4 Chopper-Controlled DC Motor Drive

- Chopper: The variable dc voltage is controlled by varying the on- and off-times of a converter.
- Fig. 4.1 is a schematic diagram of the chopper.

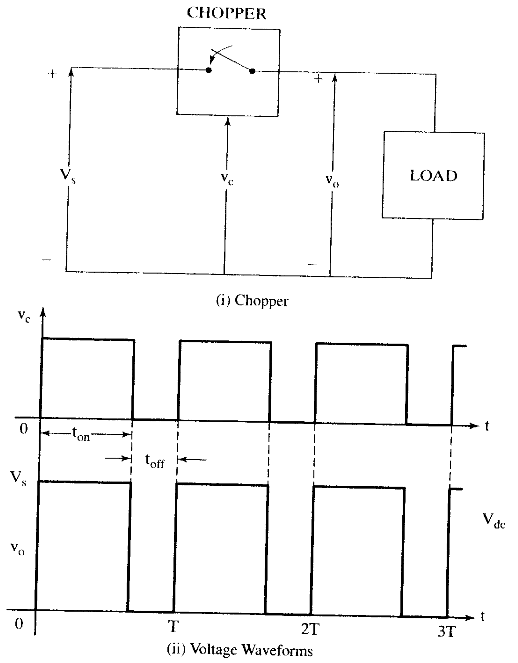


Figure 4.1 Chopper schematic and its waveforms

- Its frequency of operation is

$$f_c = \frac{1}{(t_{on} + t_{off})} = \frac{1}{T}$$

and its duty cycle is defined as

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

- Assuming that the switch is ideal, the average output is

$$V_{dc} = \frac{t_{on}}{T} V_s = dV_s$$

- varying the duty cycle changes the output voltage.

- The duty cycle d can be changed in two ways:

(i) varying the on-time (constant switching frequency).

(ii) varying the chopping frequency.

- Constant switching frequency has many advantages in practice.

4.3 Four-Quadrant Chopper Circuit

- Fig. 4.2 is the chopper circuit with transistor switches.

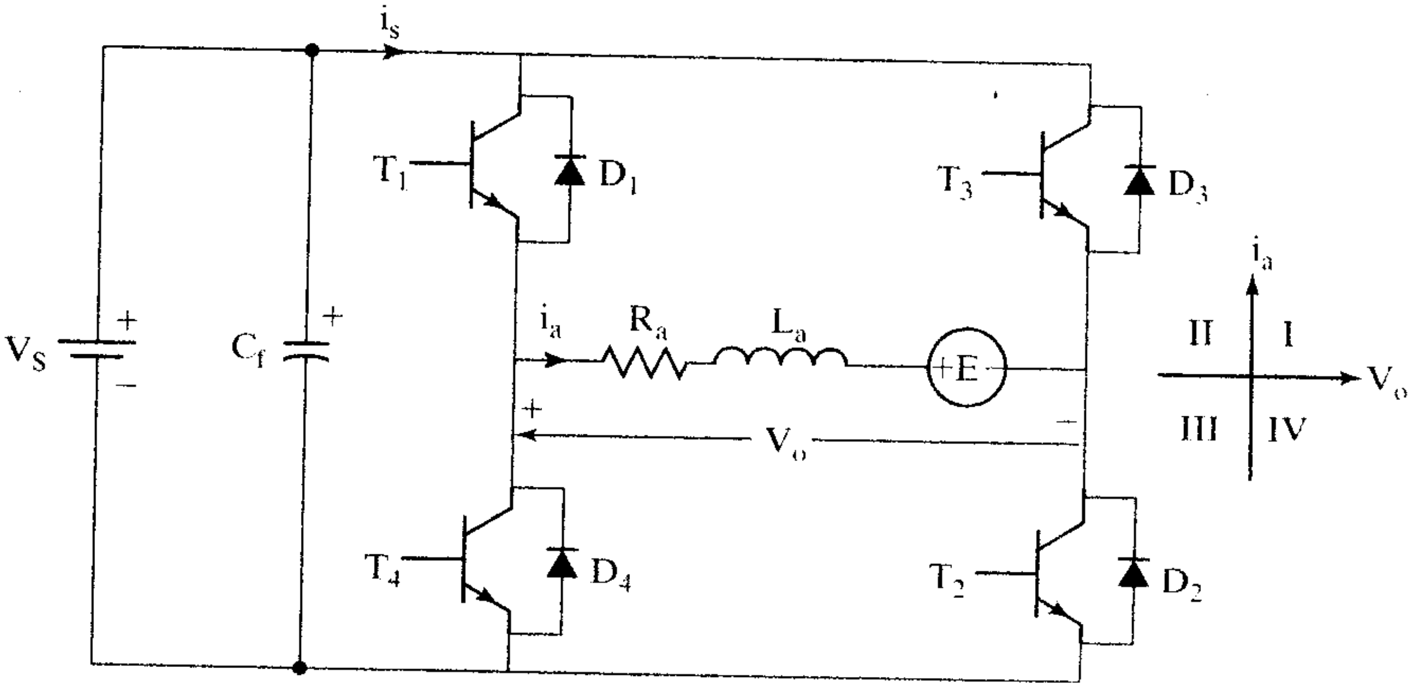


Figure 4.2 A four-quadrant chopper circuit

- Fig. 4.3 is first-quadrant operation.

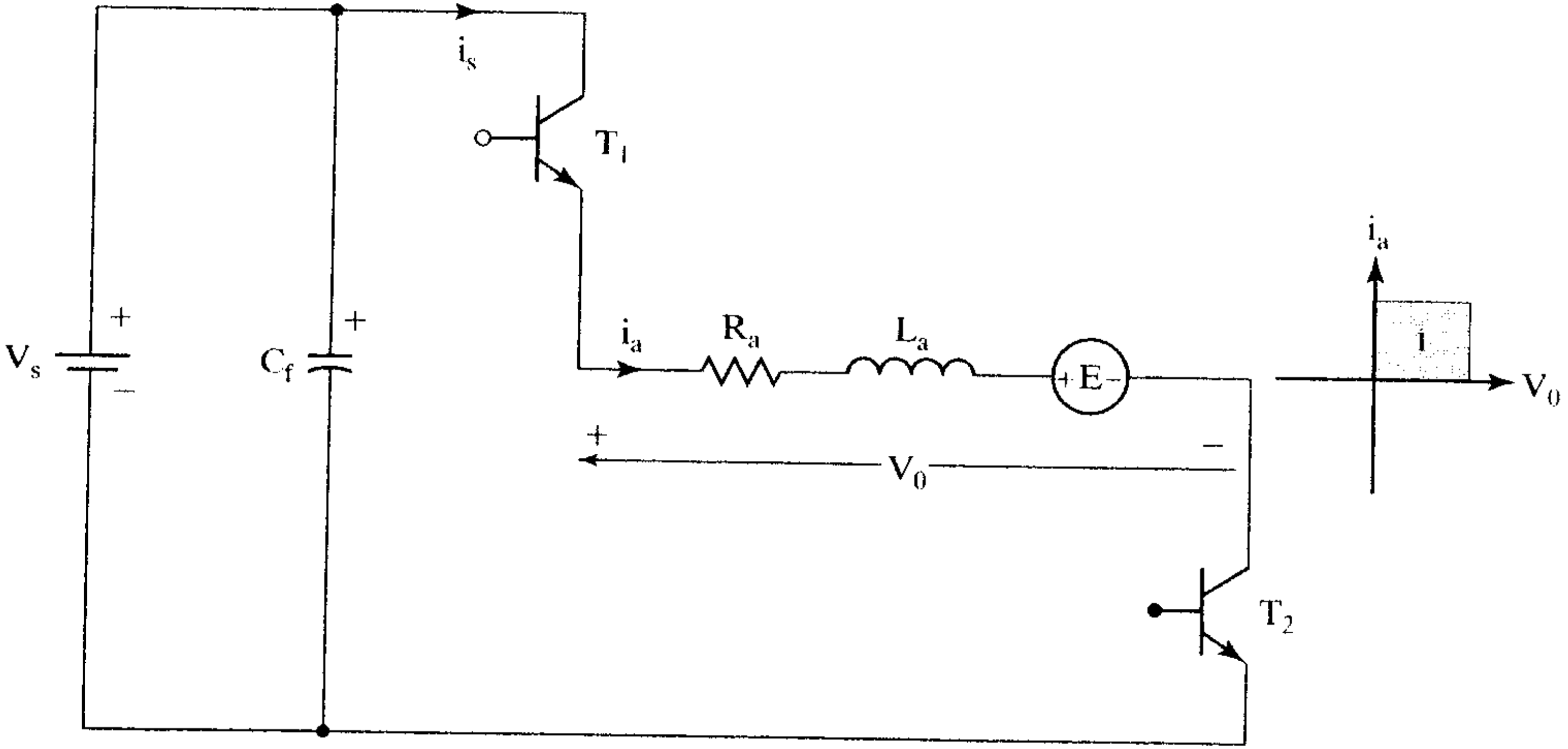


Figure 4.3 First-quadrant operation with positive voltage and current in the load

- Fig. 4.4 is first-quadrant operation with zero voltage across the load.

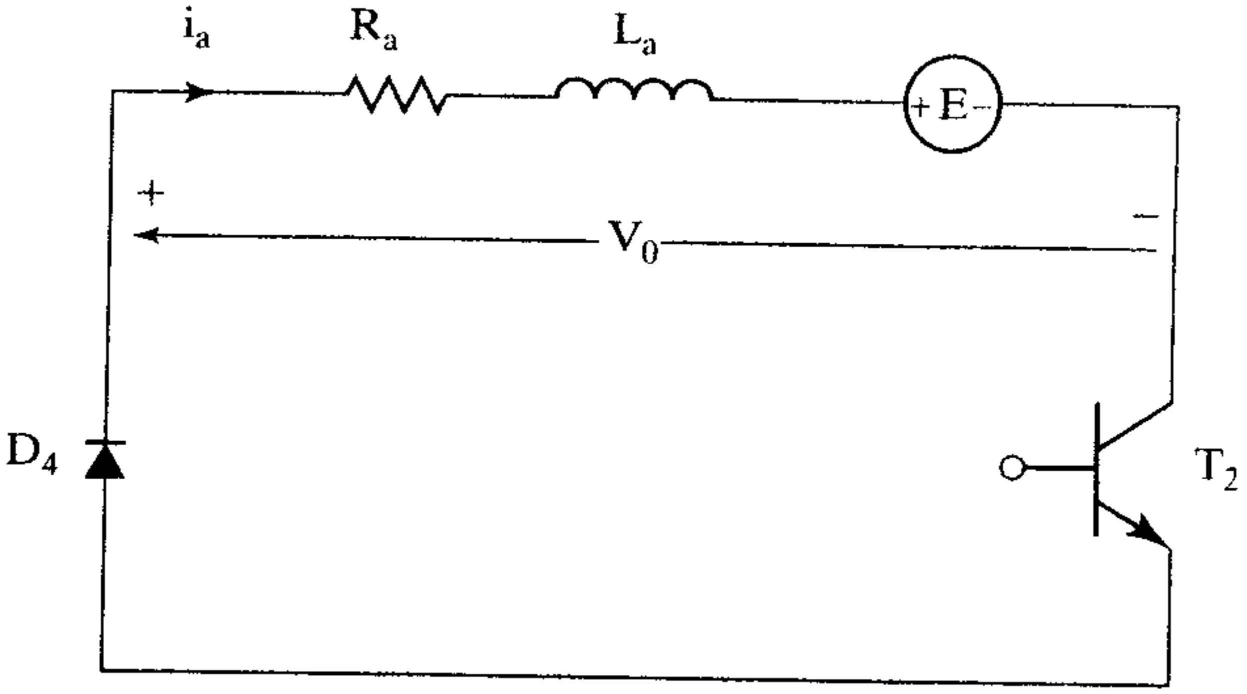
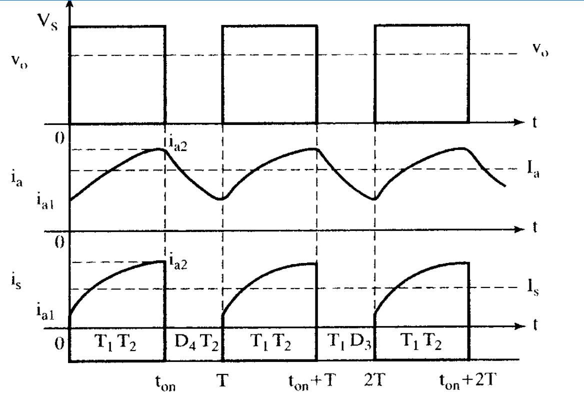
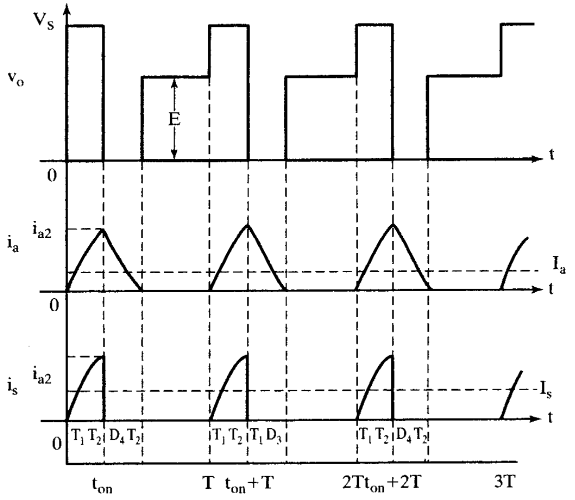


Figure 4.4 First-quadrant operation with zero voltage across the load

- Fig. 4.5 voltage and current waveforms in first-quadrant operation.



(i) Continuous Conduction



(ii) Discontinuous Conduction

Figure 4.5 Voltage and current waveforms in first-quadrant operation

- Fig. 4.6 second-quadrant operation

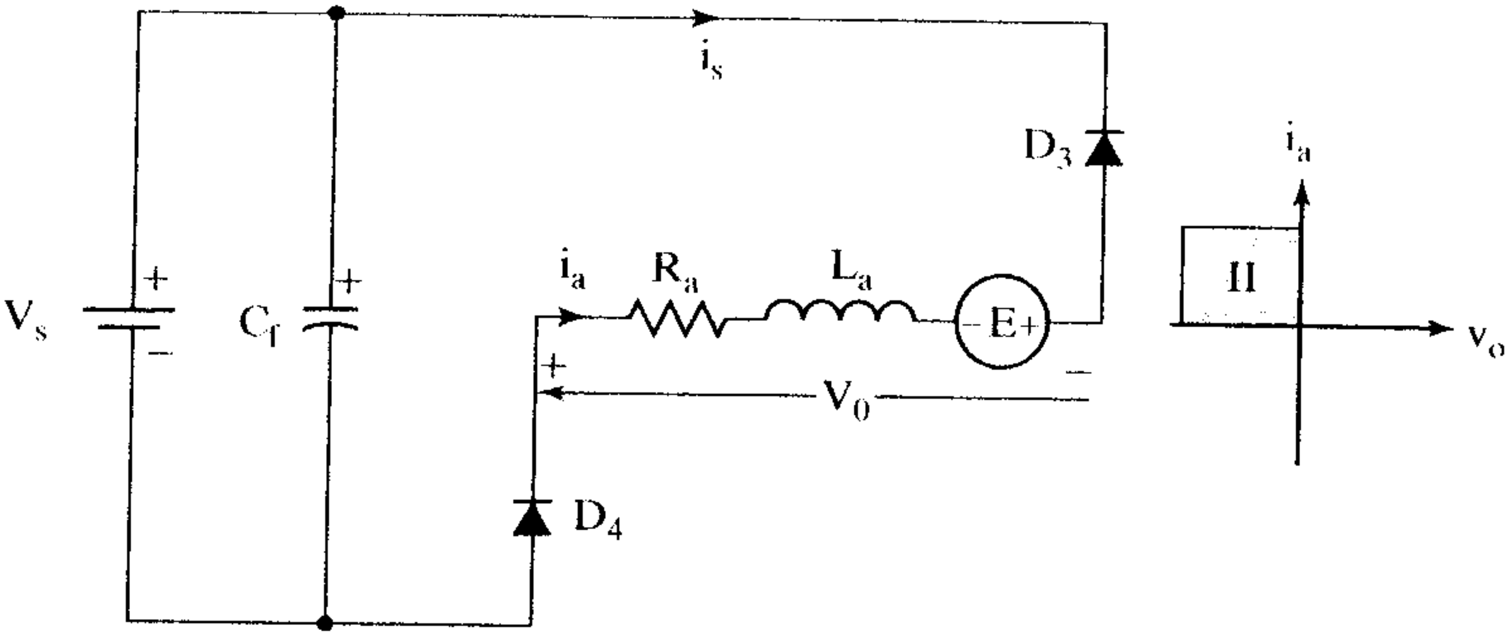


Figure 4.6 Second-quadrant operation, with negative load voltage and positive current

- Fig. 4.7 voltage and current waveforms in second-quadrant operation.

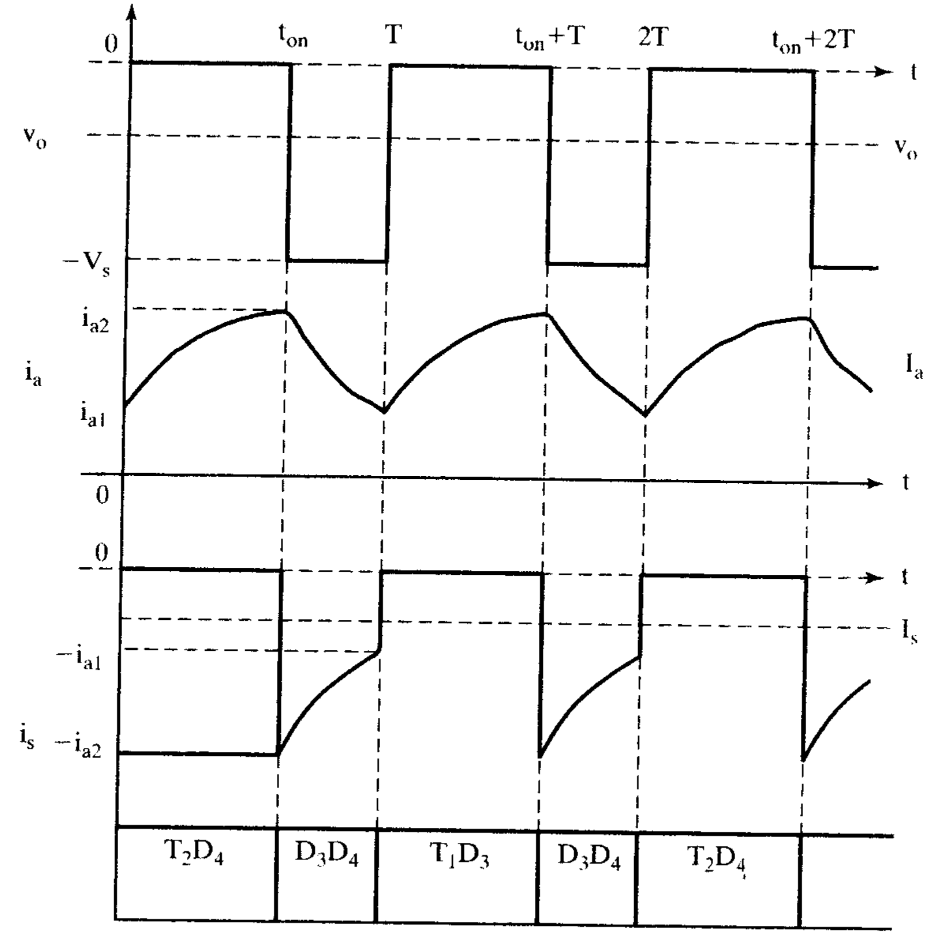
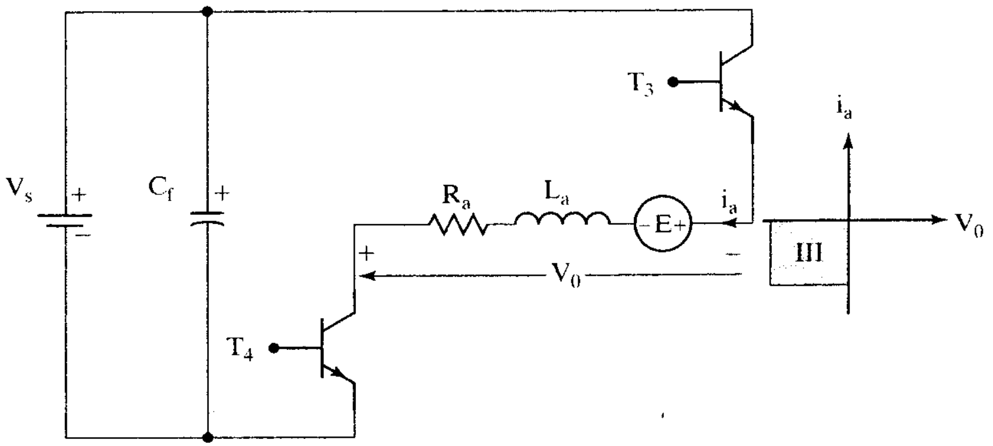
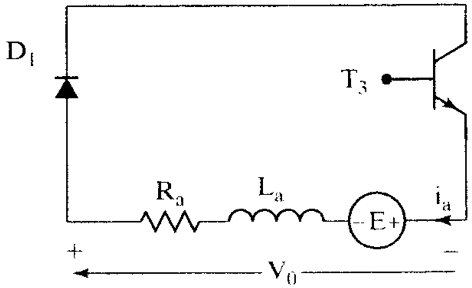


Figure 4.7 Second-quadrant operation of the chopper

- Fig. 4.8 Modes of operation in the third quadrant.



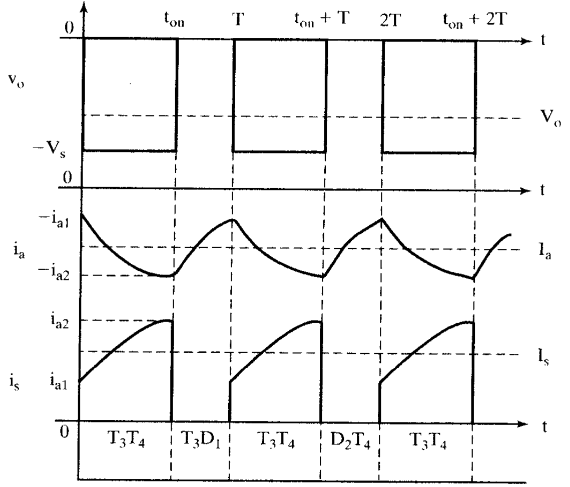
(i) Increasing load current



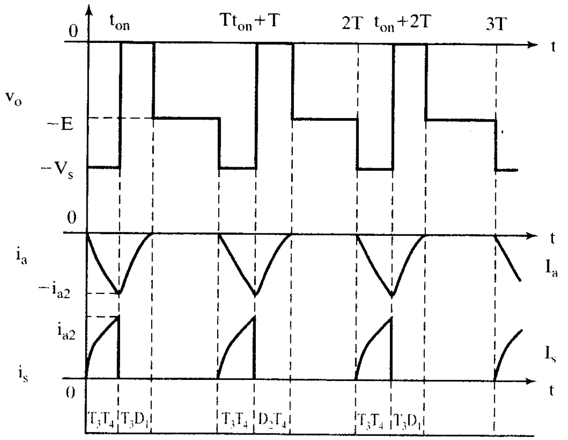
(ii) Decreasing load current

Figure 4.8 Modes of operation in the third quadrant

- Fig. 4.9 waveform in third-quadrant operation



(i) Continuous Conduction



(ii) Discontinuous Conduction

Figure 4.9 Third-quadrant operation

- Fig. 4.10 Waveforms in fourth-quadrant operation.

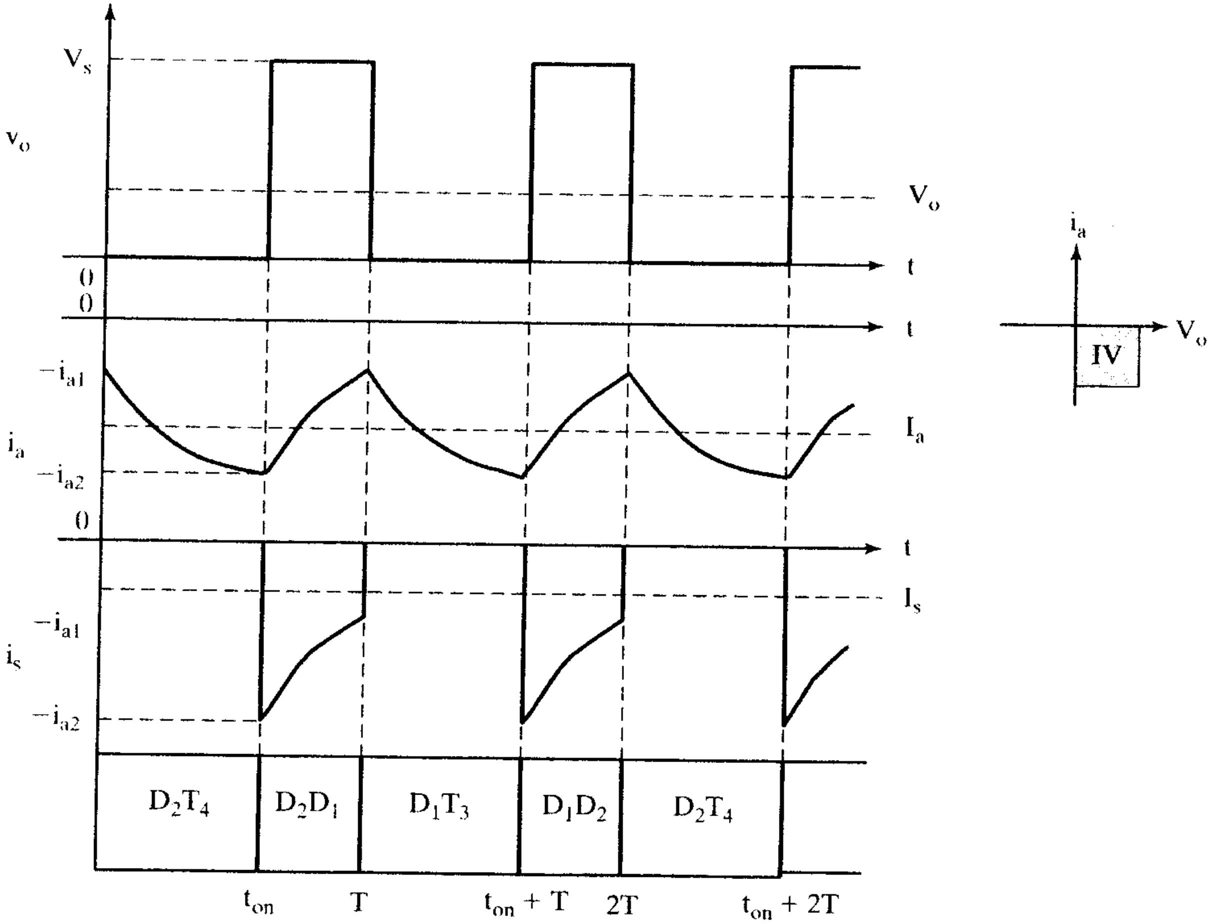


Figure 4.10 Fourth-quadrant operation of the chopper

4.4 Chopper for inversion

- Converter: DC ⇒ DC (different voltage)
- The chopper is the building block for that: AC ⇒ DC ⇒ DC(different voltage)

4.5 Chopper with other power devices

- MOSFETs, IGBTs, GTOs, or SCRs are used for different power level.
- The MOSFET and transistor choppers are used at power levels up to 50kW.

4.6 Model of The Chopper

- The transfer function of the chopper is

$$G_r(s) = \frac{K_r}{1 + \frac{sT}{2}}$$

where $K_r = V_s/V_{cm}$, V_s is the source voltage, and V_{cm} is the maximum control voltage.

- Increasing the chopping frequency decreases the delay time, and its becomes a simple gain.

4.7 Input to the chopper

- The chopper input: a battery or a rectified ac supply.
- Fig. 4.11 is the chopper with rectified circuit.

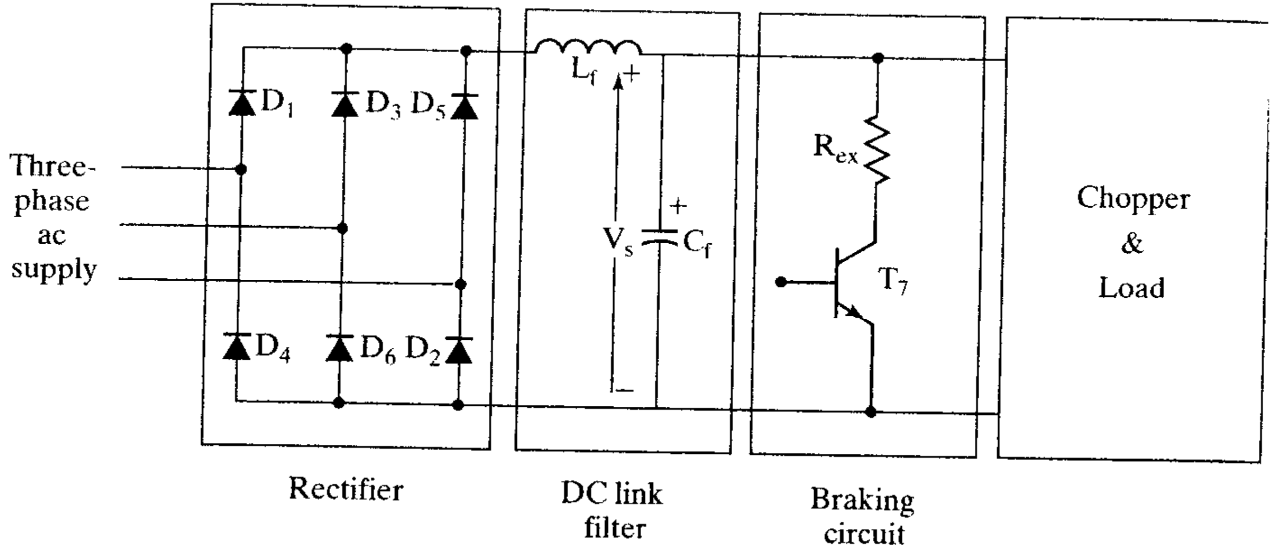


Figure 4.11 Front-end of the chopper circuit

- Its disadvantage: it cannot transfer power from dc link into ac mains.
- Fig. 4.12 Chopper with regeneration capability

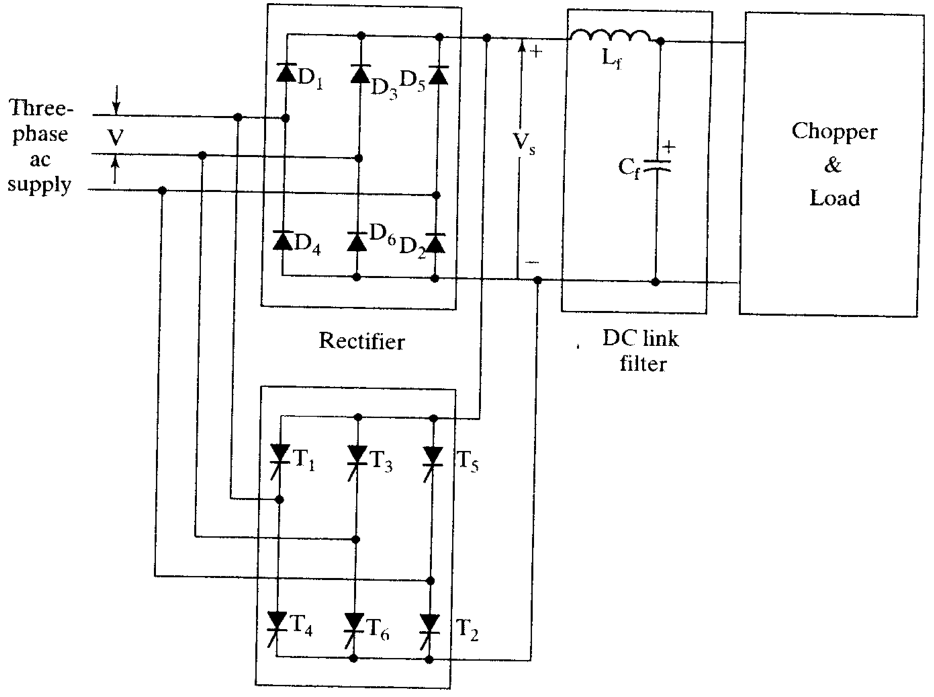
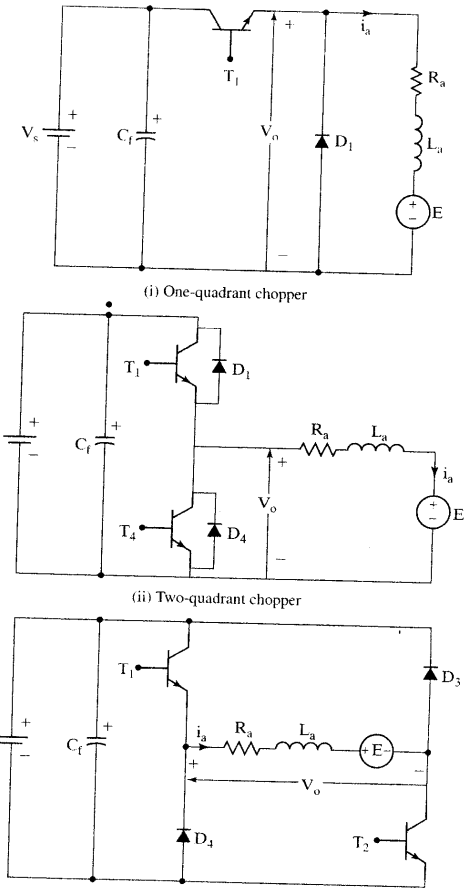


Figure 4.12 Chopper with regeneration capability

- The generating converter has to be operated at triggering angles greater that 90^{0}.

4.8 Other Chopper Circuits

- Fig. 4.13 one- and two-quadrant operation.



(i) One-quadrant chopper

(ii) Two-quadrant chopper

(iii) Two-quadrant chopper

Figure 4.13 Variations of Figure 4.2 for one- and two-quadrant operation

4.9 Steady-state analysis ...

- 4.9.1 Analysis by averaging
- The average armature current is

$$I_{av} = \frac{V_{dc} - E}{R_a}$$

where $V_{dc} = dV_s$

- The electromagnetic torque is

$T_{av} = K_b I_{av} = K_b(dV_s - K_b w_m)/R_a$ (N·m)

- The normalized torque is

$$T_{en} = \frac{T_{av} / V_b}{T_b / V_b} = \frac{K_b(dV_s - K_b\omega_m) / V_b}{K_b I_b R_a / V_b} = \frac{dV_n - \omega_{mn}}{R_{an}}, \text{ p.u.}$$

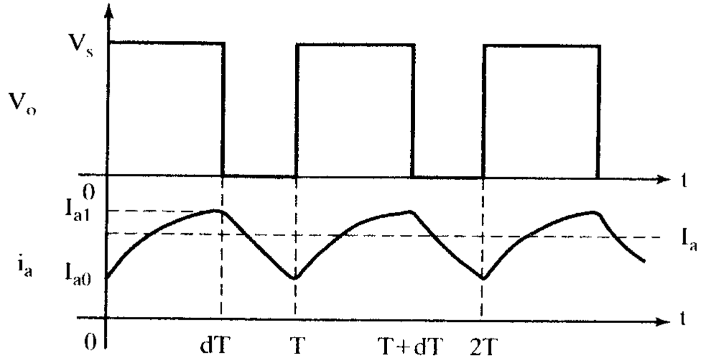
where $R_{an} = \frac{I_b R_a}{V_b}$, p.u. $V_n = \frac{V_s}{V_b}$, p.u. $\omega_{mn} = \frac{\omega_m}{\omega_b}$, p.u.

- 4.9.2 Instantaneous steady-state computation (including harmonics)
- The equations of the motor for on and off times (continuous current conduction)

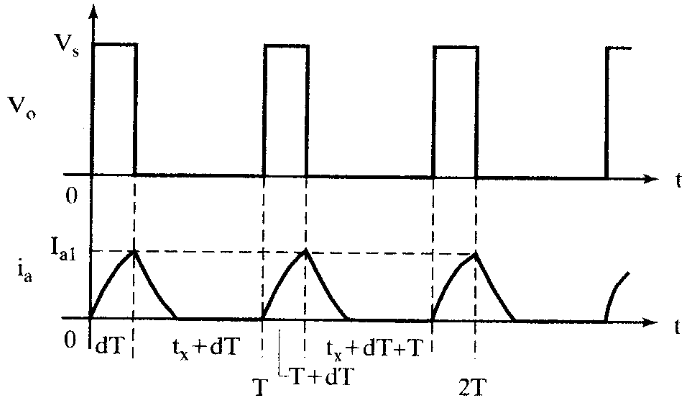
$$V_s = E + R_a i_a + L_a \frac{di_a}{dt}, \quad 0 \le t \le dT$$

$$0 = E + R_a i_a + L_a \frac{di_a}{dt}, \quad dT \le t \le T$$

- Fig. 4.15 The waveform of applied voltage and armature current.



(i) Continuous Conduction



(ii) Discontinuous Conduction

Figure 4.15 Applied voltage and armature current in a chopper-controlled dc motor drive

- The solutions of the above equations:

$$i_a(t) = \frac{V_s - E}{R_a}\left(1 - e^{-\frac{t}{T_a}}\right) + I_{a0} e^{-\frac{t}{T_a}}, \quad 0 < t < dT$$

$$i_a(t) = -\frac{E}{R_a}\left(1 - e^{-\frac{t^1}{T_a}}\right) + I_{a1} e^{-\frac{t^1}{T_a}}, \quad dT \le t \le dT$$

where $T_a = L_a/R_a$ (Armature time constant)

$t^1 = t - dT$

- By using boundary condition

$$I_{a1} = \frac{V_s(1 - e^{-dT/T_a})}{R_a(1 - e^{-T/T_a})} - \frac{E}{R_a} \qquad I_{a0} = \frac{V_s(e^{dT/T_a} - 1)}{R_a(e^{T/T_a} - 1)} - \frac{E}{R_a}$$

- The critical duty cycle: the limiting or minimum value of duty cycle for continuous current; I_{a0} equates to zero.
- The relevant equations for discontinuous current-conduction mode

$$V_s = E + R_a i_a + L_a \frac{di_a}{dt}, \quad 0 \le t \le dT$$

$$0 = E + R_a i_a + L_a \frac{di_a}{dt}, \quad dT \le t \le t_x + dT$$

with $i_a(t_x + dT) = 0; \; i_a(0) = 0$

- Hence,

$$I_{a1} = \frac{V_s - E}{R_a}(1 - e^{-dT/T_a})$$

$$i_a(t_x + dT) = -\frac{E}{R_a}(1 - e^{-\frac{t_x}{T_a}}) + I_{a1}e^{-\frac{t_x}{T_a}}$$

- tx is evaluated from (4.25) and the above eqs. as

$$t_x = T_a \log_e[1 + \frac{I_{a1}R_a}{E}]$$

- The solution for the armature current in three time segments is

$$i_a(t) = \frac{V_s - E}{R_a}(1 - e^{-\frac{t}{T_a}}), \quad 0 < t < dT$$

$$i_a(t) = I_{a1}e^{-\frac{(t-dT)}{T_a}} - \frac{E}{R_a}(1 - e^{-\frac{(t-dT)}{T_a}}), \quad dT \le t \le t_x \text{ - } dT$$

$$i_a(t) = 0, \quad (t_x + dT) < t < T$$

4.10 Rating of the device

- The rms value of the power switch current

$$I_t = \sqrt{\frac{I_{max}^2}{2T}(T + dT)} = \sqrt{\frac{1+d}{2}} \cdot I_{max}$$

- The average diode current

$$I_d = (\frac{1-d}{2}) \cdot I_{max}$$

- Transistor and diode currents for motoring operation in the continuous-conduction mode.

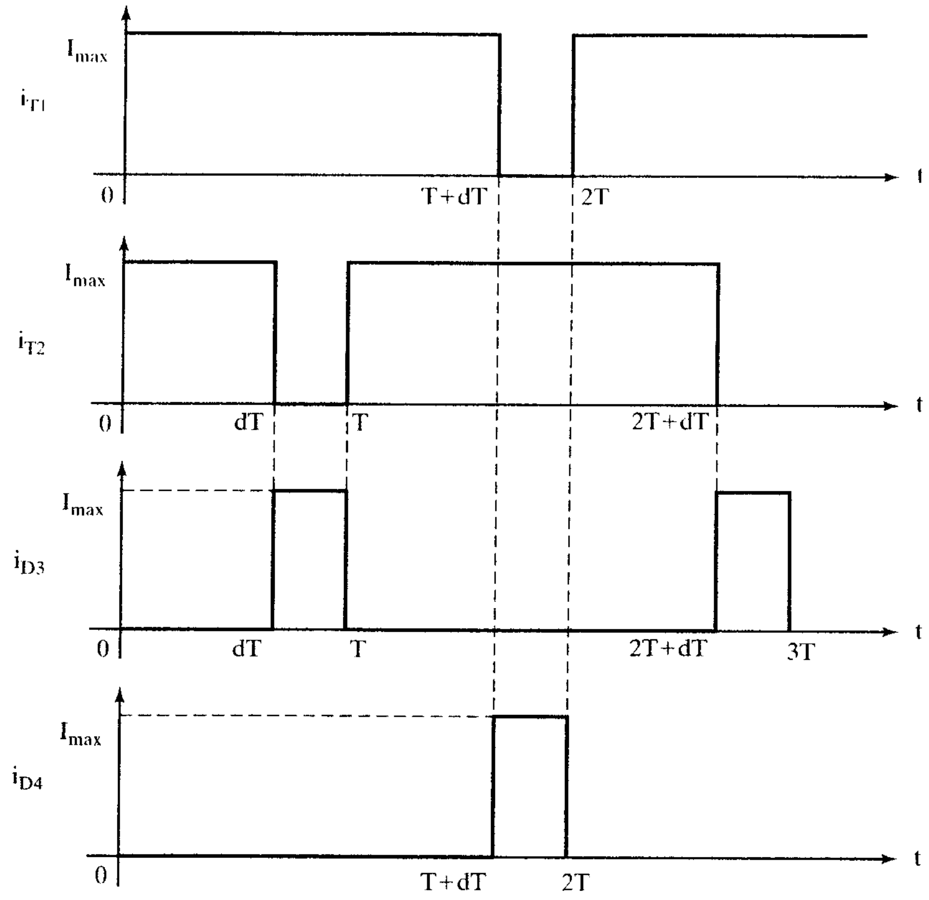


Figure 4.17 Transistor and diode currents in the chopper for motoring operation in the continuous-conduction mode

4.11 Pulsating Torque

- The average of the harmonic torque is zero.
- High-performance applications require the pulsating torque to be minimum.
- The applied voltage is resolved into Fourier components as

$$V_a(t) = V_a + \sum_{n=1}^{\infty} A_n \sin(n\omega_c t + \theta_n)$$

where $V_a = \frac{dT}{T} V_s = dV_s$ $\quad \omega_c = 2\pi f_c = \frac{2\pi}{T}$

$$A_n = \frac{2V_s}{n\pi} \sin \frac{n\omega_c dT}{2} \qquad \theta_n = \frac{\pi}{2} - \frac{n\omega_c dT}{2}$$

- The armature current is expressed as

$$i_a(t) = I_{av} + \sum_{n=1}^{\infty} \frac{A_n}{|Z_n|} \sin(n\omega_c t + \theta_n - \phi_n)$$

where $I_{av} = \dfrac{V_a - E}{R_a}$ $\quad Z_n = R_a + jn\omega_c L_a$

$$\phi_n = \cos^{-1}\left\{\frac{R_a}{\sqrt{R_a^2 + n^2\omega_c^2 L_a^2}}\right\}$$

- The input power is

$$P_i = V_a(t) i_a(t)$$

$$= \left\{\begin{array}{l} V_a I_{av} + I_{av} \sum_{n=1}^{\infty} A_n \sin(n\omega_c t + \theta_n) \\ + V_a \sum_{n=1}^{\infty} \frac{A_n}{|Z_n|} \sin(n\omega_c t + \theta_n - \phi_n) + \sum_{n=1}^{\infty} \left(\frac{A_n^2}{|Z_n|} \sin(n\omega_c t + \theta_n) \sin(n\omega_c t + \theta_n - \phi_n) \right) \end{array}\right\}$$

4.12 Closed-loop operation

- Fig. 4.20 is the closed-loop speed-controller dc motor drive.

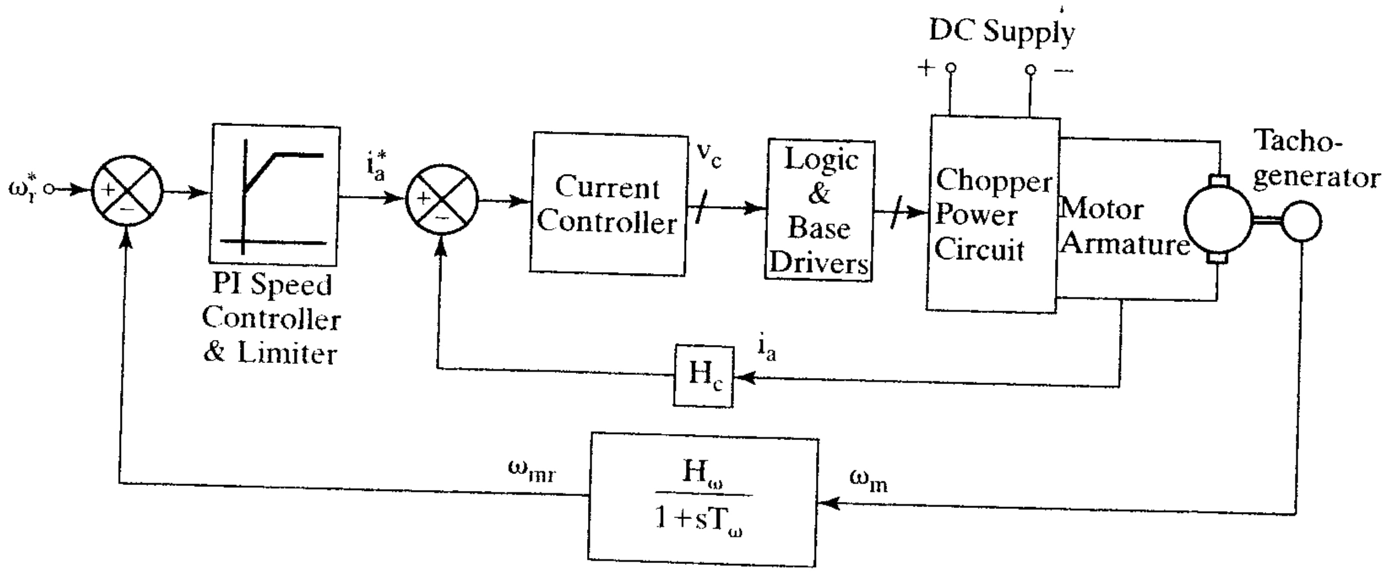


Figure 4.20 Speed-controlled dc-motor chopper drive

- The current controller can be

(i) Pulse-Width-Modulation (PWM) controller

(ii) Hysteresis controller

Fig. 4.21 shows on- and off-time for PWM

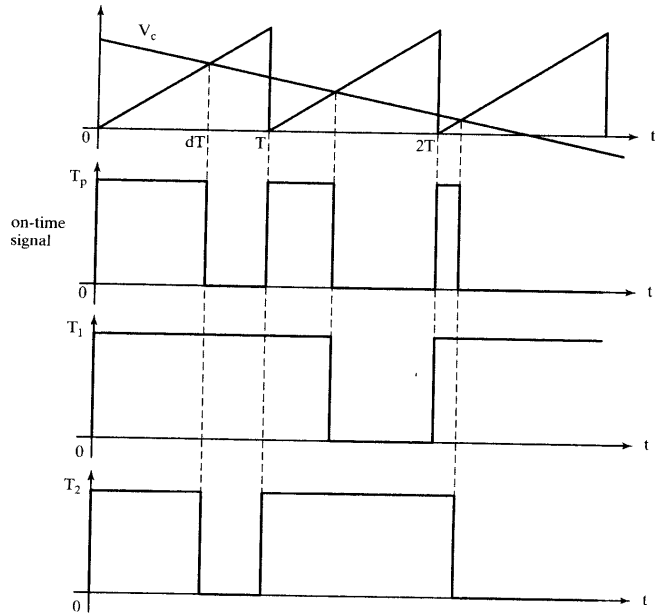
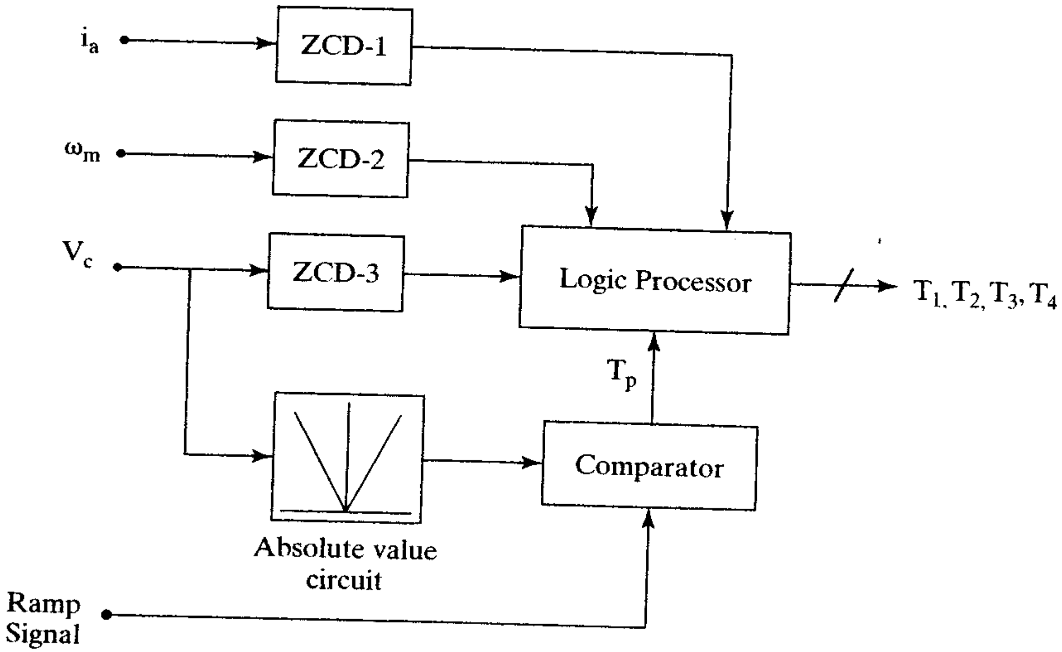


Figure 4.21 Generation of base-drive signals from current error for forward motoring when one is using the chopper shown in Figure 4.2

- Fig. 4.22 is the implementation of PWM current controller.



Note : ZCD — Zero Crossing Detector for polarity detection

Figure 4.22 PWM current-controller implementation with ramp carrier signal

- Fig. 4.24 shows hysteresis-controlled operation

$$i_a \le i_a^* - \Delta i, \quad \text{set } v_a = V_s$$

$$i_a \ge i_a^* + \Delta i, \quad \text{reset } v_a = 0$$

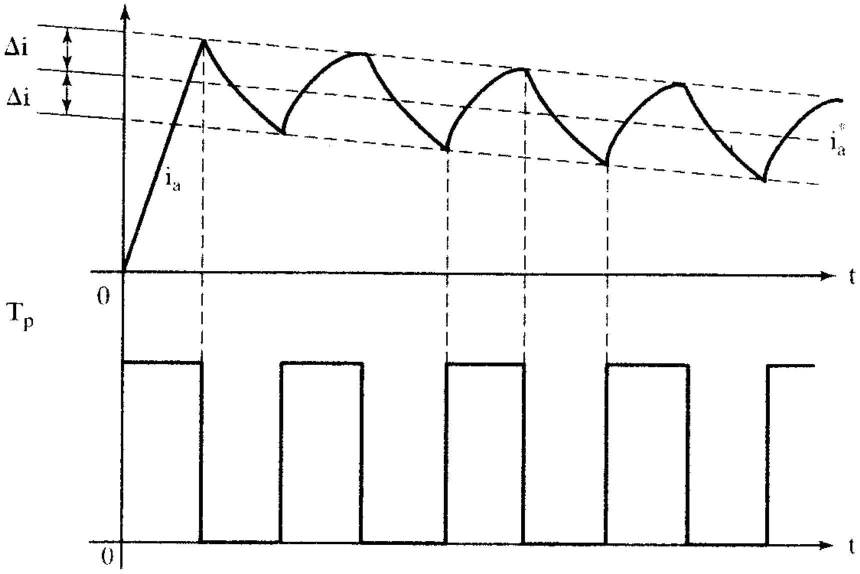


Figure 4.24 Hysteresis-controller operation

- Fig. 4.23

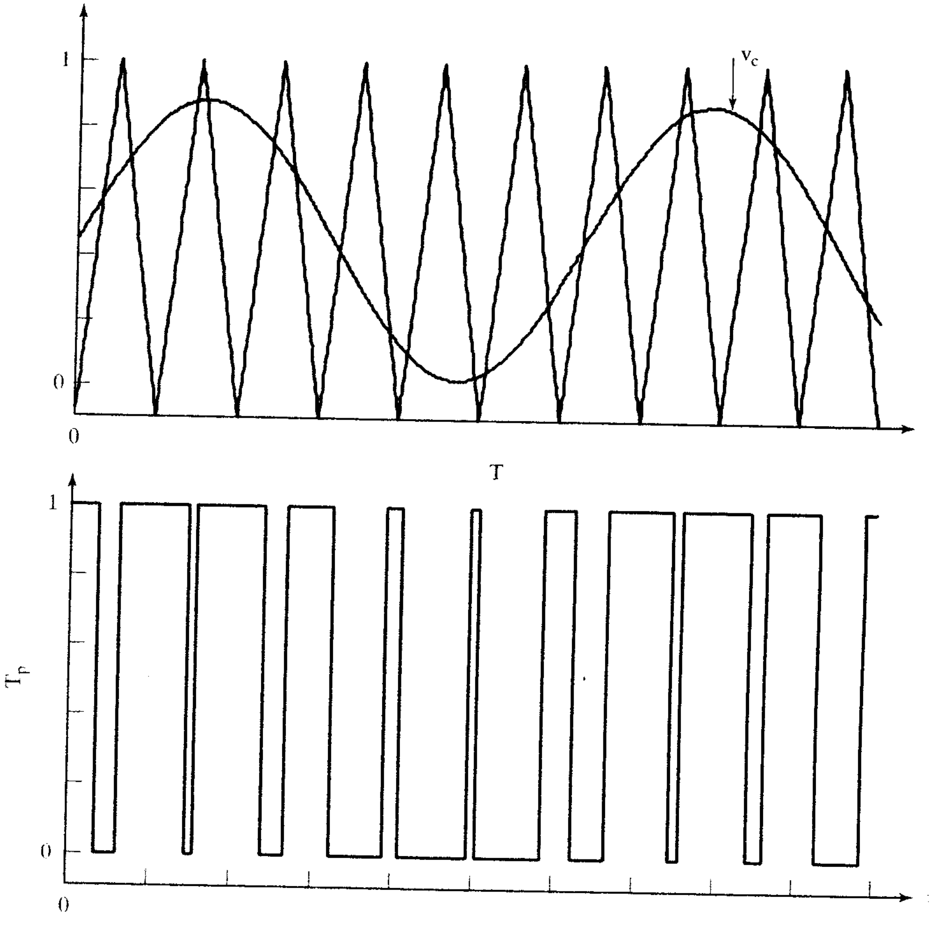


Figure 4.23 Principle of PWM operation

- Fig. 4.25 is realization of hysteresis controller.

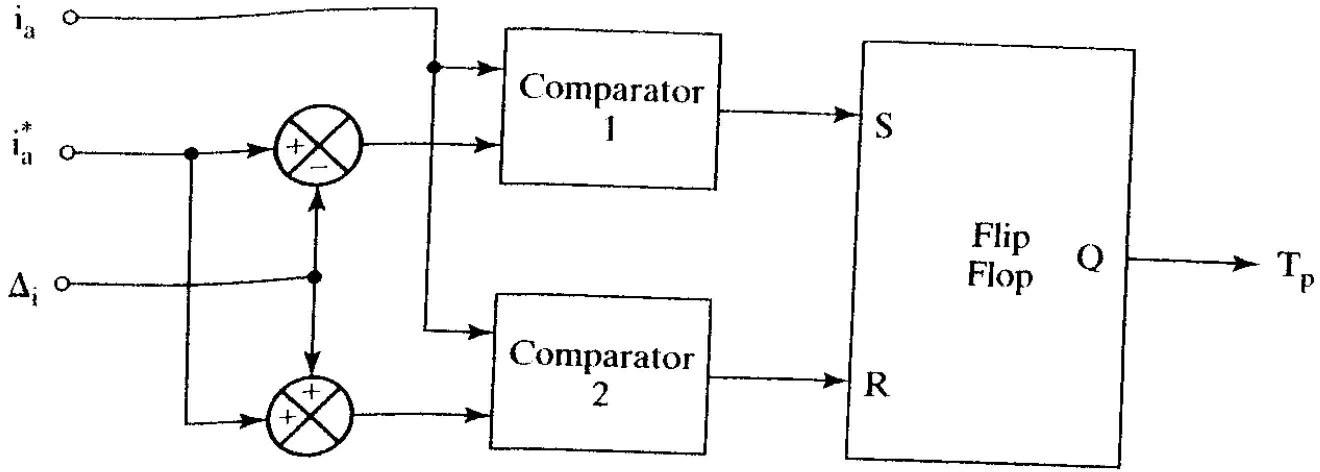


Figure 4.25 Realization of hysteresis controller