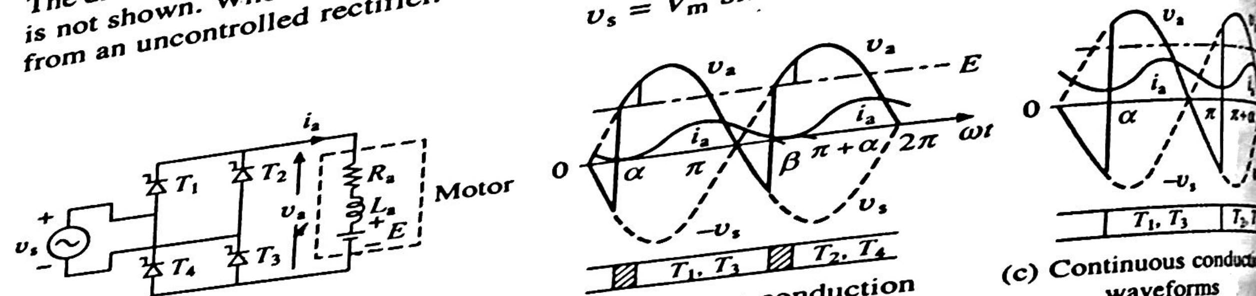
- ...organiz...
- Engage in lifelong lear... skills.
- Fulfill the needs of society in solving technical ... engineering principles, tools and practices ... responsible manner.
- Demonstrate ... skill...

(c) provide control of dc voltage in either direction and therefore, allow motor control in ... I and IV. They are known as fully-controlled rectifiers. Rectifiers of Figs. 5.25(b) and ... called half-controlled rectifiers as they allow dc voltage control only in one direction ... control in quadrant I only. For low power applications (up to around 10 kW) single ... rectifier drives are employed. For high power applications, three-phase rectifier drives ... Exception is made in traction where single phase drives are employed for large power ...

5.10 SINGLE-PHASE FULLY-CONTROLLED RECTIFIER CONTROL OF dc SEPARATELY EXCITED MOTOR

The drive circuit is shown in Fig. 5.26(a). Motor is shown by its equivalent circuit. Field is not shown. When field control is required, field is fed from a controlled rectifier, or from an uncontrolled rectifier. The ac input voltage is defined by

$$v_s = V_m \sin \omega t$$



(a) Drive circuit

(b) Discontinuous conduction waveforms

(c) Continuous conduction waveforms

Fig. 5.26 Single-phase fully-controlled rectifier-fed dc separately excited motor

In a cycle of source voltage, thyristors T_1 and T_3 are given gate signals from α to π ... thyristors T_2 and T_4 are given gate signals from $(\pi + \alpha)$ to 2π. When armature current does ... flow continuously, the motor is said to operate in discontinuous conduction. When current flows continuously, the conduction is said to be continuous. The drive under consideration, predominantly operates in discontinuous conduction. Discontinuous conduction has several modes of operation. The approximate, but a simple, method of analysis is obtained when only the dominant mode of discontinuous conduction is taken into account. The motor terminal voltage and current waveforms for the dominant discontinuous conduction and continuous conduction modes are shown in Figs. 5.26(b) and (c).

In discontinuous conduction mode, current starts flowing with the turn-on of thyristors T_1 and T_3 at $\omega t = \alpha$. Motor gets connected to the source and its terminal voltage equals v_s. The current which flows against both, E and the source voltage after $\omega t = \pi$, falls to zero at β. Due to absence of current T_1 and T_3 turn-off. Motor terminal voltage is now equal to its induced voltage E. When thyristors T_2 and T_4 are fired at $(\pi + \alpha)$, next cycle of the motor terminal voltage starts.

In continuous conduction mode, a positive current flows through the motor, and T_2 and T_4 ... in conduction just before α. Application of gate pulses turns on forward biased thyristors T_1 ...

19)

T_3 at α. Conduction of T_1 and T_3 reverse biases T_2 and T_4 and turns them off. A cycle of v_a is completed when T_2 and T_4 are turned-on at $(\pi + \alpha)$ causing turn-off of T_1 and T_3.

Since armature current i_a is not perfect dc, the motor torque fluctuates. Since torque fluctuates at a frequency of 100 Hz, motor inertia is able to filter out the fluctuations, giving nearly a constant speed and rippleless E.

Discontinuous Conduction

In a cycle of motor terminal voltage v_a, the drive operates in two intervals (Fig. 5.26(b)):

(i) Duty interval $(\alpha \le \omega t \le \beta)$ when motor is connected to the source and $v_a = v_s$.

(ii) Zero current interval $(\beta \le \omega t \le \pi + \alpha)$ when $i_a = 0$ and $v_a = E$.

Drive operation is described by the following equations:

$$v_a = R_a i_a + L_a \frac{di_a}{dt} + E = V_m \sin \omega t, \text{ for } \alpha \le \omega t \le \beta \tag{5.72}$$

$$v_a = E \quad \text{and} \quad i_a = 0 \quad \text{for} \quad \beta \le \omega t \le \pi + \alpha \tag{5.73}$$

Solution of Eq. (5.72) has two components—one due to the ac source $(V_m/Z) \sin (\omega t - \phi)$, and other due to back emf $(-E/R_a)$. Each of these components has in turn a transient component. Let these be represented by a single exponent $K_1 e^{-t/\tau_a}$, then

$$i_a(\omega t) = \frac{V_m}{Z} \sin (\omega t - \phi) - \frac{E}{R_a} + K_1 e^{-t/\tau_a} \quad \text{for } \alpha \le \omega t \le \beta \tag{5.74}$$

where

$$Z = \sqrt{R_a^2 + (\omega L_a)^2} \tag{5.75}$$

$$\phi = \tan^{-1} (\omega L_a / R_a) \tag{5.76}$$

and τ_a is given by Eq. (5.25).

Constant K_1 can be evaluated subjecting Eq. (5.74) to the initial condition $i_a(\alpha) = 0$. Substituting value of K_1 so obtained in Eq. (5.74) yields

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

$$- \frac{E}{R_a} [1 - e^{-(\omega t - \alpha)\cot \phi}], \quad \text{for } \alpha \le \omega t \le \beta \tag{5.77}$$

Since $i_a(\beta) = 0$, from Eq. (5.77)

$$\frac{V_m}{Z} \sin (\beta - \phi) - \frac{E}{R_a} + \left[\frac{E}{R_a} - \frac{V_m}{Z} \sin (\alpha - \phi) \right] e^{-(\beta - \alpha)\cot \phi} = 0 \tag{5.78}$$

β can be evaluated by iterative solution of Eq. (5.78).

Since voltage drop across the armature inductance due to dc component of armature current is zero

$$V_a = E + I_a R_a \tag{5.79}$$

The quadrant I operation of a hoist requires the movement of the cage upward, which corresponds to the positive motor speed which is in anticlockwise direction here. This motion will be obtained if the motor produces positive torque in anticlockwise direction equal to the magnitude of load torque T_{l1}. Since developed motor power is positive, this is forward motoring operation.

Quadrant IV operation is obtained when a loaded cage is lowered. Since the weight of a loaded cage is higher than that of a counter weight, it is able to come down due to the gravity itself. In order to limit the speed of cage within a safe value, motor must produce a positive torque T equal to T_{l2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking.

Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weight is heavier than an empty cage, it is able to pull it up. In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{l2} in clockwise (negative) direction. Since speed is positive and developed power negative, it is forward braking operation.

Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in clockwise direction. Since speed is negative and developed power positive, this is reverse motoring operation.

Q1 b 2.3 EQUIVALENT VALUES OF DRIVE PARAMETERS

Different parts of a load may be coupled through different mechanisms, such as gears, V-belts and crankshaft. These parts may have different speeds and different types of motions such as rotational and translational. This section presents methods of finding the equivalent moment of inertia (J) of motor-load system and equivalent torque components, all referred to motor shaft.

2.3.1 Loads with Rotational Motion

Let us consider a motor driving two loads, one coupled directly to its shaft and other through a gear with n and n_1 teeth as shown in Fig. 2.4(a). Let the moment of inertia of motor and load directly coupled to its shaft be J_0, motor speed and torque of the directly coupled load be ω_m and T_{l0} respectively. Let the moment of inertia, speed and torque of the load coupled through a gear be J_1, ω_{m1} and T_{l1} respectively. Now,

$$\frac{\omega_{m1}}{\omega_m} = \frac{n}{n_1} = a_1 \tag{2.3}$$

where a_1 is the gear tooth ratio.

If the losses in transmission are neglected, then the kinetic energy due to equivalent inertia must be the same as kinetic energy of various moving parts. Thus

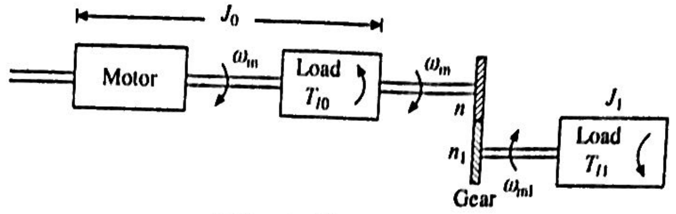
$$\frac{1}{2} J\omega_m^2 = \frac{1}{2} J_0\omega_m^2 + \frac{1}{2} J_1\omega_{m1}^2 \tag{2.4}$$

From Eqs. (2.3) and (2.4)

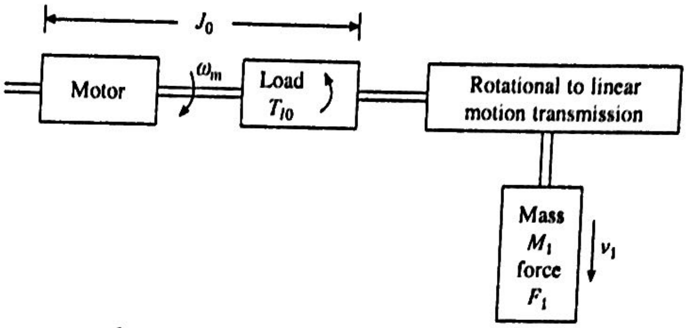
$$J = J_0 + a_1^2 J_1 \tag{2.5}$$

Power at the loads and motor must be the same. If transmission efficiency of the gears be η_1, then

Q 1.b



(a) Loads with rotational motion



(b) Loads with translational and rotational motion

Fig. 2.4 Motor load system with loads with rotational and linear motions

$$T_l \omega_m = T_{l0} \omega_m + \frac{T_{l1} \omega_{m1}}{\eta_1} \tag{2.6}$$

where T_l is the total equivalent torque referred to motor shaft.

From Eqs. (2.3) and (2.6)

$$T_l = T_{l0} + \frac{a_1 T_{l1}}{\eta_1} \tag{2.7}$$

If in addition to load directly coupled to the motor with inertia J_0 there are m other loads with moment of inertias $J_1, J_2, \dots, J_m$ and gear teeth ratios of $a_1, a_2, \dots a_m$ then

$$J = J_0 + a_1^2 J_1 + a_2^2 J_2 + \dots + a_m^2 J_m \tag{2.8}$$

If m loads with torques $T_{l1}, T_{l2}, \dots, T_{lm}$ are coupled through gears with teeth ratios $a_1, a_2, \dots a_m$ and transmission efficiencies $\eta_1, \eta_2, \dots, \eta_m$, in addition to one directly coupled, then

$$T_l = T_{l0} + \frac{a_1 T_{l1}}{\eta_1} + \frac{a_2 T_{l2}}{\eta_2} + \dots + \frac{a_m T_{lm}}{\eta_m} \tag{2.9}$$

If loads are driven through a belt drive instead of gears, then, neglecting slippage, the equivalent inertia and torque can be obtained from Eqs. (2.8) and (2.9) by considering $a_1, a_2, \dots, a_m$ each to be the ratios of diameters of wheels driven by motor to the diameters of wheels mounted on the load shaft.

2.3.2 Loads with Translational Motion

Let us consider a motor driving two loads, one coupled directly to its shaft and other through a source is dc and an induction motor is to be employed, then the power modulator is required to convert dc into a variable frequency ac.

(iv) Selects the mode of operation of the motor, i.e. motoring or braking.

When power modulator is employed mainly to perform function (iii), it is more appropriately called *converter.* While (iii) is the main function, depending on its circuit, a converter may also perform other functions of power modulator.

Controls for power modulator are built in control unit which usually operates at much lower voltage and power levels. In addition to operating the power modulator as desired, it may also generate commands for the protection of power modulator and motor. Input command signal, which adjusts the operating point of the drive, forms an input to the control unit. Sensing of certain drive parameters, such as motor current and speed, may be required either for protection or for closed loop operation.

1.2 ADVANTAGES OF ELECTRICAL DRIVES

Ans 2 a)

Electrical drives are widely used because of the following advantages:

1. They have flexible control characteristics. The steady-state and dynamic characteristics of electrical drives can be shaped to satisfy load requirements. Speed can be controlled and, if required, can be controlled in wide limits. Electric braking can be employed. Control gear required for speed control, starting and braking is usually simple and easy to operate.

Availability of semiconductor converters employing thyristors, power transistors, IGBTs and GTOs, linear and digital ICs, and microcomputers have made the control characteristics even more flexible. It is possible to reshape characteristics of drives almost at will to meet load requirements in an optimum manner. Speed and torque, and transitions from one mode to another can be controlled smoothly and steplessly. Optimal control strategies can be implemented to achieve high dynamic performance, high efficiency or to minimime a suitable performance index. Drives can be provided with automatic fault detection systems. Programmable logic controllers and computers can be employed to automatically control the drive operations in a desired sequence.

2. They are available in wide range of torque, speed and power.

3. Electric motors have high efficiency, low no load losses and considerable short time overloading capability. Can be made in variety of designs to make them compatible with load. Compared to other prime movers they have longer life, lower noise, lower maintenance requirements and cleaner operation.

4. They are adaptable to almost any operating conditions such as explosive and radioactive environment, submerged in liquids, vertical mountings, and so on.

5. Do not pollute the environment.

6. Can operate in all the four quadrants of speed-torque plane. Electric braking gives smooth deceleration and increases life of the equipment compared to other forms of braking. When regenerative braking is possible, considerable saving of energy is achieved. These features are not available in other prime movers.

7. Unlike other prime movers, there is no need to refuel or warm-up the motor. They can be started instantly and can immediately be fully loaded.

Q2c

(iii) Intermittent periodic duty.
(iv) Intermittent periodic duty with starting.
(v) Intermittent periodic duty with starting and braking.
(vi) Continuous duty with intermittent periodic loading.
(vii) Continuous duty with starting and braking.
(viii) Continuous duty with periodic speed changes.

These classes of motor duty are explained below.

(i) *Continuous Duty* (Fig. 4.2(a)): It denotes the motor operation at a constant load torque for a duration long enough for the motor temperature to reach steady-state value. This duty is characterised by a constant motor loss. Paper mill drives, compressors, conveyers, centrifugal pumps and fans are some examples of continuous duty.

(ii) *Short Time Duty* (Fig. 4.2(b)): In this, time of drive operation is considerably less than the heating time constant and machine is allowed to cool off to ambinent temperature before the motor is required to operate again. In this operation, the machine can be overloaded until temperature at the end of loading time reaches the permissible limit. Some examples are: crane drives, drives for household appliances, turning bridges, sluice-gate drives, valve drives, and many machine tool drives for position control.

(iii) *Intermittent Periodic Duty* (Fig. 4.2(c)): It consists of periodic duty cycles, each consisting of a period of running at a constant load and a rest period. Neither the duration of running period

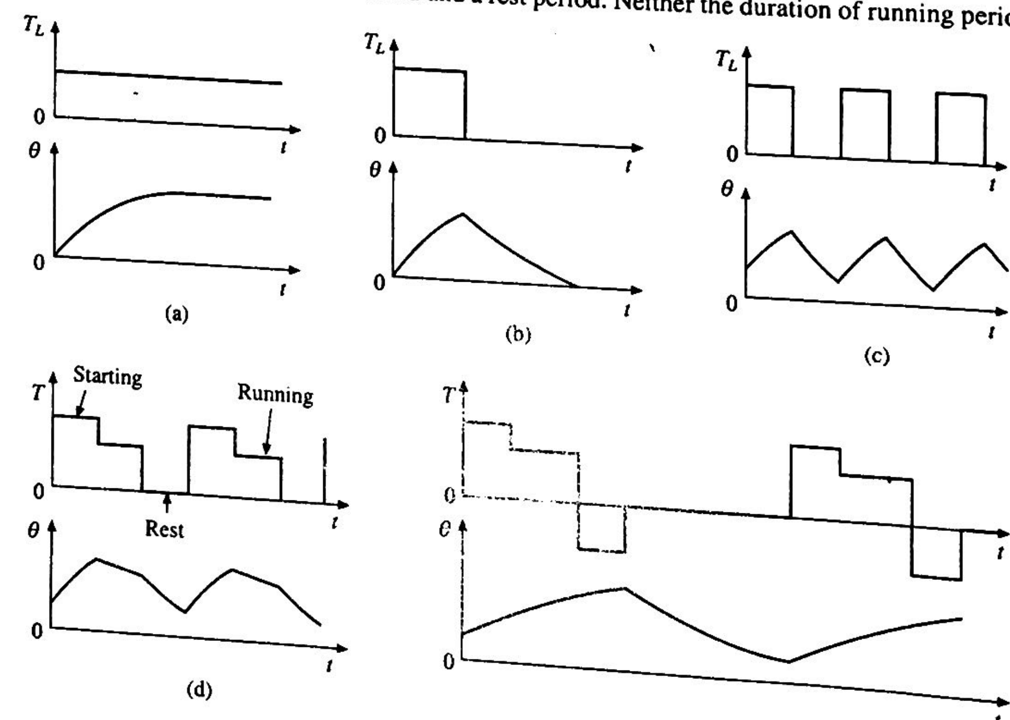


Fig. 4.2 Some classes of motor duty.

$$t = \int dt = \int_{N_1}^{N_2} \frac{dN}{-95.49 - 0.143N} \qquad (1)$$

where $N_1 = 666.7$ rpm and $N_2 = 0.95 \times -666.7 = -633.4$ rpm*.

Integrating Eq. (1) yields $t = 25.58$ S.

Q 2 d

2.7 STEADY STATE STABILITY

Equilibrium speed of a motor-load system is obtained when motor torque equals the load torque. Drive will operate in steady-state at this speed, provided it is the speed of stable equilibrium. Concept of steady-state stability has been developed to readily evaluate the stability of an equilibrium point from the steady-state speed-torque curves of the motor and load, thus avoiding solution of differential equations valid for transient operation of the drive.

In most drives, the electrical time constant of the motor is negligible compared to its mechanical time constant. Therefore, during transient operation, motor can be assumed to be in electrical equilibrium implying that steady-state speed-torque curves are also applicable to the transient operation.

As an example let us examine the steady-state stability of equilibrium point A in Fig. 2.9(a). The equilibrium point will be termed as stable when the operation will be restored to it after a small departure from it due to a disturbance in the motor or load. Let the disturbance causes a reduction of $\Delta\omega_m$ in speed. At new speed, motor torque is greater than the load torque, consequently, motor will accelerate and operation will be restored to A. Similarly, an increase of $\Delta\omega_m$ in speed caused by a disturbance will make load torque greater than the motor torque, resulting into deceleration and restoration of operation to point A. Hence the drive is steady-state stable at point A. Let us now examine equilibrium point B which is obtained when the same motor drives another load. A decrease in speed causes the load torque to become greater than the motor torque, drive decelerates and operating point moves away from B. Similarly, when working at B an increase in speed will make motor torque greater than the load torque, which will move the operating point away from B. Thus, B is an unstable point of equilibrium. Readers may similarly examine the stability of points C and D given in Figs. 2.9(c) and (d).

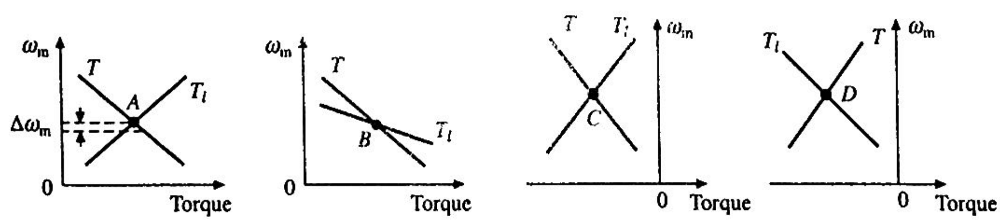


Fig. 2.9 Points A and C are stable and B and D are unstable

Above discussion suggests that an equilibrium point will be stable when an increase in speed causes load-torque to exceed the motor torque, i.e. when at equilibrium point following condition is satisfied:

*Taking $N_2 = 0.95\,N_e$ rather than $0.95\,(N_e - N_1)$ for speed reversal gives more accurate estimation of t.

Substituting these values in Eqs. (E.1) and (E.2) gives

$$\frac{d^2\omega_m}{dt^2} + 5.155\frac{d\omega_m}{dt} + 4.046\omega_m = -349.75 \quad \text{(E.3)}$$

$$\frac{d^2 i_a}{dt^2} + 5.155\frac{di_a}{dt} + 4.046 i_a = 186.8 \quad \text{(E.4)}$$

Roots of the characteristic equation are:

$$-\alpha_1, -\alpha_2 = \frac{-5.155 \pm \sqrt{(5.155)^2 - 4 \times 4.046}}{2} = -0.966, -4.19$$

The solutions of Eqs. (E.3) and (E.4) can now be written as

$$\omega_m = -86.44 + Ae^{-0.966t} + Be^{-4.19t} \quad \text{(E.5)}$$

$$i_a = 46.17 + Ce^{-0.966t} + De^{-4.19t} \quad \text{(E.6)}$$

Now $\omega_m(0) = 109.96,\ i_a(0) = 0$

From Eq. (5.19)

$$\frac{di_a}{dt}(0) = \frac{V - R_a i_a - K\omega_m}{L_a} = \frac{-220 - 0 - 216.3}{0.12} = -3635.83$$

From Eq. (5.20)

$$\frac{d\omega_m}{dt}(0) = \frac{Ki_a - B\omega_m - T_L}{J} = \frac{-172}{8} = -21.5$$

Using these initial conditions, solutions of Eqs. (E.5) and (E.6) are obtained as follows:

$$\omega_m = -86.44 + 136.24e^{-0.966t} - 26.28e^{-4.19t} \quad \text{(E.7)}$$

$$i_a = 46.17 - 1187.7e^{-0.966t} + 1141.56e^{-4.19t} \quad \text{(E.8)}$$

These equations are valid up to standstill both for active and passive load torques. After the motor accelerates in the reverse direction a passive load torque will change the sign. Therefore, these equations will not be valid for passive loads after the speed reversal.

(c) If zero speed is reached at $t = t_1$ then approximately from Eq. (E.7)

$$-86.44 + 136.24e^{-0.966t_1} = 0$$

which gives $t_1 = 0.47$ sec.

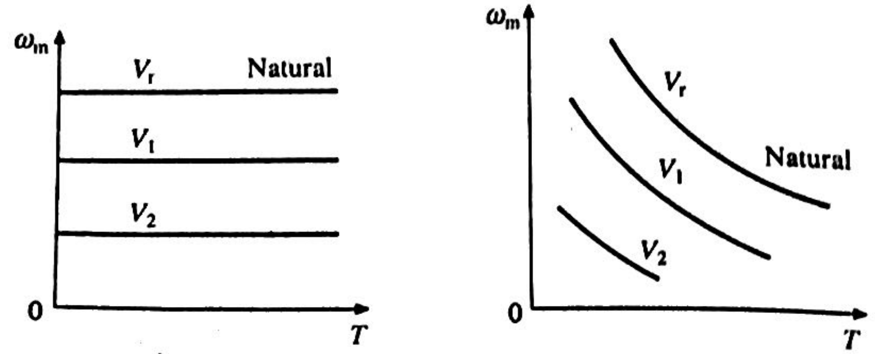
5.5 SPEED CONTROL 16

According to Eq. (5.5), speed can be controlled by any of the following methods:

(i) Armature voltage control
(ii) Field flux control
(iii) Armature resistance control

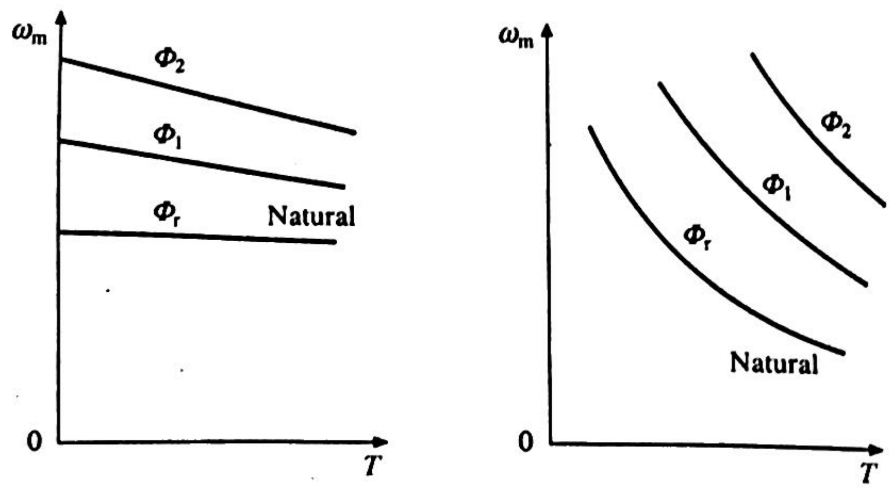
Speed-torque curves of dc motors for these methods of speed control are shown in Figs. 5.16 to 5.18.

Armature voltage control is preferred because of high efficiency, good transient response and good speed regulation. But it can provide speed control only below base (rated) speed because



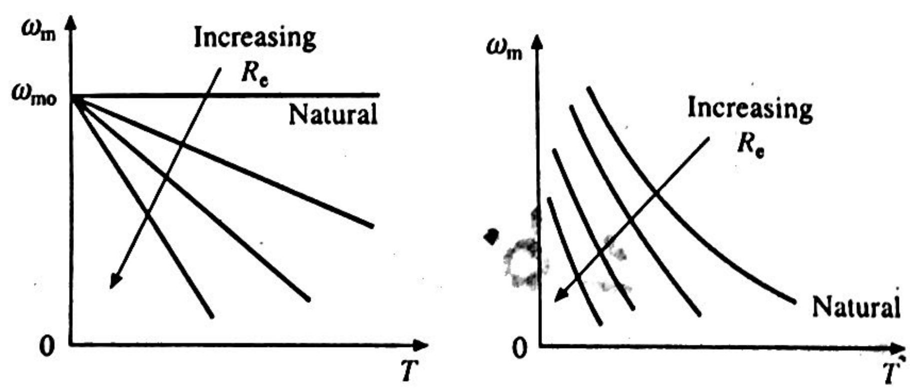
(a) Separate (b) Series

Fig. 5.16 Armature voltage control V_r (rated) > V_1 > V_2



(a) Separate (b) Series

Fig. 5.17 Field flux control Φ_r (rated) > Φ_1 > Φ_2



(a) Separately excited (b) Series

Fig. 5.18 Speed torque curves of dc motors with resistance control. R_e: external resistance