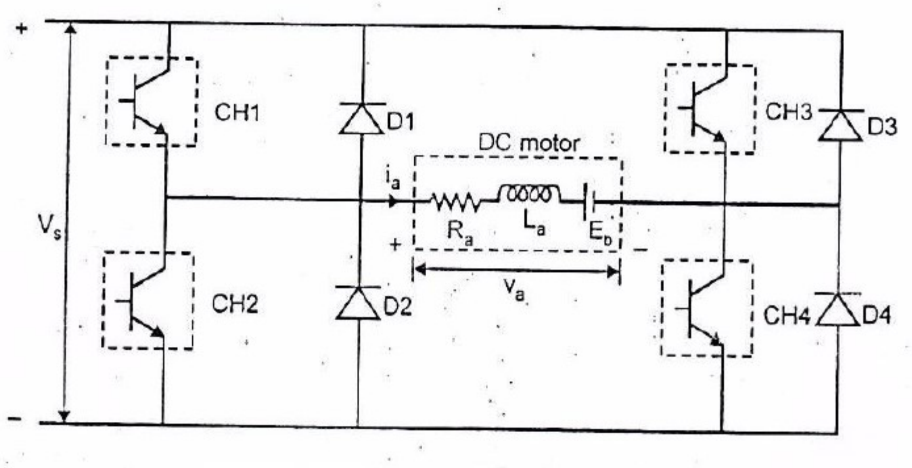


Fig (2.12.4) Four quadrant Chopper or Type E Chopper

Forward Motoring Mode

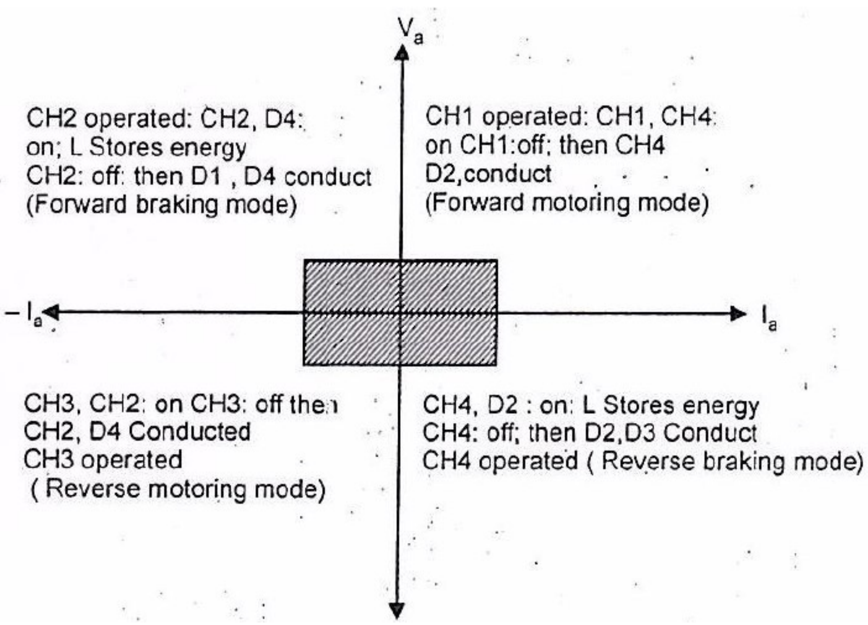
For first quadrant operation of figure CH4 is kept on, Cl-l3 is kept off and CH1 is operated. when CHI and Cl-I4 are on, load voltage is equal to supply voltage i,e, Va = Vs and load current ia begins to flow. Here both output voltage va and load current ia are positive giving first quadrant operation. When CH4 is turned off£ positive current freewheels through CH-4,D2 in this way, both output voltage va, load current ia can be controlled in the first quadrant. First quadrant operation gives the forward motoring mode.

Forward Braking Mode

Here CH2 is operated and CH1, CH3 and CH4 are kept off. With CH2 on, reverse (or negative) current flows through L, CH2, D4 and E. During the on time of CH2 the inductor L stores energy. When CH2 is turned off current is fedback to source through diodes D1, D4 note that there [E+L di/dt] is greater than the source voltage Vs. As the load voltage Va is positive and load current ia is negative, it indicates the second quadrant operation of chopper. Also power flows from load to source, second quadrant operation gives forward braking mode.

Reverse Motoring Mode

For third quadrant operation of figure, CHI is kept off, CH2 is kept on and CH3 is operated. Polarity of load emf E-must be reversed for this quadrant operation. With CH3 on, load gets connected to source Vs so that both output voltage Va and load current ia are negative. it gives third quadrant operation. lt is also known as reverse motoring mode. When CH3 is turned off, negative current freewheels through CH2, D4. ln this way, output voltage Va and load current ia can be controlled in the third quadrant.



Reverse Braking Mode

Here CH4 is operated and other devices are kept of£Load emf E must have its polarity reversed, it'is shown in figure . With CH4 on, positive current flows through CH4, D2, L and E. During the on time of CH4, the inductor L stores energy.

When CH4 is turned off; current is feedback to source through diodes D2, D3. Here load voltage is negative, but load current is positive leading to the chopper operation in the fourth quadrant.

Also power is flows from load to source. The fourth quadrant operation gives reverse braking mode.

2.13 Braking

In braking, the motor works as a generator developing a negative torque which oppose the motion. It is of three types

1. Regenerative braking
2. Plugging or Reverse voltage braking
3. Dynamic braking or Rheostatic braking

2.13.1Regenerative braking

In regenerative braking, generated energy is supplied to the source,for this to happen following condition should be satisfied

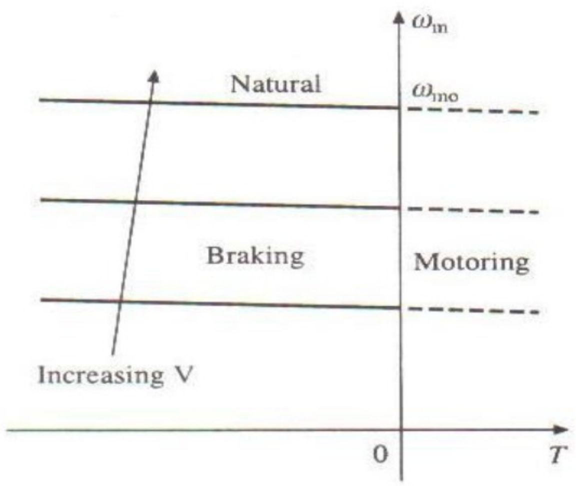
E > V and negative Ia

Field flux cannot be increased substantially beyond rated because of saturation, therefore according to equation ,for a source of fixed voltage of rated value regenerative braking is possible only for speeds higher than rated and with a variable voltage source it is also possible below rated speeds .

The speed –torque characteristics shown in fig. for a separately excited motor.

In series motor as speed increases, armature current, and therefore flux decreases

Condition of equation cannot be achieved .Thus regenerative braking is not possible



2.13.2 Plugging

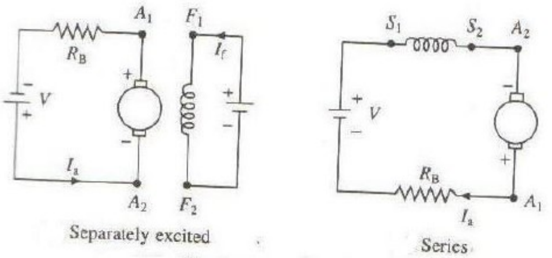
The supply voltage of a separately excited motor is reversed so that it assists the emf in forcing armature current in reverse direction .A resistance R_B is also connected in series with armature to limit the current.For plugging of a series motor armature is reversed.

A particular case of plugging for motor rotation in reverse direction arises .when a motor connected for forward motoring,is driven by an active load in the reverse direction.Here again back emf and applied voltage act in the same direction.However the direction of torque remains positive.

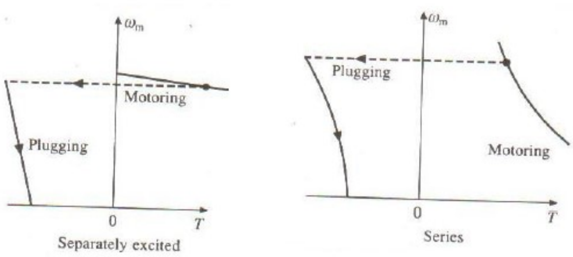
This type of situation arises in crane and the braking is then called counter – torque braking.

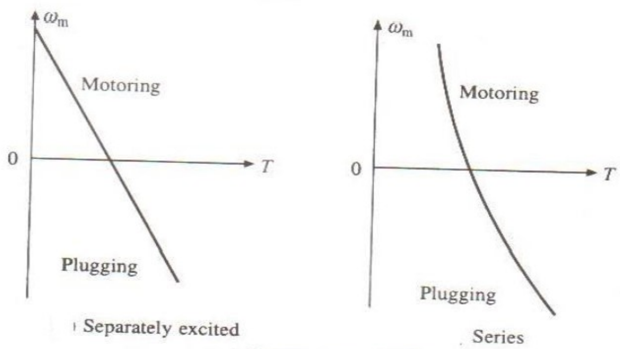
Plugging gives fast braking due to high average torque,even with one section of braking resistance RB.Since torque ia not zero speed,when used for stopping a load,the supply must be disconnected when close to zero speed.

Centifugal switches are employed to disconnect the supply.Plugging is highly inefficient because in addition to the generated power,the power supplied by the source is also wasted in resistances.



Plugging operation of dc motors





Counter-torque braking

2.13.3 Dynamic braking

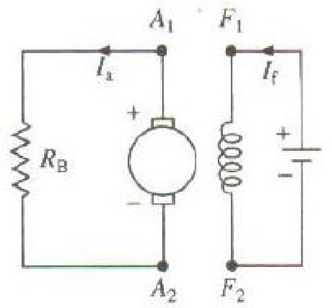
In dynamic braking ,the motor is made to act as a generator,the armature is

disconnected from the supply ,but it continues to rotate and generate a voltage.The polarity of the generated voltage remains unchanged if the direction if field excitation is unaltered.

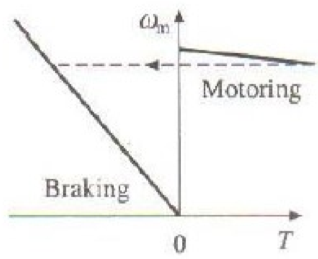
But if a resistance is connected across the coasting motor,the direction of the armature current is reversed ,because the armature represents a source of power rather than a load.

Thus a braking torque is developed ,exactly as in the generator,tending to oppose the motion.

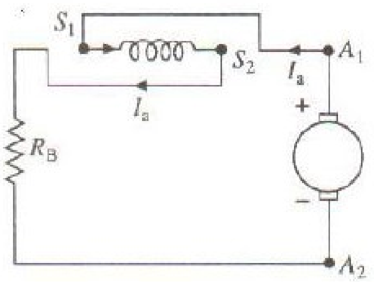
The braking torque can be controlled by the field excitation and armature current.



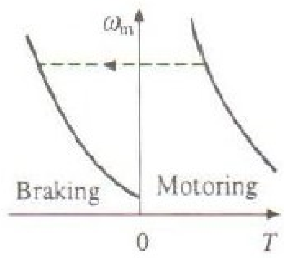
Separately excited motor



Separately excited motor



(b) Series motor



Series motor

Example 8.16 A four-quadrant chopper is driving a separately excited dc motor load. The motor parameters are $R = 0.1$ ohm, $L = 10$ mH. The supply voltage is 200 V d.c. If the rated current of the motor is 10 A and if the motor is driving the rated torque. Determine:

(i) the duty cycle of the chopper if $E_b = 150$ V.
(ii) the duty cycle of the chopper if $E_b = -110$ V.

Solution:

For a four-quadrant chopper, the average voltage in all the four-modes is given by

$$E_0 = 2\,E_{dc} \cdot (\alpha - 0.5)$$

(i) The average current, $i_0 = \dfrac{E_0 - E_b}{R} = \dfrac{2\,E_{dc} \cdot (\alpha - 0.5) - E_b}{R}$

$$10 = \frac{2 \times 200\,(\alpha - 0.5) - 150}{0.1} \quad \therefore\ \alpha = 0.876$$

Since, $\alpha > 0.5$, this mode is forward-motoring

(ii) Now, $10 = \dfrac{2 \times 200\,(\alpha - 0.5) - 110}{0.1}$, $\quad \therefore\ \alpha = 0.228$

As $\alpha < 0.5$, this mode is reverse motoring mode.

EXAMPLE 5.13

A 220-V, 22.7-A, 1,500-rpm separately excited dc motor has an armature resistance of 6.6 Ω. The motor is running in the reverse direction at 600 rpm at rated torque. The motor is driven by a single-phase dual converter powered from $230\sqrt{2}\sin 314t$ source. Compute the converter firing angles.

SOLUTION:

Back-emf at rated conditions is given by

$$\begin{aligned} E_{b(rated)} &= V_a - I_a r_a \\ &= 220 - 22.7 \times 6.6 \\ &= 136.2\ \text{V} \end{aligned}$$

Back-emf at 600 rpm at rated torque is given by

$$\frac{E_{b(600)}}{E_{b(rated)}} = \frac{600}{1500}$$

$$\frac{E_{b(600)}}{136.2} = \frac{600}{1500}$$

$$E_{b(600)} = \frac{600}{1500} \times 136.2 = 54.48\ \text{V}$$

$$\begin{aligned} V_{a(at\ 600\ rpm)} &= E_b + I_a r_a \\ &= 54.48 + 22.7 \times 6.6 \\ &= 204.3\ \text{V} \end{aligned}$$

The motor is running in the reverse direction. Converter 2 is supplying power.

$$V_a = \frac{2V_m}{\pi}\cos\alpha_2 = 204.3\ \text{V}$$

$$\cos(\alpha_2) = \frac{204.3 \times \pi}{2 \times 230\sqrt{2}} = 0.98$$

$$\alpha_2 = 11.47^\circ$$

$$\therefore \alpha_1 = 180 - \alpha_2 = 168.52^\circ$$

EXAMPLE 5.14

A 220-V, 22.7-A, 1,500 rpm separately excited dc motor has an armature resistance of 6.6 Ω. The motor is driving a load in the reverse direction at 500 rpm and 60% of rated torque. The motor is driven by a single-phase dual converter powered from a $230\sqrt{2}\sin 314t$ source. Compute the converter firing angles.

SOLUTION:

Back-emf at rated conditions is given by

$$\begin{aligned} E_{b(\text{rated})} &= V_a - I_a r_a \\ &= 220 - 22.7 \times 6.6 \\ &= 136.2\ \text{V} \end{aligned}$$

Back-emf at 500 rpm at 60% torque is given by

$$\frac{E_{b(500)}}{E_{b(\text{rated})}} = \frac{500}{1500}$$

$$\frac{E_{b(500)}}{136.2} = \frac{500}{1500}$$

$$E_{b(500)} = \frac{500}{1500} \times 136.2 = 45.39\ \text{V}$$

$$\begin{aligned} V_{a(\text{at 500 rpm})} &= E_b + I_a r_a \\ &= 45.39 + (0.6 \times 22.7) \times 6.6 \\ &= 135.282\ \text{V} \end{aligned}$$

$$V_a = \frac{2V_m}{\pi}\cos\alpha_2 = 135.3\ \text{V}$$

$$\cos(\alpha_2) = \frac{135.3 \times \pi}{2 \times 230\sqrt{2}} = 0.65$$

$$\alpha_2 = 49.20°$$

$$\therefore \alpha_1 = 180 - \alpha_2 = 130.79°$$

EXAMPLE 5.15

A 220-V, 50-A, 1,500-rpm, separately excited dc motor has an armature resistance of 0.5 Ω and is supplied from a dual converter powered from $220\sqrt{2}\sin(314t)$. If the motor runs clockwise during regenerative braking, speed is 800 rpm at rated torque. Compute the converter firing angles.

SOLUTION:

Under rated conditions,

$$\begin{aligned} E_{b(\text{rated})} &= V_{a(\text{rated})} - I_{a(\text{rated})} \times r_a \\ &= 220 - (50 \times 0.5) = 195\ \text{V} \end{aligned}$$

Back-emf at 800 rpm is given by

$$\frac{E_{b(800)}}{E_{b(\text{rated})}} = \frac{800}{1500}$$

$$E_{b(800)} = \frac{800}{1500} \times 195 = 104\ \text{V}$$

During regenerative braking

$$\begin{aligned} V_a &= E_b - I_a \times r_a \\ &= 104 - (50 \times 0.5) = 79\ \text{V} \end{aligned}$$

Because converter 1 is feeding power,

$$V_a = \frac{2V_m}{\pi}\cos\alpha_1$$

$$\text{i.e., } 79 = \frac{2 \times 220\sqrt{2}}{\pi}\cos\alpha_1$$

$$\alpha_1 = 66.49°$$

$$\alpha_2 = 180 - \alpha_1 = 180 - 66.49 = 113.51°$$

16. A single-phase dual converter is used for controlling the speed of a separately excited dc motor as shown in Fig. 2.40(a). It is supplied by a single-phase ac source of 240 V at 50 Hz. Normally, rectifier P is used for motor operation. It is required to brake the motor in a regenerative manner by operating rectifier N in the inverting mode (quadrant II) with $\alpha_N = 120^\circ$. If the motor is initially running at 1500 rpm, the combined inertia of the rotor and load (J) is 1.2×10^{-3} kg m^2, and the average current through the motor is 0.2 A, determine the time required for the braking of the motor.

Solution

The output voltage of rectifier N just at the start of regenerative braking is

$$V_{\alpha N} = \left(\frac{n}{\pi}\right) V_m \sin\left(\frac{\pi}{n}\right) \cos\alpha$$

For the single-phase rectifier N,

$$V_{\alpha N} = \left(\frac{2}{\pi}\right) V_m \sin\left(\frac{\pi}{2}\right) \cos 120^\circ = -\frac{n}{\pi} \times 240\sqrt{2} \times 0.5 = -108 \text{ V}$$

The average value of the terminal voltage is $V_{av} = -108/2 = -54$ V. Hence $E_{b(av)} = 54$ V. The kinetic energy dissipated for braking purposes = $(1/2)J\omega^2$ = $1/2 \times 1.2 \times 10^{-3} \times [2\pi \times 1500/60]^2 = 14.8$ J. The electrical energy returned back to the source is equal to the kinetic energy dissipated. That is, electrical power of the motor $\times$ time required for braking = kinetic energy dissipated. Thus,

$$E_{b(av)} I_{av} t = 14.8$$

or

$$54 \times 0.2 \times t = 14.8$$

This gives

$$t = \frac{14.8}{54 \times 0.2} = 1.37 \text{ s}$$

Example 4.12:

A single-phase dual converter is operated from a 200-V, 50-Hz supply, and the load resistance is R = 20 Ω. The circulating inductance is Lr = 50 mH; delay angles are $\alpha 1 = 50^\circ$ and $\alpha 2 = 130^\circ$. Find the peak circulating current and the peak current of converter 1.

SOLUTION

$\omega = 2\pi \times 50 = 314$ rad/s, $\alpha 1 = 50^\circ$, $Vm = \sqrt{2} \times 200 = 282.85$ V, $f = 50$ Hz, and $Lr = 50$ mH. Circulating current will be maximum at $\omega t = 2\pi$.

∵ for $\omega t = 2\pi$ and $\alpha_1 = 50^\circ$, the peak circulating current

$$Ir(max)=2Vm\omega Lr(1-\cos\alpha 1)=565.7\times 1000314\times 50(1-\cos 50^\circ)=12.87 \text{ A}$$

The peak load current is $I_p = 282.85/20 = 14.15$ A. The peak current of converter 1 is = $I_p + (I_r)_{max}$ (14.15 + 12.87) = 27.01 A.

Example 4.13:

A three-phase dual converter, operating in the circulating-current mode has the following data:
Per phase supply voltage = 220 V, f = 50 Hz, $\alpha 1 = 50°$, current-limiting reactor, L = 20 mH. Find the peak value of the circulating current.

SOLUTION

The peak value of the circulating current, for firing angle $\alpha_1 = 50°$, is given by equation (ir)max.=3Vm1 ωL[1−sin α 1]

$$\therefore \text{ (ir)max } .=3.6.2202\pi\times50\times20\times10-3[1-\sin50°]=37.772 \text{ A.}$$

Example 4.19:

A single-phase dual converter is fed by a 220-V, 50-Hz single-phase system. It feeds a resistive load of 20-ohm resistance. The firing angles are $\alpha_1 = 60°$ and $\alpha_2 = 120°$. The inductance L is 50 mH. Find the peak circulating current and peak current of converter 1.

SOLUTION

$$\text{Vm}=2\times220=311.12 \text{ V}$$

$$\alpha 1=60°, \alpha 2=120°, \omega=100\pi$$

$$\omega \text{Lr}=100\pi(50\times10-3) = 15.71 \ \Omega$$

The expression for instantaneous circulating current for $1-\phi$ dual converter is

$$\text{Ir}=2\text{Vm}\,\omega\,\text{Lr}(\cos\omega\text{t}-\cos\alpha 1)$$

$$=2\times311.1215.71(\cos\omega\text{t}-\cos60°)$$

The peak circulating current occurs at $\omega t = 2\pi$

$$\text{(Ir)max= Peak circulating current}=2\times311.1215.7l(1-0.5)=19.80\text{A}$$

Peak value of load current, (IP)=VmR=311.1220=15.56 A

The peak current of converter 1 is the sum of the peak load current and peak circulating current.

Peak current of converter 1 = $I_p + (I_r)_{max}$ = 15.56 + 19.80 = 35.36 A

Example 4.20:

A single-phase circulating current dual converter is fed by a 220-V, single-phase 50-Hz AC supply. The firing angles are $\alpha 1 = 30°$ and $\alpha 2 = 150°$. The load resistance is 15 ohms. The peak circulating current is 10.5 A. Find (a) inductance of current limiting reactor and (b) peak current of converter 1.

SOLUTION

a. $V_m = \sqrt{2} \times 220 = 311.12$ V

$$\alpha 1=30°, \alpha 2=150°, \omega=100\pi$$

Expression for circulating current,

$$Ir=2Vm\omega Lr[\cos \omega t- \cos \alpha 1]$$

Peak circulating current occurs at $\omega t = 2\pi$.

$$\therefore\ 10.5=2\times311.12100\pi L(\cos2\pi-\cos30°)$$

or

$$10.5=2\times311.12100\ \pi L(1-0.886)$$

or

$$Lr=2\times311.12\times0.134100\pi(10.5)=0.0252H$$

b. Peak load current=311.1215=20.74 A
Peak current of converter 1 is the sum of peak load current and peak circulating current.
Peak current converter 1 = 20.74 + 10.5 = 31.24 A

Example 4.21:

A single-phase circulating current dual converter is fed by a 220-V, single-phase, 50-Hz AC supply. The load is purely resistive. The peak current of converter 1 is 40 A. The firing angles are 45° and 135°, respectively. If peak circulating current is 12.5 A find (a) inductance of current limiting reactor and (b) load resistance.

Solution

a. Vm=2×220=311.12V

$$\omega=100\ \pi, \alpha 1=45°, \alpha 2=135°$$

The instantaneous circulating current,

$$Ir=2Vm\omega Lr(\cos\omega t-\cos\alpha 1)$$

Peak circulating current occurs at $\omega t = 2\pi$.

∴ (Ir)max=2VmωLr(cos2π−cosα1)

or

$$12.5=2\times311.12100\pi Lr(\cos2\pi-\cos45°)$$

or

$$12.5=2\times311.12100\pi Lr(1-0.707)$$

or

$$Lr=2\times311.12\times(1-0.707)100\pi(12.5)=0.046H$$

b. Peak load current=40−12.5=27.5 A

$$\text{Peak load current}=VmR=311.12R$$

or

$$R=311.1227.5\ \text{A} = 11.31\ \Omega$$

Example 4.22:

A three-phase dual converter is fed by a 400-V, 50-Hz supply. The inductance of the current-limiting reactor is 60 mH. Find the circulating current at ωt = 0°, 30°, and 90°. Assume that the firing angle is zero. Also find the maximum value of the circulating current.

SOLUTION

$$Vm=40023=326.56V$$

$$\omega Lr=2\pi(50)(60\times10-3)=18.85\ \Omega$$

Instantaneous value of circulating current I_r for $3-\varphi$ dual converter,

$$ir=3Vm\omega Lr[\sin(\omega t-30°)-\sin\alpha 1]$$

For $\omega t = 0$ and $\alpha_1 = 0$, ir=3×326.5618.85[sin(−30°)]=−25.99 A

The negative sign indicates the direction of flow of circulating current.

For $\omega t = 30°$ and $\alpha_1 = 0$, $i_r = 0$

For $\omega t = 90°$ and $\alpha_1 = 0$

$$ir=3\times326.5618.85[\sin(60-0)]=45A$$

The peak value of circulating current occurs at ωt = 120° and is equal to (ir)max=3×326.5618.85 [sin90−0] =51.97A

Example 4.23:

A three-phase circulating-current dual converter is fed from a 400-V, 50-Hz AC supply. The peak value of the circulating current is 40 A. If the firing angle is zero, find the inductance of the current-limiting reactor.

SOLUTION

$$Vm=40023=326.56V$$

$$\omega Lr=100\pi\ \ Lr, \alpha 1=0$$

Instantaneous value of circulating current i_r for $3-\varphi$ dual converter, $ir=3Vm\omega Lr[\sin(\omega t-30)-\sin\alpha 1]$

The peak value of the circulating current occurs at $\omega t = 120°$ and is equal to

$$(ir)max=3Vm\omega Lr[\sin(120-30°)-\sin\alpha 1]$$

$$\therefore\ 40=3\times 326.56100\pi L[\sin(120-30°)-\sin 0]$$

or

$$40=3\times 326.56100\pi L[\sin\ 90-\sin\ 0]$$

or

$$L=3\times 326.56100\ \pi(40)=0.077\ \ H$$

7.7 COMPARISON BETWEEN NON-CIRCULATING CURRENT MODE AND CIRCULATING CURRENT MODE

The comparison between non-circulating current mode and circulating-current mode of dual-converters is given below:

Non-circulating current mode	*Circulating current mode*
1. In this mode of operation, only one converter operates at a time and the second converter remains in a blocking state.	In this mode of operation, one converter operates as a rectifier and the other converter operates as an inverter.
2. Converters may operate in discontinuous current mode.	Converters operates in continuous current mode.
3. Reactors may be needed to make load-current continuous.	Reactors are needed to limit circulating current. These reactors are costly.
4. Since no circulating current flows through the converters, efficiency is higher.	Circulating current flows through the converters and hence increases the losses.
5. Due to discontinuous current, non-linear transfer characteristics are obtained.	Due to continuous current, linear transfer characteristics are obtained.

6.	Due to discontinuous current, response is sluggish.	Due to continuous-current in the converters, response is fast.
7.	Due to spurious firing, faults between converters results in dead short-circuit conditions.	Due to spurious firing, fault currents between converters are restricted by the reactor.
8.	In this mode of operation, the cross-over technique is complex.	In this mode of operation, the crossover technique is simple.
9.	Loss of control for 10 to 20 ms is observed in this mode of operation.	Since converters do not have to pass through blocking unlocking and safety intervals of 10 to 20 ms, hence control is never lost in this mode of operation.
10.	The control scheme needs command module to sense the change in polarity.	As both the converters are operating at the same time, the control scheme does not require command module.
11.	The complete scheme is cheaper compared to circulating current mode.	The complete scheme is expensive.
12.	In this mode of operation, the converter loading is the same as the output load.	In this mode of operation the converter loading is higher than the output load.

SOLVED EXAMPLES

Example 7.1 Compute the peak value of the circulating current for the 3-ϕ circulatory current type dual converter consisting of two three-phase fully controlled bridges for the given data.

Per phase supply RMS voltage = 230 V, ω = 315 rad/s, L = 12 mH

$$\alpha_1 = 60°, \alpha_2 = 120°.$$

Solution: The peak value of the circulating current from Eq. (7.18) is given by

$$i_{cp} = \frac{3\sqrt{2}E_{\text{rms}}}{\omega L}(1 - \cos \pi/6), = \frac{3\sqrt{2} \times 230}{315 \times 12 \times 10^{-3}}(1 - \cos \pi/6) = 34.58 \text{ A}.$$

Example 7.2 Design a dual converter to achieve a four-quadrant operation of the separately excited d.c. motor. Motor and converter specifications are given by

(i) Motor specifications

$E_a = 220$ V, $I_a = 30$ A, $N = 1500$ rpm.

(ii) Converter specifications

Supplied from 3-ϕ, 400 V, 50 Hz supply

Assume drop in the circuit is 15%.

Solution: Consider that dual converter consist of six-pulse converters to achieve a four-quadrant operation.

(i) Step 1 Rectifier operation:

Total drop in the system = $220 \times 0.15 = 33$ V.

$\therefore$ Total d.c. voltage, $E_{dc\alpha} = E_{dc}$ + drop, = 220 + 33 = 253 V.

For six-pulse bridge converter, we have the relation

$$E_{dc\ \alpha} = 1.35\ E_{ac} \cos \alpha_1.$$

where E_{ac} = RMS value of a.c. voltage.

$\therefore$ $253 = 1.35 \times 400 \times \cos \alpha_1 \quad \therefore \cos \alpha_1 = 0.469 \quad \therefore \alpha_1 = 62°.$

A.C. line current $I_{ac} = 0.817 . I_{dc} = 0.817 \times 30 = 24.51$ A.

A.C. terminal power, $P_{ac} = \sqrt{3} \times E_{ac} \times I_{ac} = \sqrt{3} \times 400 \times 24.51 = 16.98$ kW.

$$P_{ac} = 1.05\, P_{dc}, \quad \therefore P_{dc} = \frac{P_{ac}}{1.05} = \frac{16.98 \times 10^3}{1.05} = 16.17 \text{ kW.}$$

(ii) *Step* 2

Current limiting inductance L_C is given by, $L_C = \dfrac{2 \times 1.35 \times E_{ac}}{6\omega I_{ripple}}\left[\dfrac{1}{7} + \dfrac{1}{5}\right]$

where $\quad I_{ripple} = \dfrac{I_d}{5}$ for six-pulse converter $= \dfrac{30}{5} = 6$ A.

$$\therefore \quad L_c = \frac{2 \times 1.35 \times 400}{6 \times 2\pi \times 50 \times 6} = 33 \text{ mH}$$

(iii) *Step* 3

Firing angle $\quad \alpha_2° = 180° - \alpha_1 = 180° - 62 = 118°$

(iv) Selection of SCR

(a) Voltage rating, PIV $= 2\sqrt{2}\, E_{ac} = 2\sqrt{2} \times 400 = 1131.37$ PIV $= 1200$ V.
(b) Current rating

$$I_T = 2\sqrt{2} \times I_{ac} = 2\sqrt{2} \times 24.51 = 69.32 \text{ A} \cong 70 \text{ A.}$$

The average dc output voltage of converter 1 is

$$V_{dc1} = \frac{2V_m}{\pi}\cos\alpha_1$$

The average dc output voltage of converter 2 is

$$V_{dc2} = \frac{2V_m}{\pi}\cos\alpha_2$$

$$\frac{2V_m}{\pi}\cos\alpha_1 = \frac{-2V_m}{\pi}\cos\alpha_2 = \frac{2V_m}{\pi}(-\cos\alpha_2)$$

$$\therefore \quad \cos\alpha_1 = -\cos\alpha_2$$

or

$$\cos\alpha_2 = -\cos\alpha_1 = \cos(\pi - \alpha_1)$$

$$\therefore \quad \alpha_2 = (\pi - \alpha_1) \text{ or}$$

$$(\alpha_1 + \alpha_2) = \pi \text{ radians}$$

$$V_{o_1(av)} = \frac{2V_m}{\pi}\cos\alpha_1$$

$$V_{o_2(av)} = \frac{2V_m}{\pi}\cos\alpha_2$$

$$\alpha_1 + \alpha_2 = 180°$$

$$i_{cir} = \frac{2V_m}{\omega L_r}[\cos\omega t - \cos\alpha_1]$$

In ac to dc circulating current dual converters if triggering angles are α_1 and α_2, than it is necessary that

$$\alpha_1 + \alpha_2 = 180°$$

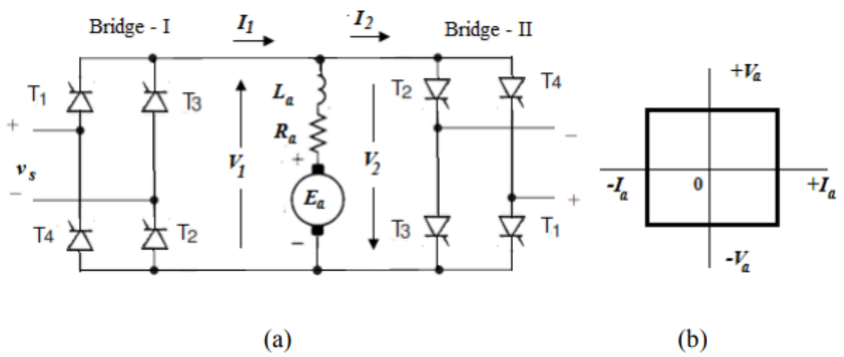


Fig.13.11 Dual converter drive: (a) Circuit diagram, and (b) Quadrants of operation.

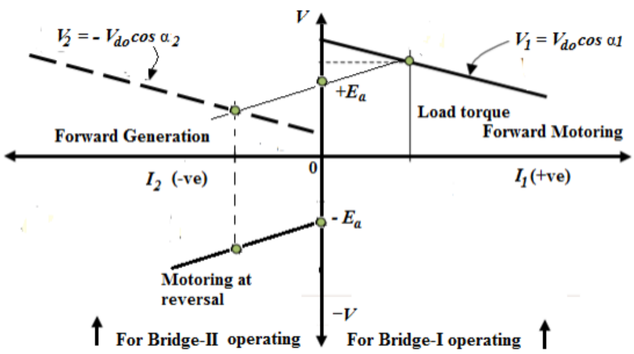


Fig.13.12 Dual converter.

Bridge – I operating:

$$V_1 = V_{a(av)\,1} = \frac{2V_m}{\pi}\cos\alpha_1 = V_{do}\,\cos\alpha_1 = E_a + I_1\,R_a \qquad (13.29)$$

Bridge – II operating:

$$V_2 = V_{a(av)\,2} = -\left(\frac{2V_m}{\pi}\cos\alpha_2\right) = V_{do}\,\cos\alpha_2 = E_a - I_1\,R_a \qquad (13.30)$$

Example 13.9

A d.c. separately-excited motor rated at 10 kW, 200 V is to be controlled by dual converter. The armature circuit resistance is 0.2 Ω and the machine constant $K_e\emptyset$ is 0.35 V/ rpm. For the following conditions, determine the firing angles of the converter, the back *emf* and the machine speed given that for the converter system V_{do} = 250 V. Neglect any losses in the converter circuit.

(a) Machine operates in a forward motoring mode at rated current and with terminal voltage of 200 V.

(b) Machine operates at forward generation mode at rated current and with terminal voltage of 200 V.

Solution

(a) For the motoring case,

$$V = V_{do}\ \cos\alpha \ \rightarrow \quad 200 = 250\cos\alpha \ \rightarrow \quad \cos\alpha = \frac{200}{250} = 0.8$$

$$\therefore\ \alpha = cos^{-1}(0.8) = 36.8°$$

The rated current of the machine $I_a = 10000 / 200 = 50$ A.

$$V = E_a + I_a\ R_a \ \rightarrow \quad 200 = E_a + 50 \times 0.2$$

$$\therefore \quad E_a = 200 - 10 = 190\text{ V}$$

The speed of the motor can be calculated as,

$$E_a = K_e\emptyset\, n \quad \rightarrow \quad n = \frac{E_a}{K_e\emptyset} = \frac{190}{0.35} = 542.85\ \text{rpm}$$

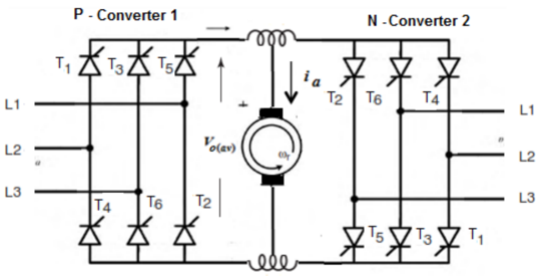
(b) For generating mode,

$$-V = V_{do}\ \cos\alpha \ \rightarrow \quad -200 = 250\cos\alpha$$

$$\therefore\ \alpha = cos^{-1}(-0.8) = 143.13°$$

$$E_a = V + I_a\ R_a \ \rightarrow \ E_a = \ 200 + \ 50 \times 0.2 \ = 210\text{ V}$$

$$E_a = K_e\emptyset\, n \quad \rightarrow \quad n = \frac{E_a}{K_e\emptyset} = \frac{210}{0.35} = 600\ \text{rpm}$$



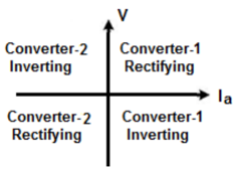


Fig.13.20 Four-quadrant three-phase d.c. drive.

where $\quad V_{do} = \dfrac{3\sqrt{3}V_m}{\pi}$

and $\quad \alpha_2 = \pi - \alpha_1$.

Two modes of operation can be achieved with this circuit:

Bridge – I operating:

$$V_1 = V_{a(av)1} = \frac{3\sqrt{3}V_m}{\pi}\cos\alpha_1$$

$$= V_{do}\ \cos\alpha_1 \ = E_a + I_1\ R_a \qquad (13.43)$$

Bridge – II operating:

$$V_2 = V_{a(av)2} = -\left(\frac{3\sqrt{3}V_m}{\pi}\cos\alpha_2\right)$$

$$= V_{do}\ \cos\alpha_2 = E_a - I_1\ R_a \qquad (13.44)$$

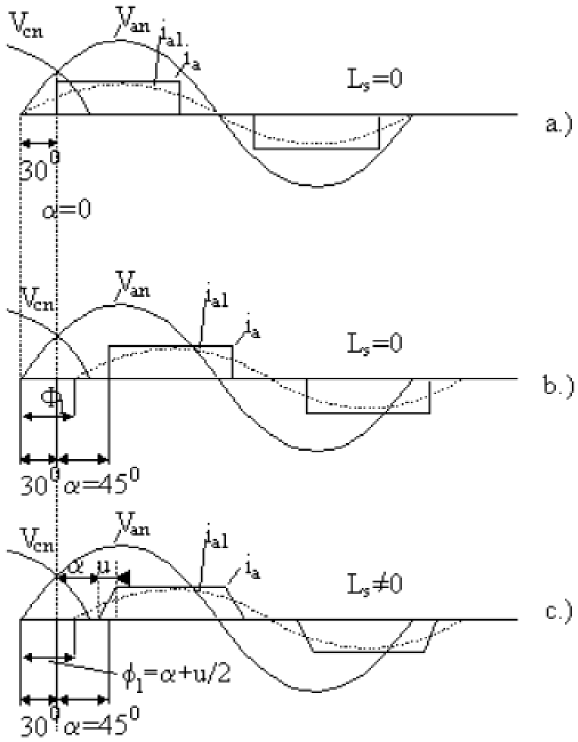


Fig. 2.1.18. A.c. source currents in a three phase full converter and constant motor current

a) for $\alpha = 0°$, $L_s = 0$; ***b)*** for $\alpha = 45°$, $L_s = 0$; ***c)*** for $\alpha = 45°$, $L_s = 1$mH

For the total a.c. source current which is made of rectangular 120° wide "blocks":

$$I_a = \sqrt{\frac{2}{3}} \cdot I_d = 0.816 \cdot 50 = 40.8A$$

In the absence of L_s the displacement power factor (DPF) angle is equal to α and thus the DPF is:

$$DPF = \cos\varphi_1 = \cos\alpha = \begin{cases} 1 \text{ for } \alpha = 0 \\ 0.709 \text{ for } \alpha = 45^0 \end{cases}$$

In the presence of L_s the displacement power factor is approximately:

$$DPF = \cos\left(\alpha + \frac{u}{2}\right)$$

To calculate u for $\alpha = 45°$ we use equation (2.1.91):

$$\cos(\alpha + u) = \cos\alpha - \frac{3\omega_1 L_s I_d}{\sqrt{2} V_L} = 0.707 - \frac{3 \cdot 2\pi \cdot 60 \cdot 50 \cdot 10^{-3}}{\sqrt{2} \cdot 220} = 0.5248$$

$$45 + u = 58.34^0; \quad u = 13.34^0$$

Finally:

$$\mathrm{DPF} = \cos\left(45 + \frac{13.34}{2}\right) = 0.62$$

The current commutation in the presence of L_s produces a further reduction of displacement power factor.

In general the DPF decreases with α increasing which constitutes a notable disadvantage of phase delay a.c. - d.c. converters. Special measures are required to improve DPF with α increasing.

d) The a.c. source current overlapping during commutation produces notches in the line voltage. From figure 2.1.19 we may obtain $V_{ab} = V_{an} - V_{bn}$ of the waveform shown in figure 2.1.19.

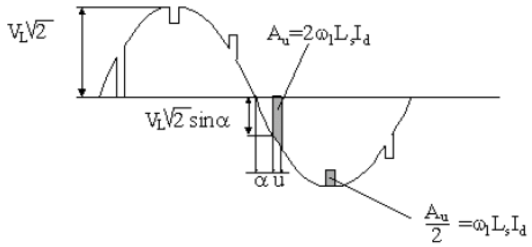


Fig. 2.1.19. A.c source line voltage notches due to L_s (commutation)

Considering u as small, the deep notch depth is considered equal to $\sqrt{2}V_L \sin\alpha$ and thus the notch width u is approximately:

$$u = \frac{A_u}{\text{notch depth}} = \frac{2\omega_1 L_s I_d}{\sqrt{2}V_L \sin\alpha} \tag{2.1.100}$$

The depth of shallow notches is considered half of that of deep notches. IEEEE standard 519 - 1981 suggests the limitation of line notches to 250µs (5.4. electrical degrees) and the deep notch depth to 70% of rated peak line voltage in order to perform satisfactorily.

Special filtering is required to cope with more recent standards. The voltage distorsion due to notches depends on the harmonics currents I_ν and the a.c. source inductance L_s:

$$\text{voltage\%THD} = \frac{\sqrt{\left[\sum_{\nu>1}\left(I_\nu \cdot \nu\omega_1 L_s\right)^2\right]}}{V_{\text{phase (fundamental)}}} \cdot 100 \tag{2.1.101}$$

With $I_\nu \approx \frac{I_{a1}}{\nu} = \frac{\sqrt{6}}{\pi} \cdot \frac{I_d}{\nu}$ due to the almost rectangular form of a.c. source current.

2.1.12 THE DUAL CONVERTER - FOUR QUADRANT OPERATION

A high power d.c. motor drive has to undergo sometimes four quadrant operation. Two full converters are connected back to back for this purpose (figure 2.1.20).

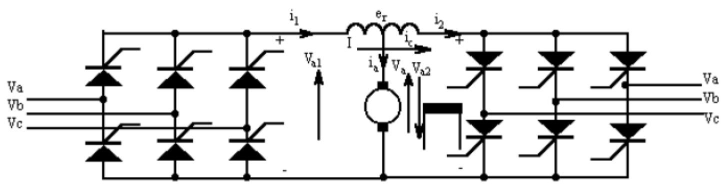


Fig. 2.1.20. Dual converter with circulating current supplying a d.c. brush motor

a) Assuming that the converters are ideal and produce pure d.c. output voltages with one converter as rectifier and the other as inverter, calculate the relationship between the delay angles α_1 and α_2 in the two converters.

b) With $\alpha_1 + \alpha_2$ as above calculate the circulating current between the two converters and show the voltage and current actual output waveforms. The numerical data are $V_L = 220V$, $\omega_1 = 377.8rad/s$, $L = 10mH$, $\alpha_1 = 60°$

Solution:

a) In an ideal dual converter the voltages produced by the two full converters should be equal and opposite.

By now we know that:

$$V_{a1} = V_{max} \cdot \cos\alpha_1$$
$$V_{a2} = V_{max} \cdot \cos\alpha_2 \qquad (2.1.102)$$

With $V_a = V_{a1} = -V_{a2}$ it follows that: $\cos\alpha_1 + \cos\alpha_2 = 0$

Hence $\alpha_1 + \alpha_2 = 180°$ (figure 2.1.21). In the ideal converter the load voltage is equal to the converter output voltages and thus the current may flow equally through either converter

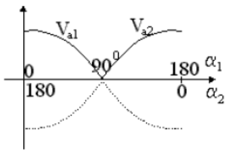


Fig. 2.1.21. Ideal dual converter voltages

b) In a real nonideal converter each converter produces a voltage with ripples. The ripple voltages of the two converters are out of phase (figure 2.1.22). The instantaneous voltage difference produces a circulating current which is limited through a reactor *L*.

With:

$$V_{a,b,c} = \frac{V_L\sqrt{2}}{\sqrt{3}}\sin\left[\omega_1 t - (i-1)\frac{2\pi}{3}\right] \qquad (2.1.103)$$

during the interval:

$$\frac{\pi}{6} + \alpha_1 < \omega_1 t < \frac{\pi}{6} + \alpha_1 + \frac{\pi}{3} \qquad (2.1.104)$$

$$V_{a1} = V_a - V_b$$
$$V_{a2} = -(V_c - V_b)$$
$$e_r = V_{a1} - V_{a2} = V_a + V_c - 2V_b = -3V_b \qquad (2.1.105)$$

The circulating current i_c is:

$$i_c = \frac{1}{\omega_1 L}\int_{\alpha_1+\frac{\pi}{6}}^{\omega_1 t} e_r\,dt = \frac{\sqrt{6}V_L}{\omega_1 L}\left[\cos\left(\omega_1 t - \frac{2\pi}{3}\right) - \cos\left(\alpha_1 - \frac{\pi}{2}\right)\right] \qquad (2.1.106)$$

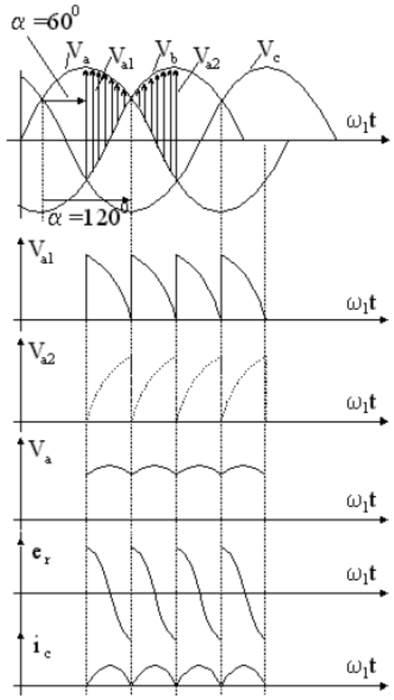
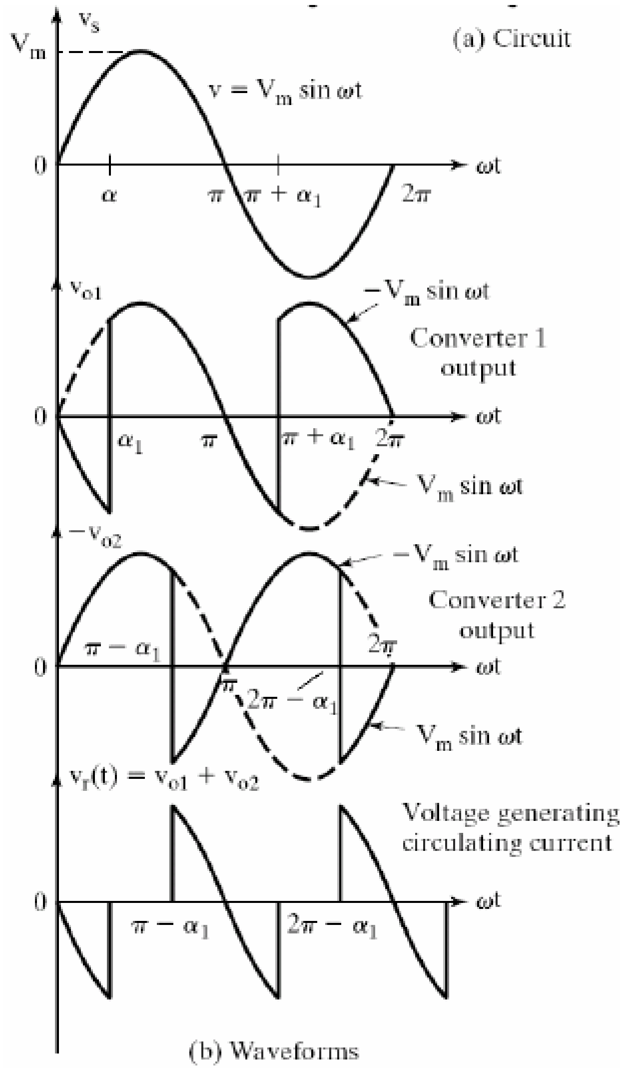


Fig. 2.1.22. The real dual converter



When the motor current is zero the converter currents are equal to the circulating current $i_1 = i_2 = i_c$ ($i_o = 0$). Consequently the converters have a continuous current though the load current is zero. However for $\alpha_1 = 60°$ and $\alpha_2 = 120°$ the peak value of circulating current occurs at $\omega_1 t = 2\pi / 3$:

$$\left(i_c\right)_{peak} = \frac{V_L\sqrt{6}}{\omega_1 L}\left[1 - \cos\frac{\pi}{6}\right] = \frac{220\sqrt{6}}{2\cdot\pi\cdot 60\cdot 10^{-2}}\left[1 - 0.867\right] = 19.02 \tag{2.1.107}$$

If the load current i_o is constant (no ripples) the first converter ($\alpha_1 = 60°$) carries $i_o + i_c$ while the second converter ($\alpha_1 = 120°$) the circulating current i_c only. Thus the first converter is "overloaded' with the circulating current. However for low load current the discontinuous current mode in the converters is avoided as shown above. This could be an important advantage in terms of control performance.

EXAMPLE 3.16 A three-phase full converter bridge is connected to a 3-phase 400 V, 50 Hz supply having a source inductance of 5 mH. The load current is constant at 20 A. If the load consists of a dc voltage source of 400 V, having an internal resistance of 1 Ω, calculate the firing angle α and overlap angle μ for this condition.

Solution

The dc source may be a battery which is getting charged.

Output voltage of the converter, V_o = the dc source voltage + drop in the 1 Ω internal resistance

$$= 400 + (20 \times 1)$$
$$= 420 \text{ V}$$

$$V_o = \frac{3V_{lm}}{\pi}\cos\alpha - \frac{3\omega L_s}{\pi} I_o$$

$$420 = \frac{3 \times 400\sqrt{2}}{\pi}\cos\alpha - \frac{3 \times 2\pi \times 50 \times 5}{1000}$$

$$\Rightarrow \alpha = 33.58°$$

$$420 = \frac{3 \times 400\sqrt{2}}{\pi}\cos(\alpha + \mu) + \frac{3 \times 2\pi \times 50 \times 5}{1000} \times 20$$

$$(\alpha + \mu) = 42.78°$$

$$\mu = 42.78° - 33.58° = 9.2°$$

Thus,

$$\alpha = 33.58° \text{ and } \mu = 9.2°$$

EXAMPLE 3.17 A three-phase six-pulse fully controlled converter is connected to a three-phase ac supply of 400 V and 50 Hz and operates with a firing angle of $\alpha = \pi/4$. The load current is maintained constant at 10 A and the load voltage is 360 V. Calculate the load resistance, source inductance, and overlap angle.

Solution

$$360 = \frac{3 \times 400 \times \sqrt{2}}{\pi}\frac{1}{\sqrt{2}} - \frac{3\omega L_s}{\pi} I_o$$

$$L_s = 7.3 \text{ mH}$$

$$\text{Load resistance} = \frac{360}{10} = 36\,\Omega$$

$$300 = \frac{3 \times 400\sqrt{2}}{\pi}\cos(\alpha + \mu) + \frac{3\omega L_s}{100} \times 10$$

$$\cos(\alpha + \mu) = 0.63$$

$$\mu = 6°$$

■ ***Example 6-1*** In the converter circuit of Fig. 6-8*a*, L_s is 5% with the rated voltage of 230 V at 60 Hz and the rated volt-amperes of 5 kVA. Calculate the commutation angle u and V_d/V_{do} with the rate input voltage, power of 3 kW, and $\alpha = 30°$.

Solution

The rated current is

$$I_{\text{rated}} = \frac{5000}{230} = 21.74 \text{ A}$$

The base impedance is

$$Z_{\text{base}} = \frac{V_{\text{rated}}}{I_{\text{rated}}} = 10.58 \ \Omega$$

Therefore,

$$L_s = \frac{0.05Z_{\text{base}}}{\omega} = 1.4 \text{ mH}$$

The average power through the converter can be calculated using Eq. 6-26:

$$P_d = V_d I_d = 0.9V_s I_d \cos \alpha - \frac{2}{\pi} \omega L_s I_d^2 = 3 \text{ kW}$$

Using the given values in the above equation gives

$$I_d^2 - 533.53I_d + 8928.6 = 0$$

Therefore,

$$I_d = 17.3 \text{ A}$$

Using this value of I_d in Eqs. 6-24 and 6-26 results in

$$u = 5.9° \quad \text{and} \quad V_d = 173.5 \text{ V}$$

SOLVED EXAMPLES

Example 8.16 A four-quadrant chopper is driving a separately excited dc motor load. The motor parameters are $R = 0.1$ ohm, $L = 10$ mH. The supply voltage is 200 V d.c. If the rated current of the motor is 10 A and if the motor is driving the rated torque. Determine:

(i) the duty cycle of the chopper if $E_b = 150$ V.
(ii) the duty cycle of the chopper if $E_b = -110$ V.

Solution:

For a four-quadrant chopper, the average voltage in all the four-modes is given by

$$E_0 = 2\,E_{dc} \cdot (\alpha - 0.5)$$

(i) The average current, $i_0 = \dfrac{E_0 - E_b}{R} = \dfrac{2\,E_{dc} \cdot (\alpha - 0.5) - E_b}{R}$

$$10 = \frac{2 \times 200\,(\alpha - 0.5) - 150}{0.1} \qquad \therefore\ \alpha = 0.876$$

Since, $\alpha > 0.5$, this mode is forward-motoring

(ii) Now, $10 = \dfrac{2 \times 200\,(\alpha - 0.5) - 110}{0.1}, \qquad \therefore\ \alpha = 0.228$

As $\alpha < 0.5$, this mode is reverse motoring mode.

8.5.5 Four-Quadrant Chopper (or Class E Chopper)

Figure 8.25(a) shows the basic power circuit of Type E chopper. From Fig. 8.25, it is observed that the four-quadrant chopper system can be considered as the parallel combination of two Type C choppers. In this chopper configuration, with motor load, the sense of rotation can be reversed without reversing the polarity of excitation. In Fig. 8.25, CH_1, CH_4 D_2 and D_3 constitute one Type C chopper and CH_2, CH_3, D_1 and D_4 form another Type C chopper circuit. Figure 8.25(b) shows Class-E with R–L load.

If chopper CH_4 is turned on continuously, the antiparallel connected pair of devices CH_4 and D_4 constitute a short-circuit. Chopper CH_3 may not be turned on at the same time as CH_4 because that would short circuit source E_{dc}.

With CH_4 continuously on, and CH_3 always off, operation of choppers CH_1 and CH_2 will make E_0 positive and I_0 reversible, and operation in the first and second quadrants is possible. On the other hand, with CH_2 continuously on and CH_1 always off, operation of CH_3 and CH_4 will make E_0 negative and I_0 reversible, and operation in the third and fourth quadrants is possible.

The operation of the four-quadrant chopper circuit is explained in detail as follows:

When choppers CH_1 and CH_4 are turned-on, current flows through the path, $E_{dc+} - CH_1$ – load – $CH_4 - E_{dc-}$. Since both E_0 and I_0 are positive, we get the first quadrant operation. When both the choppers CH_1 and CH_4 are turned-off, load dissipates its energy through the path load–$D_3 - E_{dc+} - E_{dc-} - D_2$ – load. In this case, E_0 is negative while I_0 is positive, and fourth-quadrant operation is possible.

When choppers CH_2 and CH_3 are turned-on, current flows through the path, $E_{dc+} - CH_3$ – load – $CH_2 - E_{dc-}$. Since both E_0 and I_0 are negative, we get the third-quadrant operation. When both choppers CH_2 and CH_3 are turned-off, load dissipates its energy through the path load– $D_1 - E_{dc+}- E_{dc-} - D_2$ – load. In this case, E_0 is positive and I_0 is negative, and second-quadrant operation is possible.

This four-quadrant chopper circuit consists of two bridges, forward bridge and reverse bridge. Chopper bridge CH_1 to CH_4 is the forward bridge which permits energy flow from source to load. Diode bridge D_1 to D_4 is the reverse bridge which permits the energy flow from load-to-source. This four-quadrant chopper configuration can be used for a reversible regenerative d.c. drive.

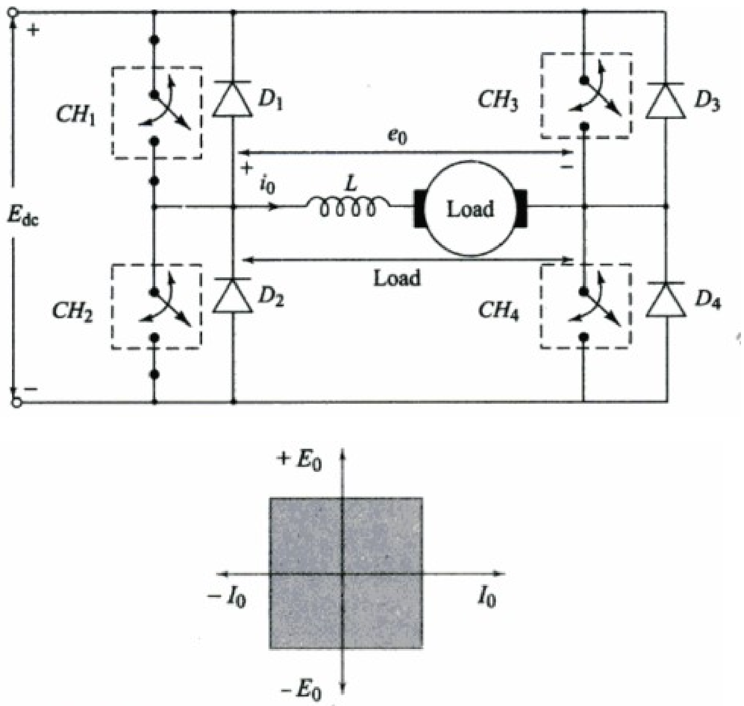


Fig. 8.25(a) *Type E chopper circuit and characteristic*

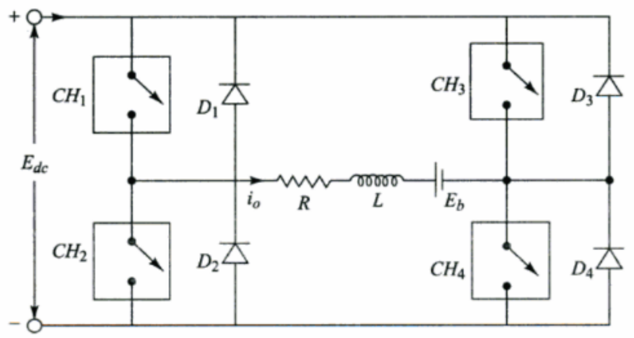


Fig. 8.25(b) *Class E chopper with R–L load*