$$PF = \frac{\text{Real Power}}{\text{Apparent Power}} = \frac{VI_1 \cos \phi_1}{VI_{rms}}$$

where

V = rms source voltage, V

I_{rms} = rms source current, A

I_1 = fundamental component of source current, A

ϕ_1 = phase difference between V and I_1, rad

Therefore

$$PF = \frac{I_1}{I_{rms}} \cos \phi_1 = \mu \cos \phi_1 \tag{5.109}$$

where μ is called the distortion factor and cos ϕ_1 is the displacement factor. The distortion in source current makes μ lower than 1. When motor current is assumed to be perfect dc, ϕ_1 has a value of α for fully controlled single phase and three phase rectifiers and $\alpha/2$ for single phase half controlled rectifiers, thus giving displacement factors of cos α and cos $\alpha/2$ respectively. Therefore, supply power factor is low when the drive operates at low speeds.

Pulsewidth modulated rectifiers are being built using insulated gate bipolar transistors (IGBT) and gate turn-off thyristors (GTO) as they have high power factor and low harmonic content in source current but then their efficiency is low because of high switching losses.

(iii) *Ripple in motor current:* The rectifier output voltage is not perfect dc but consists of harmonics in addition to dc component. Therefore, motor current also has harmonics in addition to dc component. The presence of harmonics, makes rms and peak values of motor currents higher than average value (dc component). Since flux is constant, torque is contributed only by the average value of current. The harmonics produce fluctuating torques, the average value of which is zero. The presence of harmonics increases both copper loss and core loss. Hence for a allowable temperature rise, the torque and power outputs have lesser values than rated values. Due to the presence of harmonics, peak value of current increases and commutation condition deteriorates. Hence, the current that the motor can commutate without sparking at the brushes has a lower dc component than the rated motor current. Thus the derating of motor occurs due to this also. On the whole the motor output (power and torque) has to be restricted considerably below rated value in order to avoid thermal overloading and sparking at brushes.

5.18 CHOPPER-CONTROLLED dc DRIVES

Choppers, also commonly known as dc-to-dc converters, are used to get variable dc voltage from a dc source of fixed voltage. Self commutated devices, such as MOSFETS, power transistors, IGBT (insulated gate bipolar transistor), GTO (gate turn-off thyristor) and IGCT (insulated gate commutated thyristor), are preferred over thyristors for building choppers because they can be commutated by a low power control signal and do not need commutation circuit. Further, they can be operated at a higher frequency for the same rating. The operation at a high frequency improves motor performance by reducing current ripple and eliminating discontinuous conduction.

While MOSFETS are used for low power and low voltage applications, IGBT and power transistor are employed in medium power ratings, and GTO and IGCT are employed for high power ratings. One important feature of chopper control is that regenerative braking can be carried out up to very low speeds even when the drive is fed from a fixed voltage dc source.

5.19 CHOPPER CONTROL OF SEPARATELY EXCITED dc MOTORS

Motoring Control

A transistor chopper controlled separately excited motor drive is shown in Fig. 5.41(a). Transistor T_r is operated periodically with period T and remains on for a duration t_{on}. Present day choppers operate at a frequency which is high enough to ensure continuous conduction. Waveforms of motor terminal voltage v_a and armature current i_a for continuous conduction are shown in Fig. 5.41(b). During on-period of the transistor, $0 \le t \le t_{on}$, the motor terminal voltage is V. The operation is described by

$$R_a i_a + L_a \frac{di_a}{dt} + E = V, \quad 0 \le t \le t_{on} \tag{5.110}$$

In this interval, armature current increases from i_{a1} to i_{a2}. Since motor is connected to the source during this interval, it is called *duty interval.*

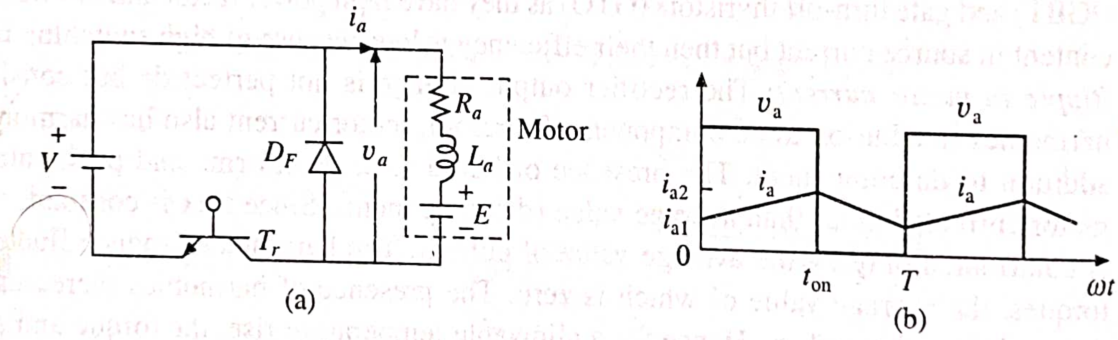

Fig. 5.41 Chopper control of separately excited motor

At $t = t_{on}$, T_r is turned-off. Motor current freewheels through diode D_F and motor terminal voltage is zero during interval $t_{on} \le t \le T$. Motor operation during this interval, known as *freewheeling interval*, is described by

$$R_a i_a + L_a \frac{di_a}{dt} + E = 0, \quad t_{on} \le t \le T \tag{5.111}$$

Motor current decreases from i_{a2} to i_{a1} during this interval.

Ratio of duty interval t_{on} to chopper period T is called *duty ratio* or *duty cycle* (δ). Thus

$$\delta = \frac{\text{Duty interval}}{T} = \frac{t_{on}}{T} \tag{5.112}$$

From Fig. 5.41(b)

$$V_a = \frac{1}{T}\int_0^{t_{on}} V\,dt = \delta V \tag{5.113}$$

Equation (5.2) and (5.7) are also applicable due to reasons explained in Sec. 5.10

Now
$$I_a = \frac{\delta V - E}{R_a} \tag{5.114}$$

From Eqs. (5.7), (5.8) and (5.114)

$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2} T \tag{5.115}$$

The nature of speed torque characteristic is shown in Fig. 5.43.

Regenerative Braking

Chopper for regenerative braking operation is shown in Fig. 5.42(a). Transistor T_r is operated periodically with a period T and on-period of t_{on}. Waveforms of motor terminal voltage v_a and armature current i_a for continuous conduction are shown in Fig. 5.42(b). Usually an external inductance is added to increase the value of L_a. When T_r is on, i_a increase from i_{a1} to i_{a2}. The

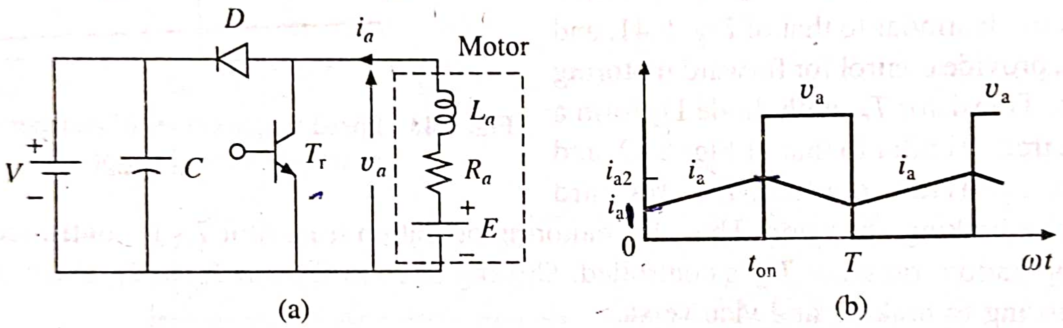

Fig. 5.42 Regenerative braking of separately excited motor by chopper control

mechanical energy converted into electrical by the motor, now working as a generator, partly increases the stored magnetic energy in armature circuit inductance and remainder is dissipated in armature resistance and transistor. When T_r is turned off, armature current flows through diode D and source V, and reduces from i_{a2} to i_{a1}. The stored electromagnetic energy and energy supplied by machine is fed to the source. The interval $0 \le t \le t_{on}$ is now called *energy storage interval* and interval $t_{on} \le t \le T$ the *duty interval*. If δ is again defined as the ratio of duty interval to period T, then

$$\delta = \frac{\text{Duty interval}}{T} = \frac{T - t_{on}}{T} \tag{5.116}$$

From Fig. 5.42(b)

$$V_a = \frac{1}{T}\int_{t_{on}}^{T} V\,dt = \delta V \tag{5.117}$$

and from Fig. 5.42(a)

$$I_a = \frac{E - \delta V}{R_a} \tag{5.118}$$

Since I_a has reversed

$$T = -KI_a \tag{5.119}$$

From Eqs. (5.8), (5.118) and (5.119)

$$\omega_m = \frac{\delta V}{K} - \frac{R_a}{K^2}T \tag{5.120}$$

The nature of speed torque characteristic is shown in Fig. 5.43.

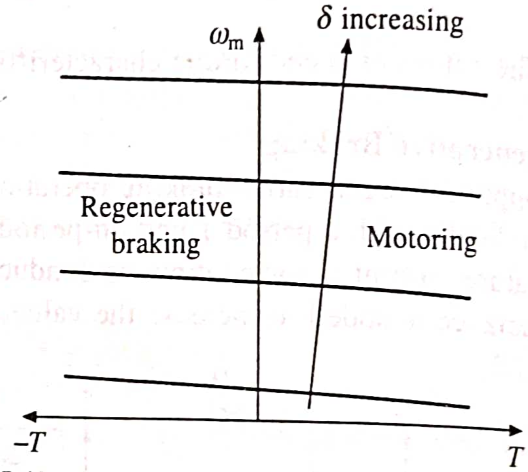

Fig. 5.43 Speed torque curves of chopper controlled separately excited motor

Motoring and Regenerative Braking

Chopper circuits of Figs. 5.41 and 5.42 can be combined to get a two quadrant chopper of Fig. 5.44, which can provide motoring and regenerative braking operations in the forward direction. Transistor T_{r1} with diode D_1 form a chopper circuit similar to that of Fig. 5.41, and therefore, provide control for forward motoring operation. Transistor T_{r2} with diode D_2 form a chopper circuit similar to that of Fig. 5.42, and therefore, provide control for forward regenerative braking operation. Thus, for motoring operation transistor T_{r1} is controlled and for braking operation transistor T_{r2} is controlled. Shifting of control from T_{r1} to T_{r2} shifts operation from motoring to braking and vice versa.

In servo drives where fast transition from motoring to braking and vice versa is required, both T_{r1} and T_{r2} are controlled simultaneously. In a period T, T_{r1} is given gate drive from 0 to δT and T_{r2} is given gate drive from δT to T, where δ is the duty ratio for T_{r1}. Therefore, from 0 to δT motor is connected to source either through T_{r1} or D_2 depending on whether the motor current i_a is positive or negative. Since $V > E$, during this period the rate of change of current is always positive. Similarly from δT to T, motor armature is shorted either through D_1 or T_{r2} depending on whether i_a is positive or negative and during this period rate of change of current is always negative. Motor terminal voltage and current waveforms are shown in Fig. 5.44 (b).

From Fig. 5.44(b)

$$V_a = \delta V \tag{5.113}$$

and

$$I_a = \frac{\delta V - E}{R_a} \tag{5.114}$$

Above equation suggests that motoring operation (+ve I_a) takes place when $\delta > (E/V)$ and regenerative braking operation takes place when $\delta < (E/V)$ and transition from motoring to braking and vice versa occurs when $\delta = (E/V)$. The above equations are similar to those obtained for chopper of Fig. (5.41), and therefore, given the same numbers.

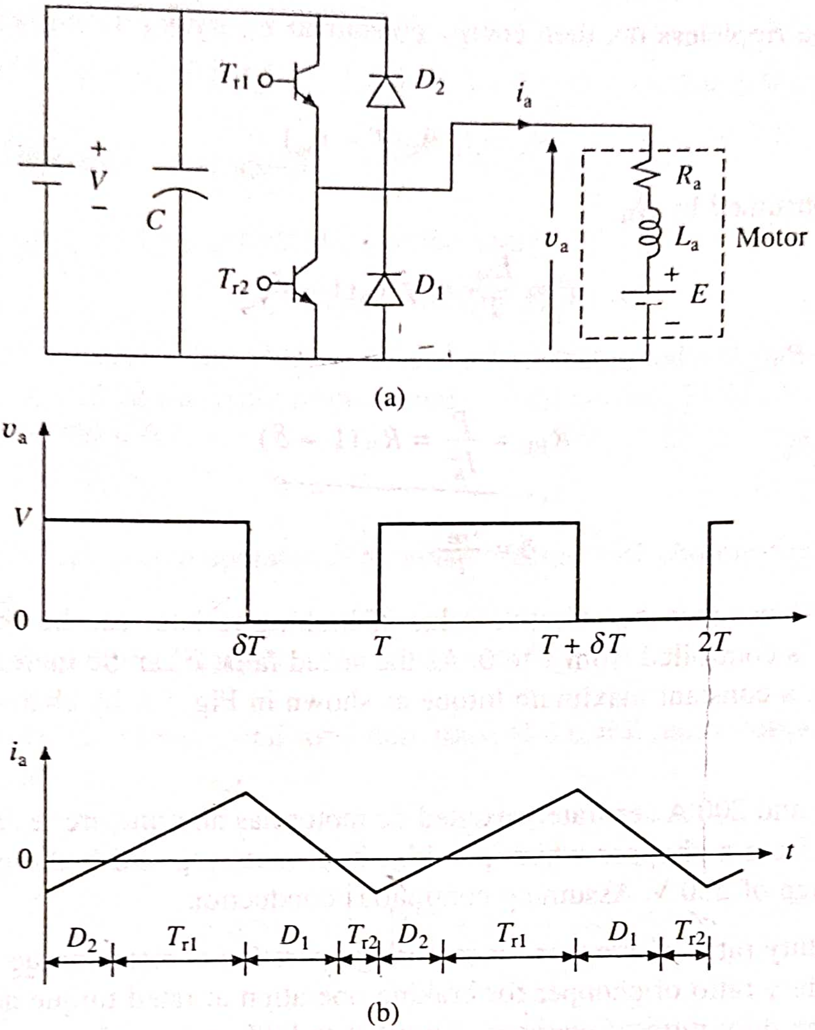

Fig. 5.44 Chopper for forward motoring and braking control

Dynamic Braking

Dynamic braking circuit and its waveforms are shown in Fig. 5.45. During the interval $0 \le t \le t_{on}$, i_a increases from i_{a1} to i_{a2}. A part of generated energy is stored in inductance and rest is dissipated in R_a and T_r. During interval $t_{on} \le t \le T$, i_a decreases from i_{a2} to i_{a1}. The energies generated and stored in inductance are dissipated in braking resistance R_B, R_a and diode D. Transistor T_r controls the magnitude of energy dissipated in R_B, and therefore, controls its effective value. If

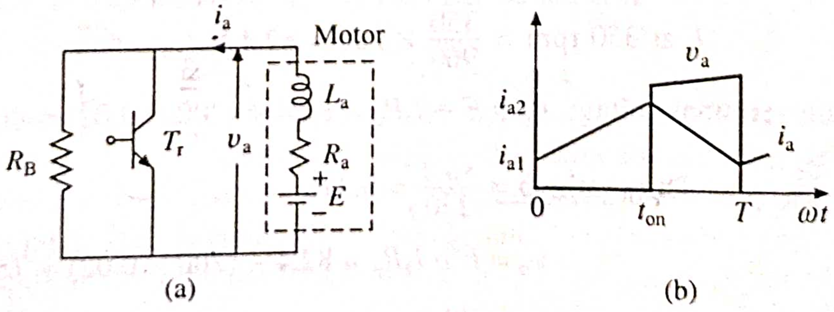

Fig. 5.45 Dynamic braking of separately excited motor by chopper control

i_a is assumed to be rippleless dc, then energy consumed E_N by R_B during a cycle of chopper operation is

$$E_N = I_a^2 R_B (T - t_{on})$$

Average power consumed by R_B

$$P = \frac{E_N}{T} = I_a^2 R_B (1 - \delta) \tag{5.121}$$

Effective value of R_B

$$R_{BE} = \frac{P}{I_a^2} = R_B (1 - \delta) \tag{5.122}$$

where

$$\delta = \frac{t_{on}}{T} \tag{5.123}$$

Equation (5.122) shows that the effective value of braking resistor can be changed steplessly from 0 to R_B as δ is controlled from 1 to 0. As the speed falls, δ can be increased steplessly to brake the motor at a constant maximum torque as shown in Fig. 5.8 by chain-dotted line.

EXAMPLE 5.19

A 230 V, 960 rpm and 200 A separately excited dc motor has an armature resistance of 0.02 Ω. The motor is fed from a chopper which provides both motoring and braking operations. The source has a voltage of 230 V. Assuming continuous conduction.

(i) Calculate duty ratio of chopper for motoring operation at rated torque and 350 rpm.
(ii) Calculate duty ratio of chopper for braking operation at rated torque and 350 rpm.
(iii) If maximum duty ratio of chopper is limited to 0.95 and maximum permissible motor current is twice the rated, calculate maximum permissible motor speed obtainable without field weakening and power fed to the source.
(iv) If motor field is also controlled in (iii), calculate field current as a fraction of its rated value for a speed of 1200 rpm.

Solution

At rated operation

$$E = 230 - (200 \times 0.02) = 226 \text{ V}$$

(i) $$E \text{ at } 350 \text{ rpm} = \frac{350}{960} \times 226 = 82.4 \text{ V}$$

$$\text{Motor terminal voltage } V_a = E + I_a R_a = 82.4 + (200 \times 0.02) = 86.4 \text{ V}$$

$$\text{Duty ratio } \delta = \frac{86.4}{230} = 0.376$$

(ii) $$V_a = E - I_a R_a = 82.4 - (200 \times 0.02) = 78.4 \text{ V}$$

$$\delta = \frac{78.4}{230} = 0.34$$

(iii) Maximum available $V_a = 0.95 \times 230 = 218.5$ V

$$E = V_a + I_a R_a = 218.5 + (200 \times 2 \times 0.02) = 226.5 \text{ V}$$

Maximum permissible motor speed $= \dfrac{226.5}{226} \times 960 = 962$ rpm

Assuming lossless chopper, power fed into the source

$$V_a I_a = 218.5 \times 400 = 87.4 \text{ kW}$$

(iv) As in (iii) $E = 226.5$ V for which at rated field current speed = 960 rpm. Assuming linear magnetic circuit, E will be inversely proportional to field current. Field current as a ratio of its rated value = 960/1200 = 0.8. at I_f = const

EXAMPLE 5.20

Motor of Example 5.19 is now operated in dynamic braking with chopper control with a braking resistance of 2 Ω.

(i) Calculate duty ratio of chopper for a motor speed of 600 rpm and braking torque of twice the rated value.

(ii) What will be the motor speed for a duty ratio of 0.6 and motor torque equal to twice its rated torque?

Solution

(i) $$E \text{ at } 600 \text{ rpm} = \frac{600}{960} \times 226 = 141.25 \text{ V}$$

$$R_{BE} = (1 - \delta) R_B = \frac{E}{I_a} - R_a$$

or $$(1 - \delta) \times 2 = \frac{141.25}{400} - 0.02 \text{ or } \delta = 0.83$$

(ii) $$E = I_a[(1 - \delta)R_B + R_a] = 400[(1 - 0.6) \times 2 + 0.02] = 328 \text{ V}$$

$$\text{Speed} = \frac{328}{226} \times 960 = 1393.3 \text{ rpm}$$

5.20 CHOPPER CONTROL OF SERIES MOTOR

Motoring

Chopper circuit and v_a and i_a waveforms will be same as shown in Fig. 5.41. V_a is given by Eq. (5.113). However, e is not constant but varies with i_a. Due to saturation of magnetic circuit, relationship between e and i_a is non-linear. The approximation described in Sec. 5.15 by Eqs. (5.105) through (5.108) is applicable. Consequently, motor performance can be calculated following the sequence of steps described in Sec. 5.15. The nature of speed torque curves is shown in Fig. 5.46.

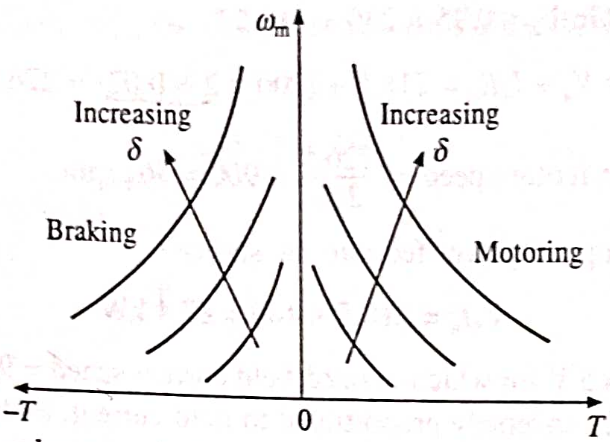

Fig. 5.46 Motoring and regenerative braking characteristics of chopper controlled series motor

Regenerative Braking

With chopper control, regenerative braking of series motor can also be obtained. Power circuit of Fig. 5.42(a) is employed. During regenerative braking, series motor functions as a self-excited series generator. For self-excitation, current flowing through field winding should assist residual magnetism. Therefore, when changing from motoring to braking connection, while direction of armature current should reverse, field current should flow in the same direction. This is achieved by reversing the field with respect to armature when changing from motoring to braking operation. Waveforms of v_a and i_a will be same as those of Fig. 5.42(b). Approximation of Eqs. (5.105) and (5.106) is applicable and V_a is given by (5.117). From Fig. 5.42(a) and Eqs. (5.105) and (5.117)

$$\omega_m = \frac{\delta V + I_a R_a}{K_a} \tag{5.124}$$

and

$$T = -K_a I_a \tag{5.125}$$

For a chosen value of I_a, K_a is obtained from magnetization characteristic. Then T and ω_m are obtained from Eqs. (5.125) and (5.124), respectively. The nature of speed-torque characteristics is shown in Fig. 5.46. Such characteristics give unstable operation with most loads. Consequently, regenerative braking of the series motor is difficult.

Dynamic Braking

Chopper circuit of Fig. 5.45(a) is used. Since motor works as a self-excited generator, when changing from motoring to braking, field should be reversed.

EXAMPLE 5.21

A 220 V, 70 A dc series motor has combined resistance of armature and field of 0.12 Ω. Running on no load with the field winding connected to a separate source it gave following magnetization characteristic at 600 rpm:

Field current, A	10	20	30	40	50	60	70	80
Terminal voltage, V	64	118	150	170	184	194	202	210

Motor is controlled by a chopper with a source voltage = 220 V. Calculate

(i) motor speed for a duty ratio of 0.6 and motor current of 60 A.
(ii) torque for a speed of 400 rpm and duty ratio of 0.65.

Solution

(i)
$$V_{a1} = \delta V = 0.6 \times 220 = 132 \text{ V}$$
$$E_1 = V_{a1} - I_{a1}R_a = 132 - 60 \times 0.12 = 124.8$$

From magnetization characteristic, for a speed of 600 rpm and $I_a = 60$ A, $E = 194$ V

Motor speed
$$N_1 = \frac{E_1}{E} \times 600 = \frac{124.8}{194} \times 600 = 386 \text{ rpm}$$

(ii)
$$\delta V = E + I_a R_a$$
$$0.65 \times 220 = E + 0.12\, I_a$$

or
$$0.12 I_a = 143 - E \qquad \text{(i)}$$

Equation (i) being nonlinear can be solved by trial and error. Let us try $I_a = 70$ A. From magnetization characteristic for $I_a = 70$ A and speed of 400 rpm $E = 134.667$. Substitution of these values of I_a and E in (i) balances the equation. Hence $I = 70$ A is the solution of Eq. (i). Now

$$T = \frac{EI_a}{\omega_m} = \frac{134.667 \times 70}{400 \times 2\pi/60} = 225 \text{ N-m}$$

EXAMPLE 5.22

Motor of Example 5.21 is now controlled in regenerative braking by a chopper with a source voltage of 220 V.

(i) Calculate motor speed for a duty ratio of 0.5 and motor braking torque equal to the rated motor torque.
(ii) Calculate maximum allowable motor speed for a maximum permissible current of 70 A and maximum permissible duty ratio of 0.95.
(iii) What resistance must be inserted in armature circuit for the drive to run at 1000 rpm without exceeding armature current beyond 70 A? The duty ratio of chopper has a range from 0.05 to 0.95.
(iv) To what extent the number of turns in field winding should be reduced to run the motor at 1000 rpm without exceeding the armature current beyond 70 A.

Solution

(i) At rated motor torque, $I_a = 70$ A. Now

$$E_1 = \delta V + I_{a1}R_a = 0.5 \times 220 + 70 \times 0.12 = 118.4 \text{ V}$$

From magnetization characteristic, for $I_a = 70$ A and $N = 600$ rpm, $E = 202$ V

Required motor speed $N_1 = \dfrac{118.4}{202} \times 600 = 351.7$ rpm

(ii) At 70 A and $\delta_{max} = 0.95$

$$E_2 = 0.95 \times 220 + 70 \times 0.12 = 217.4 \text{ V}$$

For $I_a = 70$ A and $N = 600$ rpm, $E = 202$ V (from the magnetization curve)

$$\text{Required speed } N_2 = \frac{E_2}{E} \times N = \frac{217.4}{202} \times 600 = 645.7 \text{ rpm}$$

(iii) For $I_a = 70$ A and speed $N_3 = 1000$ rpm

$$E_3 = \frac{1000}{600} \times 202 = 336.67 \text{ V}$$

$$R + 0.12 = \frac{E_3 - \delta V}{I_a} = \frac{336.67 - 0.95 \times 220}{70}$$

which gives the resistance to be inserted, $R = 1.7\ \Omega$.

(iv) It is assumed that even after changing field turns

$$R_a = 0.12\ \Omega$$

$$E_4 = (0.95 \times 220) + (70 \times 0.12) = 217.4 \text{ V}$$

This is the back emf developed by machine at 1000 rpm. At 600 rpm

$$E' = \frac{600}{1000} \times 217.4 = 130.44$$

Fraction to which the number of turns in the field are reduced

$$= \frac{E'}{E} = \frac{130.44}{202} = 0.646$$

EXAMPLE 5.23

Motor of Example 5.21 is now controlled in dynamic braking. Available chopper provides a variation in duty ratio from 0.1 to 0.9.

(i) Calculate braking resistor so that maximum braking speed at the armature current of 70 A will be 800 rpm.

(ii) Also calculate the maximum available motor torque for a speed of 87 rpm with braking resistance as calculated in (i).

Solution

(i) From magnetization curve, motor back emf at 800 rpm and $I_a = 70$ A

$$E_1 = \frac{800}{600} \times 202 = 269.33 \text{ V}$$

Effective value of braking resistance

$$R_{BE} = \frac{E_1}{I_a} - R_a = \frac{269.33}{70} - 0.12 = 3.73\ \Omega$$

For a given value of R_B, maximum value of R_{BE} is obtained at minimum value of duty ratio δ_{min}. Thus

$$(1 - \delta_{min})R_B = R_{BE}$$

or

$$(1 - 0.1)R_B = 3.73 \text{ which gives } R_B = 4.14\ \Omega$$

(ii) For a given speed, torque will be maximum when duty ratio is maximum . Total armature circuit resistance at maximum duty ratio δ_{max}

$$R = R_B(1 - \delta_{max}) + R_a = 4.14(1 - 0.9) + 0.12 = 0.534\ \Omega$$

Now $$E = RI_a \qquad \text{(i)}$$

Equation (i) must be satisfied for a speed of 87 rpm. Trying various values of I_a and the value of corresponding E (at 87 rpm = 26.68 V) obtained from magnetization characteristic, gave a approximate solution of $I_a = 50$ A.

At 50 A, $$K_e\phi = \frac{184}{600 \times 2\pi/60} = 2.928$$

$$T = K_e\phi I_a = 2.928 \times 50 = 146.4 \text{ N-m}$$

5.21 SOURCE CURRENT HARMONICS IN CHOPPERS

Source current of a chopper fed dc drive consists of pulses which are rich in harmonics and can also cause fluctuations in supply voltage. Usually the L-C input filter is provided to reduce harmonics and eliminate voltage fluctuations.

5.22 CONVERTER RATINGS AND CLOSED-LOOP CONTROL

The converters (rectifiers and choppers) are built using semiconductor devices, which have very low thermal capacity. Consequently their transient and steady state current ratings are same. The dc motors can carry 2 to 3.5 times the rated current during transient operations of short durations, such as starting, braking and reversing. Higher the current, higher is the torque and faster is the transient response. Therefore, when fast response during transient operations is required, motor current is allowed to have maximum permissible value. The converter rating is then chosen equal to the maximum permissible value of motor current. Because of large current rating, the converter cost will now be higher. When fast transient response is not required, the converter current rating is chosen to be equal to the motor current rating in order to keep the converter cost low.

Open-loop drives are provided with current limit control described in Sec. 3.3.1, in order to protect the converter against current overloads. The closed loop speed control schemes are provided with inner current control loop described in Sec. 3.3.3 in order to limit the current within a safe limit and also to accelerate and decelerate the drive at the maximum permissible current and torque during transient operations. It should, however, be noted that deceleration at the maximum current or torque will be possible when the converter used has the capability for braking operation also. It may further be noted that controlled rectifier will be used when supply is ac and chopper will be used when supply is dc.

The basic approach of closed-loop speed control below and above the speed is explained by the drive of Fig. 5.47. The drive employs inner current control loop and outer speed loop like the drive described in Sec. 3.3.3. Such a drive will operate at a constant field current and variable armature voltage below the base speed, and at a constant armature voltage and variable field current above the base speed. Both armature and field, are therefore, fed from fully-controlled rectifiers. Since, the armature is fed from a fully-controlled rectifier, forward braking is not possible; the drive will decelerate due to load torque only. Because of inner current control with current limiter, the acceleration will take place at the maximum permissible current and torque. In semiconductor converter fed drives PI (proportional and integral) controller is often used because it filters out noise which can otherwise become a problem. PI controller also gives good steady-state accuracy.

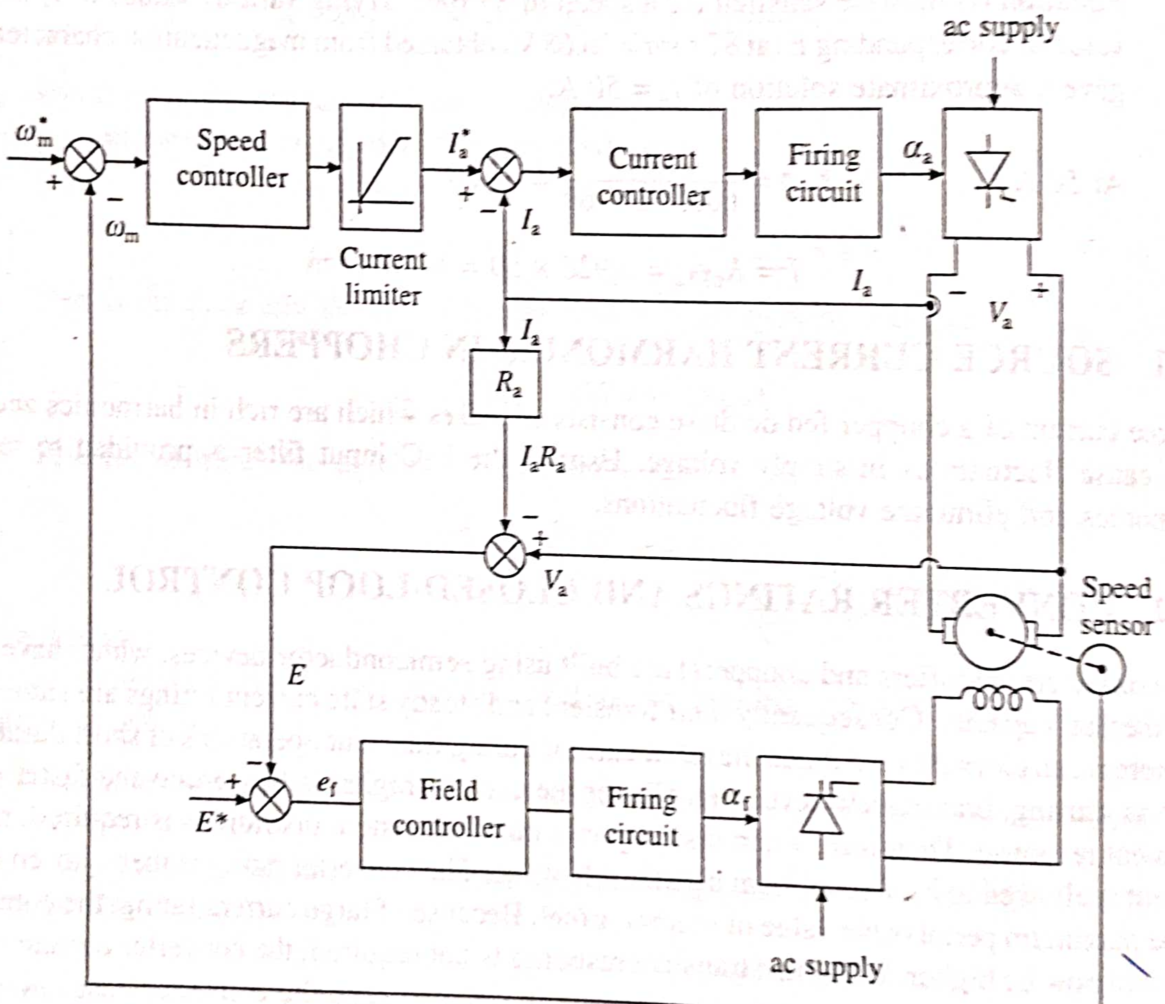

Fig. 5.47 Closed-loop speed control scheme for control below and above base speed

Let us first examine the operation below the base speed. In the field control loop, the back emf E is compared with a reference voltage E^* which is chosen to be between 0.85 to 0.95 of the rated armature voltage. The higher value is used for motors with low armature circuit resistance. For speeds below base speed, the field controller saturates due to large value of error e_f. The firing angle of field rectifier α_f is maintained at zero, applying rated voltage to the field. This ensures rated field current for motor operation below base speed (ω_{mb}). When speed reference is increased from ω_{m1}^* to $\omega_{m2}^*(\omega_{m2}^* < \omega_{m_1})$ due to large speed error, the current limiter saturates

$I_{a1}^2 = 0.8 I_{a2}$ $\frac{E_1}{E_2} = \frac{N_1 I_{a1}}{N_2 I_{a2}}$ 212 $E_2 = -200 - I_{a2}(0.05 + 0.09)$.

and sets the current reference at the maximum permissible value. The drive accelerates at the maximum available current and torque. When speed reaches close to ω^*_{m2}, the current limiter desaturates and the drive settles at speed ω_{m2} and at the current which gives motor torque equal to the load torque. If speed reference is reduced back to ω^*_{m1}, the current reference is set at zero and the drive decelerates due to load torque. When ω_m becomes slightly less than ω^*_{m1} motor current flows again and finally drive settles at speed ω_{m1} and current for which motor torque balances the load torque. For negative speed error, I_a^* is set at zero because negative I_a^* is of no use. It will however charge PI controller. When reference speed is increased again, making speed error positive, the charged PI controller takes longer time to respond, making the transience response slower.

Let us now examiner the operation above base speed. When close to base speed, the field controller comes out of saturation. Now if the reference speed is set for a speed above base speed, the current reference is set at the maximum permissible value. The firing angle of the armature rectifier α_a is reduced to initially increase V_a. The motor accelerates, E increases, e_f decreases, reducing the field current. Thus the motor speed continues to increase and field current continues to decrease until the motor speed becomes equal to the reference speed. Since, the speed error will now be small, V_a will return to a value close to original value. Thus, the speed control above base speed is obtained by field control with the armature voltage maintained near the rated value. In the field control region (above base speed), the drive responds very slowly due to large value of the field time constant.

1.104 $T = K\phi I_a$ $E = 212V$ $220 = E + I_a R_a$ 220 $K I_a^2 = T = K$ $-200 = \phi - 800 f$

PROBLEMS

dc Motor Characteristics

5.1 A dc motor is to be selected for driving a load having a large torque of short duration followed by a long no-load period. A flywheel of suitable inertia is already mounted on the load shaft. Suggest the most suitable dc motor for this application and explain your choice.

5.2 Explain why a dc series motor is more suited to deal with torque over loads than other dc motors.

5.3 A dc separately excited motor is running at 800 rpm driving a load whose torque is constant. Motor armature current is 500 A. The armature resistance drop and rotational losses are negligible. Magnetic circuit can be assumed to be linear. Calculate motor speed and armature current if terminal voltage is reduced to 50% and field current is reduced to 80%.

5.4 What will be the answers to Problem 5.3, if load torque were proportional to speed squared?

5.5 A 220 V, 800 rpm, 80 A separately excited motor has an armature resistance of 0.12 Ω. Motor is driving under rated conditions, a load whose torque is same at all speeds. Calculate motor speed if the source voltage drops to 200 V.

5.6 A dc shunt motor is running at 500 rpm, driving a load whose torque is same at all speeds. Armature current is 90 A. The armature resistance drop can be neglected and field circuit can be assumed to be linear. If source voltage is reduced to 80% calculate motor speed and armature current.

5.7 A 220 V, 960 rpm and 80 A dc series motor is driving a load which has the same torque at all speeds. Resistances of armature and field are each 0.05 Ω. Calculate magnitude and direction of motor speed and current if motor terminal voltage is changed from 220 to –200 V and the number of turns in field winding is reduced to 80%. Will motor speed reverse? Assume linear magnetic circuit.

5.8 A 230 V, 750 rpm, 25 A dc series motor is driving at rated conditions a load, whose torque is proportional to speed squared. The combined resistance of armature and field is 1 Ω. Calculate the motor terminal voltage and current for a speed of 400 rpm. State the assumption made for solving problem.

205 = 750 × 25k 13.33 $\propto x$ = 400 × 13.

$T \propto N^2$ $I_a \propto N$