ELECTRICAL DRIVES

MODULE I

Requirements, AC and DC drives, Advantages of Electrical Drives, Fundamentals of Torque Equations, Speed Torque Conventions and Multi-quadrant Operation, Equivalent Values of Drive Parameters, Components of Load Torques, Calculation of Time and Energy Loss in Transient Operations, Steady State Stability, Load Equalization, Control of Electrical Drives,

Thermal Model of Motor for Heating and Cooling, Classes of Motor Duty, Determination of Motor Rating.

MODULE II

Steady State Performance of DC/AC Drives : DC Motors and their Performances, Starting , Braking, Transient Analysis, Speed Control, Methods of Armature Voltage Control, Controlled Rectifier Fed DC Drives , Induction Motor Drives: Speed Control, Pole Changing , Pole Amplitude Modulation, Stator Voltage Control, Variable Frequency Control from Voltage Source , Voltage Source Inverter Control, Variable Frequency Control from Current Source , Current Source Inverter Control, Current Regulated Voltage Source Inverter Control, Rotor Resistance Control, Slip Power Recovery.

MODULE III

Synchronous Motor Drives: Synchronous Motor Variable Speed Drives , Variable Frequency Control of Multiple Synchronous Motors. Electric Traction: System of electrictraction Mechanics of Train Movement: Speed- time, distance- time and simplified speed-time curves, Attractive effort for acceleration and propulsion, effective weight, train resistance , adhesive weight, specific energy output and consumption. Traction Motors: Review of characteristics of different types of DC and AC motors used in traction and their suitability.

MODULE IV

Drives for specific application like Textile Mills, Steel Rolling Mills, Cranes and Hoist Drives, Cement Mills, Sugar Mills, Machine Tools, Paper Mills, Coal Mines, Centrifugal Pumps. Application Areas and Functions of Microprocessors in Drive Technology.

MODULE 1

Electrical drive technology converts electrical energy from the power supply system or from a battery into mechanical energy and transmits the resulting force who motion.

There are three general categories of electric drives :

(1) DC motor drives
(2) AC motor drives
(3) Eddy current drives

- Electric drives generally include both an electric motor and speed control unit or system.
- System employed for motion control are called Drives.
- Prime mover such as Diesel & petrol, engine, turbine. Drives the electrical motor are for supplying mechanical energy for motion control.
- Drives employing electric motors are known as ELECTRICAL DRIVES.

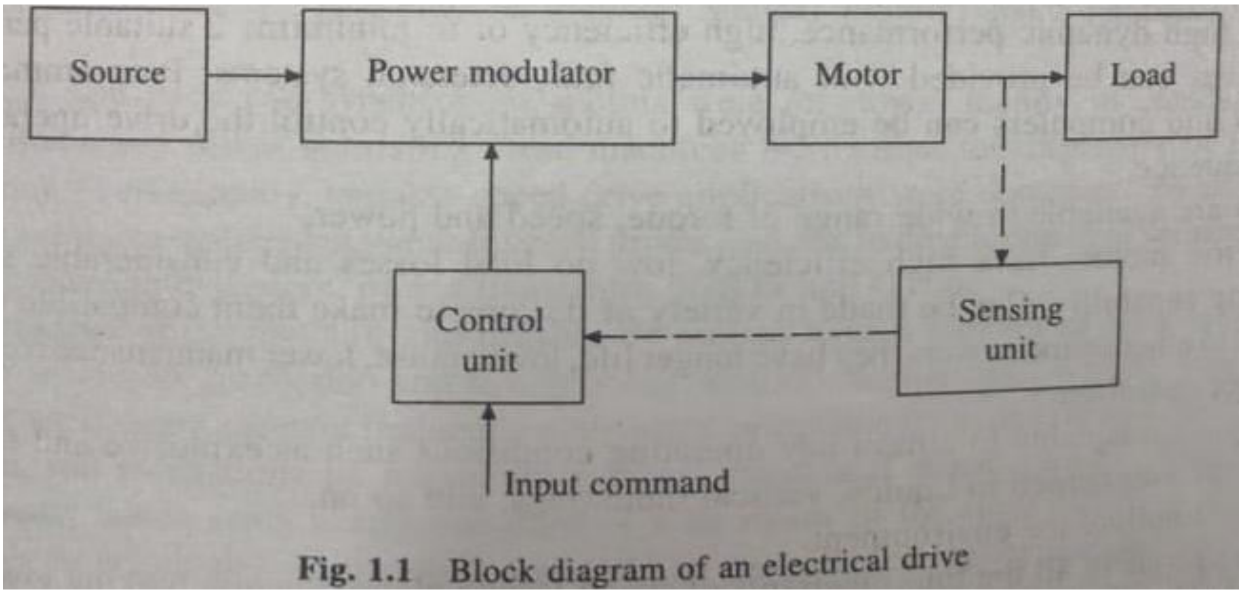


Fig. 1.1 Block diagram of an electrical drive

Function of power Modulator: -

- Modulates flow of pores from the source to the motors in Such a manner that motor is imparted speed-torque characteristics required by the load.
- During transient operation, such as starting, braking and speed reversal, it restricts source and motor currents within permissible values; excessive current drawn from source may over load it or may cause a voltage dip.
- Converts electrical energy of the source in the form suitable to the motor, e. g if the 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.
- It selects the mode of operation of the motor I.e., motoring or braking.

Advantages of electrical drives: -

Choice of an electrical drive depends on a number of factors. Some of the important factors are:

(1) Steady state operation requirements: Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings.

(2) Transient operation requirements: Values of acceleration and deceleration, starting, braking and reversing performance.

(3) Requirements related to the source: Type of source, and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerated power.

(4) Capital and running cost, maintenance needs, life.

(5) Space and weight restrictions if any.

(6) Environment and location.

(7) Reliability.

Parts of electrical drives: -

Electrical drive has the following parts: -

- Load
- Motor
- Power modulator
- Control unit
- Source

Electrical Motors

Motors commonly used in electrical drives are: dc motors-shunt, series, compound and permanent magnet; Induction motors-squirrel-cage, wound rotor and linear; Synchronous motors-wound field and permanent magnet; Brushless dc motors; Stepper motors; and Switched reluctance motors.

Modulators Power

It is difficult to classify power modulators. A somewhat satisfactory classification is:

(a) Converter;

(b) Variable impedances and

(c) Switching circuits.

Some drives may employ more than one of these modulators. Those power modulators which are employed in industrial drives will be discussed.

(a) Converters

When a power modulator performs function, it can be classified as converter. Usually, a converter also performs function in addition to. Depending on the circuit, it may also be able to perform function of the power modulator. Need for a converter arises when nature of the available electrical power is different than what is required for the motor. Power sources are usually of the following types:

- Fixed voltage and fixed frequency ac
- Fixed voltage dc.

DC to AC Converters:

AC – DC converters are shown in Fig. 1.2. The converter of Fig. 1.2(a) is used to get de supply of fixed voltage from the ac supply of fixed voltage. Such a converter is known as uncontrolled rectifier. Converters, of Fig. 1.2(b) to (j) allow a variable voltage de supply to be obtained from the fixed voltage ac supply. In converters of Figs. 1.2(b) and (c), a stepless variation of output voltage can be achieved by controlling firing angle of converter thyristors by low power signals from a control unit. Converter of Fig. 1.2(b) is a two-quadrant converter in the sense that it is capable of providing variable de voltage of either polarity with positive current. However, converter of Fig. 1.2(c) is a single-quadrant converter (positive voltage and current). Converters of Fig. 1.2(b) and (c) produce harmonics both on dc and ac side and have low power factor for low de voltages. The converters of Fig. 1.2(d), (e) and (f) operate at unity fundamental power factor. The output voltage in converter 1.2(d) is changed by applying mechanical force. Few discrete steps of de voltage can only be obtained. In converter of Fig. 1.2(e)

output voltage can be varied sleeplessly by controlling the duty ratio of semiconductor devices of the chopper by low power electrical signals from a control unit. The converter of Fig. 1.2(f) is a controlled rectifier employing self-commutated device such as power transistors, IGBTs and GTOS. It can be a single or two quadrant converters depending on the circuit. When connected in antiparallel, converters of Figs. 2(b) and (f) can provide four quadrant operation (variable voltage and current of either polarity). In ac to de converter of Fig. 1.2(g), the output voltage can be controlled by controlling field current of the generator from a control unit (amplifier) of higher power level than the control units of converters of Figs. 1.2(b), (c), (e) and (f). This can operate in all four quadrants.

Because of the two rotating machines, it has a number of disadvantages: bulky, heavy, noisy, less efficient, slow response, expensive and requires special foundation. Disadvantages associated with commutator and brushes of the de generator (Fig. 1.2(g)) are removed in converter of Fig. 1.2(h). However, this converter can operate in a single quadrant only. Some very old equipment's may also employ ac to dc converter of Figs. 1.2(I) and (ii) employing magnetic amplifier and amplidyne respectively. Magnetic amplifiers and amplidynes are controlled from low power de signals.

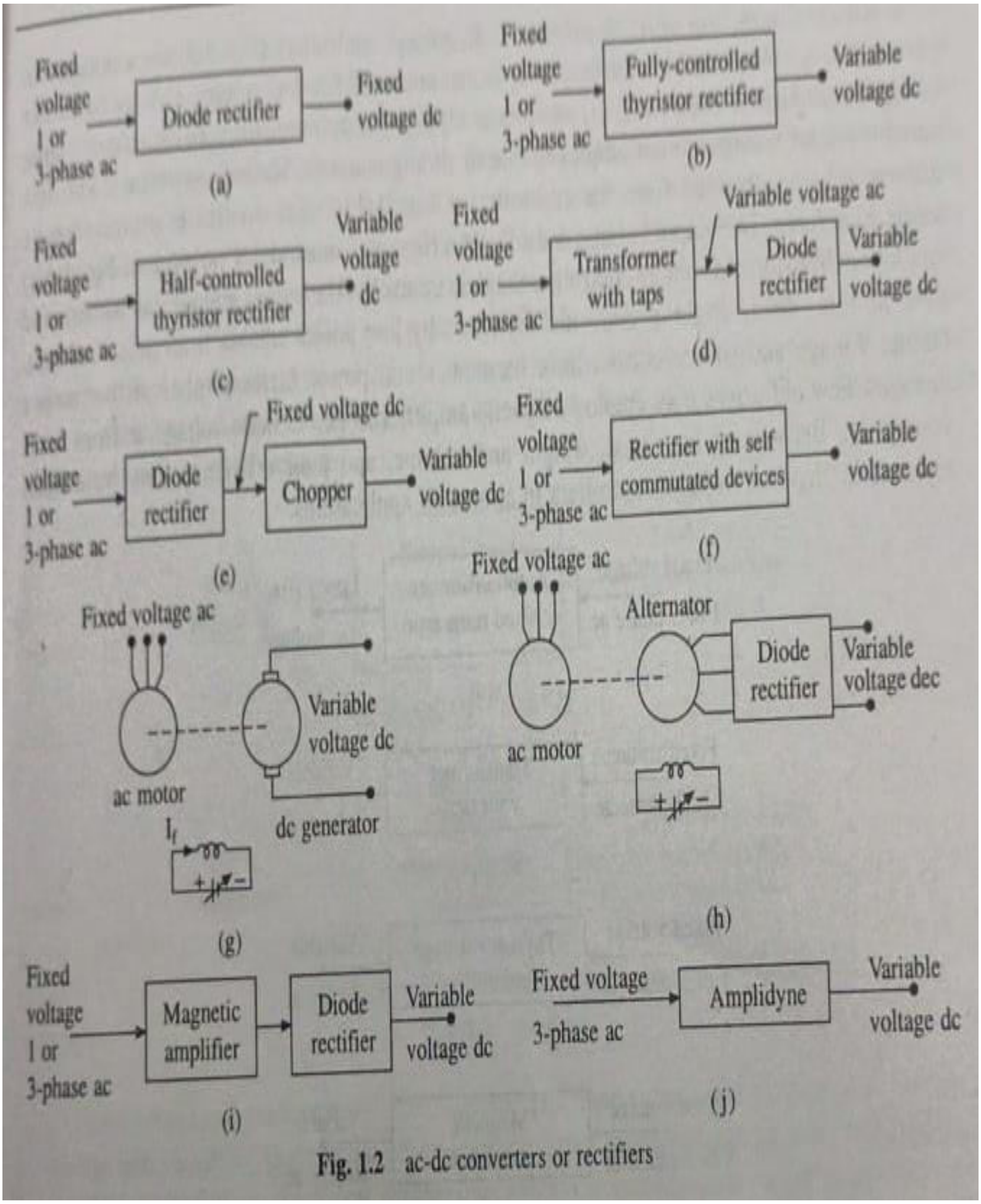


Fig. 1.2 ac-dc converters or rectifiers

ac Voltage Controllers or ac Regulators:

ac voltage controllers (Fig. 1.3) are employed to get variable ac voltage of the same frequency from a source of fixed ac voltage. Voltage controller of Fig. 1.3(a) gives a fixed (smaller) ac voltage supply. The autotransformers capable of giving variable output voltage are not employed due to sliding contacts. Variable ac voltage with few discrete steps is obtained from the controller of Fig. 1.3(b). The control is exercised by a mechanical force. The output voltage and source current are sinusoidal. Converter of Fig. 1.3(c) employs a thyristor voltage controller. Stepless control of the output voltage can be obtained by controlling firing angle of converter thyristors by low power signals from a control unit. Output voltage and source current have harmonics and power factor is poor at low output voltages. Few old drives may employ magnetic amplifier to get variable voltage ac from fixed voltage ac. Because of high cost, weight and volume, and poor efficiency they have been replaced by thyristor voltage controllers in almost all applications.

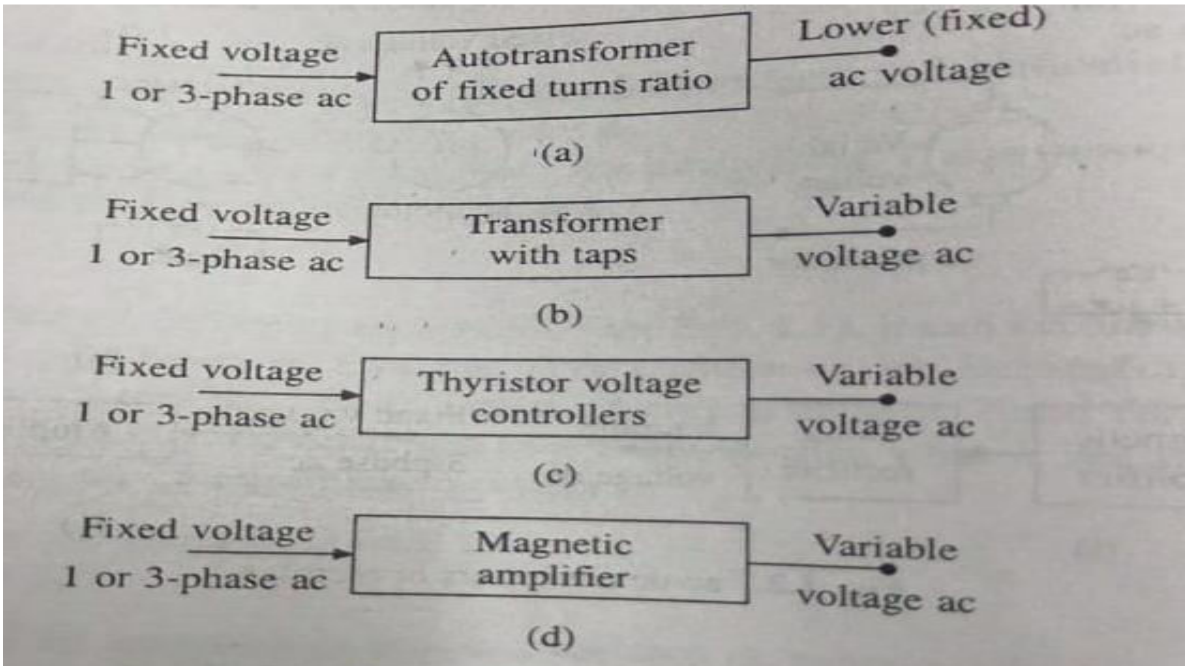


Fig. 1.3 ac voltage controllers

Choppers or dc-dc Converters:

They are used to get variable voltage de from a fixed voltage dc and are designed using semiconductor devices such as power transistors, IGBTs, GTOS, power MOSFETs and thyristors. Output voltage can be varied step less by controlling the duty ratio of the device by low power signals from a control unit.

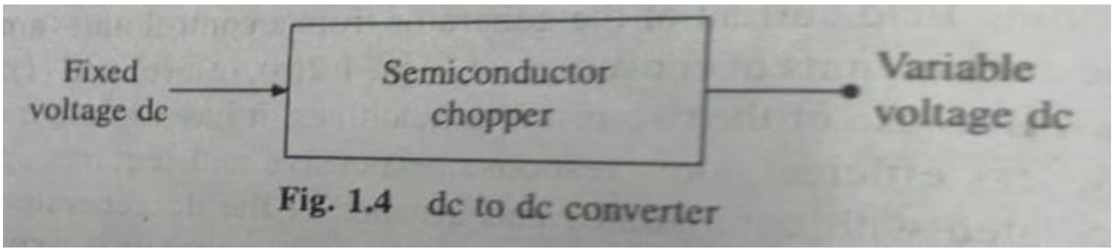
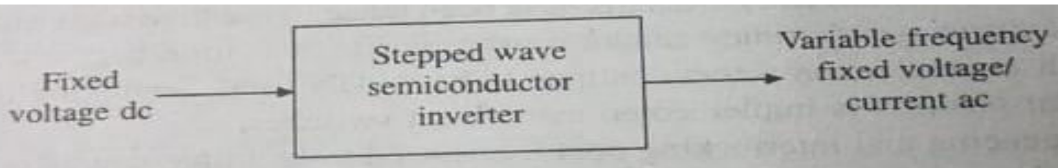


Fig. 1.4 dc to dc converter

Inverters:

Inverters are employed to get a variable frequency as supply from a de supply. Stepped-wave inverters of Fig. 1.5(a) can be designed to behave as voltage source or current source. Accordingly, they are known as voltage source or current source inverters. For the control of ac motor, voltage/current should also be controlled along with frequency. Variation in output voltage/current can be achieved by varying the input de voltage. This is achieved either by interposing a chopper in between fixed voltage de source and the inverter or the inverter may be fed from an ac-dc converter from among those of Figs. 1.2(b), (c) or (f). Output voltage and current have stepped waveform, consequently they have substantial number of harmonics. Variable frequency and variable voltage ac are directly obtained from fixed voltage dc when the inverter is controlled by pulse-width modulation (PWM) (Fig. 1.5(b)). The PWM control also reduces harmonics in the output voltage. Inverters are built using semiconductor devices such as thyristors. power transistors, IGBTs, GTOS and power MOSFETs. They are controlled by firing pulses obtained from a low power control unit. In the past variable frequency supply used to be obtained from a frequency changer employing a rotating machine. Such schemes have become outdated due to numerous disadvantages.



(a) Stepped wave inverters

(b) Pulse width modulated inverters

Fig. 1.5 Inverters

Cycloconverter:

Cycloconverter (Fig. 1.6) converts fixed voltage and frequency ac to variable voltage and variable frequency ac. They are built using thyristors and are controlled by firing signals derived from a low power control unit. Output frequency is restricted to 40% of supply frequency in order to keep harmonics in the output voltage and source current within acceptable limits.

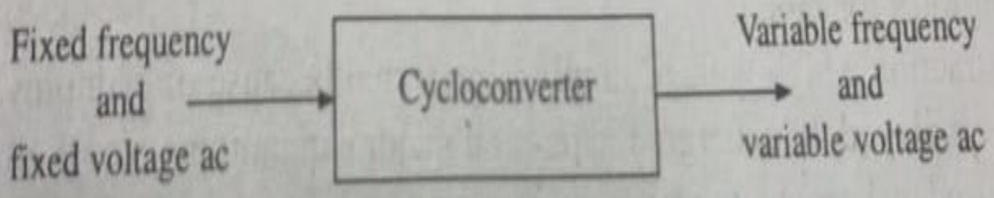


Fig. 1.6 Cycloconverter

Variable impedance: - Variable resistors are commonly used for the control of low cost de and ac drives and are also needed for dynamic braking of drives. Variable resistors may have two (full and zero) or more steps and can be controlled manually or automatically with the help of contactors. Stepless variation of resistance can be obtained using a semiconductor switch in parallel with a fixed resistance; variation of duty ratio of the switch gives a stepless variation in effective value of the resistance. In high power applications liquid rheostats, known as slip regulators, are employed to get stepless variation of resistance. Inductors, usually in two steps (full and zero), are employed for limiting the starting current of ac motors. Old drives may also employ saturable reactors for the control of induction motor arable reactors, reactance is controlled stepless by controlling de current of the control winding.

Switching circuits: -Switching operations are required to achieve any one of the following: (1) for changing motor connections to change its quadrant of operation, (a) for changing motor circuit parameters in steps for automatic starting and braking control, (1) for operating motors and drives according to a predetermined sequence, (iv) to provide interlocking to prevent maloperation and (v) to disconnect motor when abnormal operating conditions occur.

Switching operations in motor's power circuit are carried out by high power electromagnetic relays known as contactors. Recently attempts have been made to use thyristor switches. Thyristor switches have disadvantages that they cannot provide perfect isolation between the source and motor circuit. Consequently, contactors continue to be widely used. Switching operation based on load's particular position is implemented using limit switches.In the past sequencing and interlocking operations used to be implemented using low power electromagnetic relays. Solid state relays have replaced them almost in all applications. For the implementation of complicated sequencing and interlocking operations, programmable logic controllers (PLCs) are employed.

Dynamic of electric drives

Fundamental torque equations: -

A motor generally drives a load (machine) through some transmission system. While motor always rotates, the load may rotate or may undergo a translational motion. Load speed may be different from that of motor, and if the load has many parts, their speeds may be different and while some may rotate, others may go through a translational motion. It is, however, convenient to represent the motor load system by an equivalent rotational system shown in Fig.

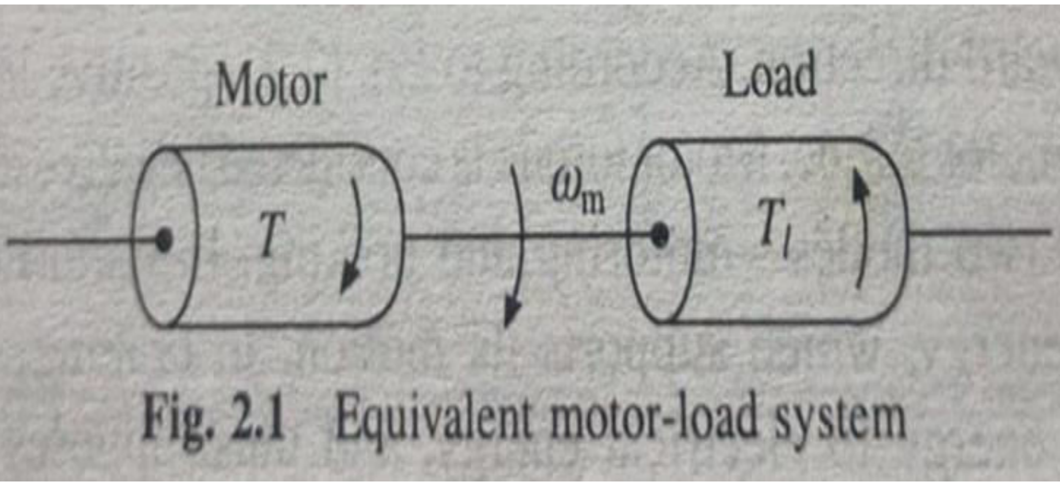


Fig. 2.1 Equivalent motor-load system

Various notations used are:

J=Polar moment of inertia of motor-load system referred to the motor shaft, kg-m^2.

ω_m= Instantaneous angular velocity of motor shaft, rad/sec.

T= Instantaneous value of developed motor torque, N-m.

T_l= Instantaneous value of load (resisting) torque, referred to motor shaft, N-m.

Load torque includes friction and windage torque of motor.

- Motor-load system can be described by the following fundamental torque equation:

$$T-T_l=\frac{d}{dt}(J\omega_m)=J\frac{d\omega_m}{dt}+\omega_m\frac{dJ}{dt} \qquad (1.1)$$

Application—

variable inertia drives such as mine winders, reel drivers, industrial robots.

- for drives with constant inertia, $\frac{dJ}{dt}$=0.
  Therefore $T=T_L+J\frac{d\omega_m}{dt}$
- Torque component $J\frac{d\omega_m}{dt}$ is called the DYNAMIC TORQUE because it is present only during the transient operations.

- During acceleration, motor should supply not only the load torque but an additional torque component $J\frac{d\omega_m}{dt}$ in order to overcome the drive inertia.

- During deceleration, dynamic torque $J\frac{d\omega_m}{dt}$ has a negative sign. Therefore, it assists the motor developed torque T and maintains drive motion by extracting energy from stored kinetic energy.

SPEED TORQUE CONVENTIONS AND MULTIQUADRANT OPERATION

For consideration of multi-quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed. Motor speed is considered positive when rotating in the forward direction. For drives which operate only in one direction, forward speed will be their normal speed. In loads involving up-and-down motions, the speed of motor which causes upward motion is considered forward motion. For reversible drives, forward speed is chosen arbitrarily. Then the rotation in opposite direction gives reverse speed which is assigned the negative sign. Positive motor torque is defined as the torque which produces acceleration or the positive rate of change of speed in forward direction. positive load torque is opposite in direction to the positive motor torque. Motor torque is considered negative if it produces deceleration.

A motor operates in two modes-motoring and braking. In motoring, it converts electrical energy to mechanical energy, which supports its motion. In braking, it works as a generator converting mechanical energy to electrical energy, and thus, opposes the motion. Motor can provide motoring and braking operations for both forward and reverse directions. torque and speed coordinates for both forward (positive) and reverse (negative) motions. Power developed by a motor is given by the product of speed torque. In quadrant I, developed power is positive. Hence, machine works as a motor supplying mechanical energy. Operation in quadrant I is, therefore, called forward motoring. In quadrant II, power is negative. Hence, machine works under braking opposing the motion.

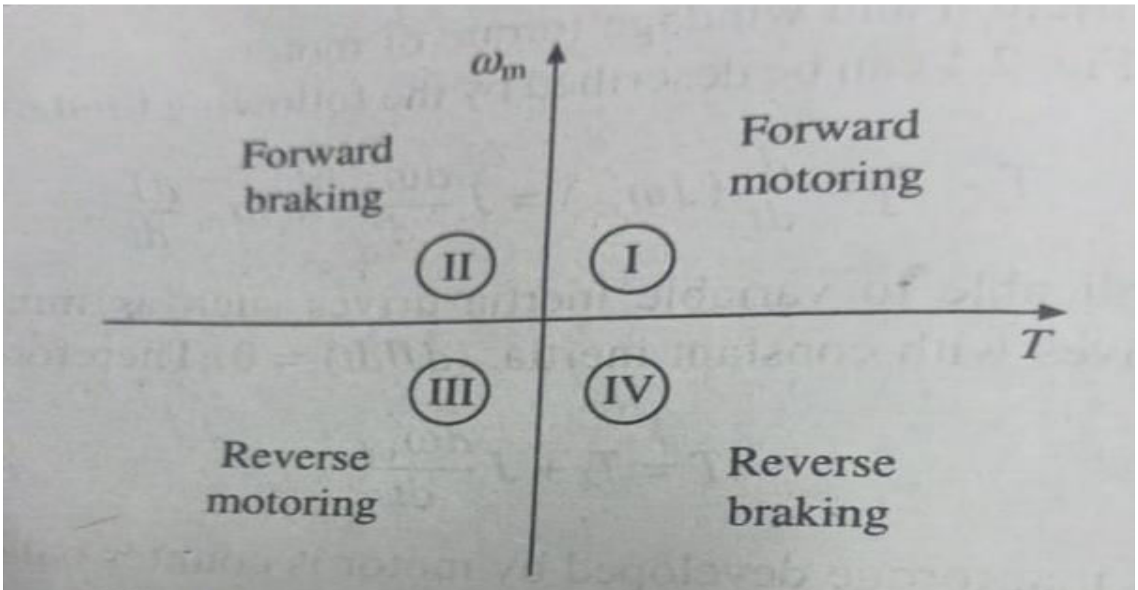


Fig. 2.2 Multiquadrant-operation of drives

Therefore, operation in quadrant II is known as forward braking. Similarly, operation in quadrant III and IV can be identified as reverse motoring and braking respectively.

For better understanding of the above notations, let us consider operation of a hoist in four quadrants as shown in fig. directions of motor and load torques, and direction of speed are marked by arrows.

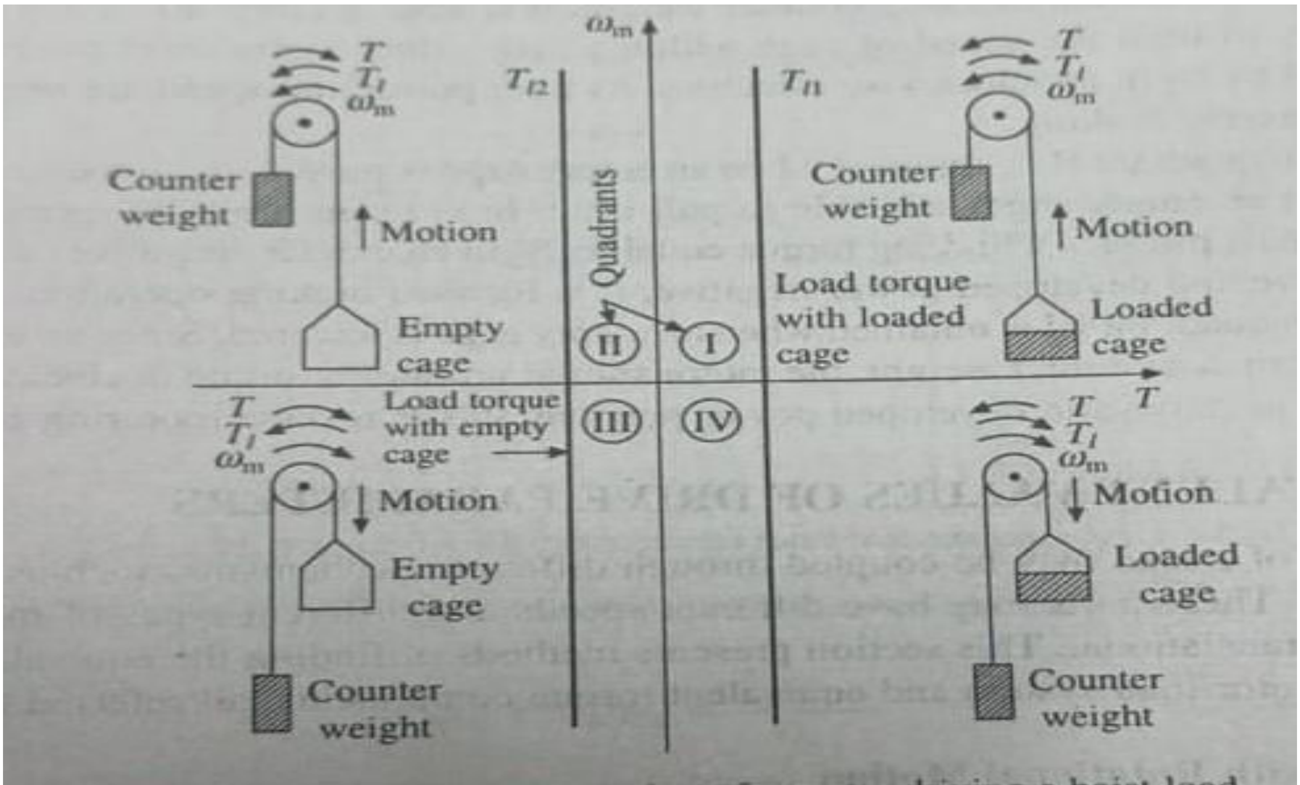


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

Assumption

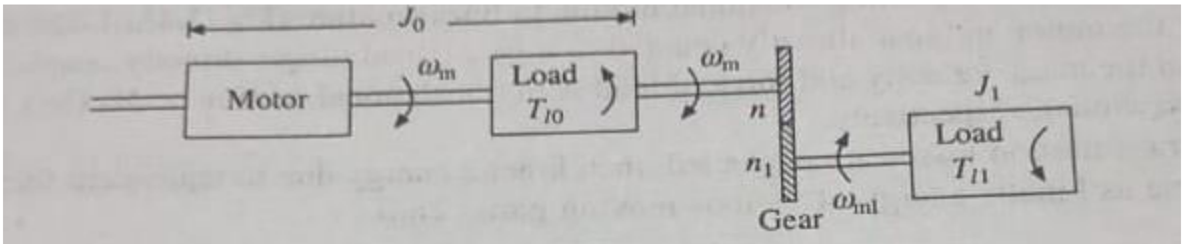
- There are three parameters namely ω_m ,T,T_l
- These parameters May rotate in clockwise or anti-clockwise direction.
- If it is clockwise then we should take the sign convention as negative.
- If it is anti-clockwise then the sign convention will be positive.
- T_l and T_m always opposes each other.
- Counter weight › Empty cage
- Counter weight ‹ loaded cage
- Forward direction –if the cage is moving from bottom to top.
- Reverse direction--- if the cage is moving from top to bottom.

Operation of the hoist. Parameters.	Quadrant I	Quadrant II	Quadrant III	Quadrant IV
T_l	Clockwise (Negative)	Anti-clockwise (positive)	Anti-clockwise (positive)	Clockwise (Negative)
T	Anti-clockwise (positive)	Clockwise (Negative)	Clockwise (Negative)	Anti-clockwise (positive)
ω_m	Anti-clockwise (positive)	Anti-clockwise (positive)	Clockwise (Negative)	Clockwise (Negative)
Power	Anti-clockwise (positive)	Clockwise (Negative)	Anti-clockwise (positive)	Clockwise (Negative)
Result	Forward Motoring	Forward braking	Reverse Motoring	Reverse braking

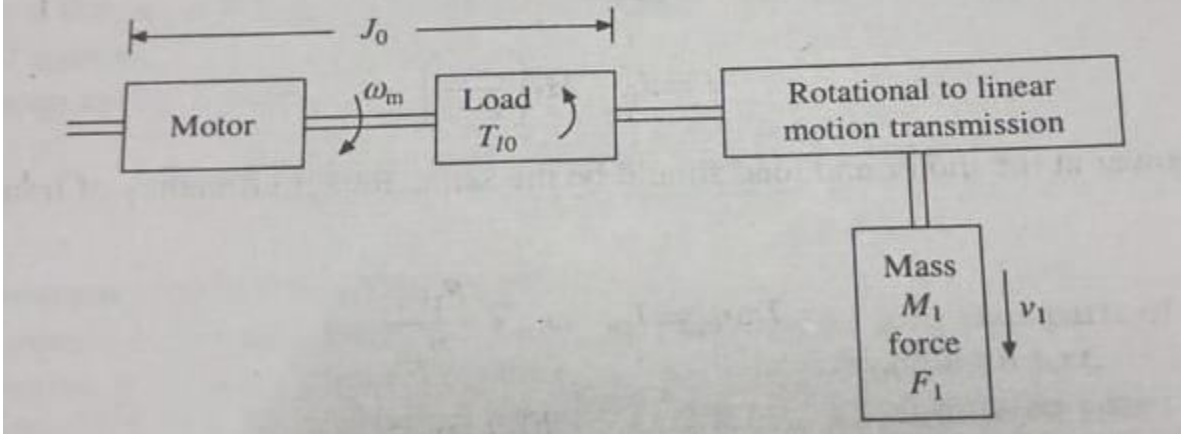
Load torque has been shown to be constant and independent of speed. This is nearly true with a low-speed hoist where forces due to friction and windage can be considered to be negligible compared to those due to gravity. Gravitational torque does not change its sign even when the direction of driving motor is reversed. Load torque line T in quadrants I and IV represents speed-torque characteristic for the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight. The load torque line 72 in quadrants II and III is the speed- torque characteristic for an empty hoist. This torque is the difference of torques due to counter weight and the empty hoist. Its sign is negative because the weight of a counter weight is always higher than that of an empty cage.

Equivalent values of drive parameters

Loads with rotational motion



(a) Loads with rotational motion



(b) Loads with translational and rotational motion

Let us consider a motor driving two loads, one coupled directly to its shaft and other through a gear with a and n, teeth as shown in Fig. Let the moment of inertia of motor and load n directly coupled to its shaft be Jo, 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

$$\frac{\omega_{m1}}{\omega_m}=\frac{n}{n1}=a1 \qquad (1)$$

Where a1 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

$$\frac{1}{2}J\omega_M^2=\frac{1}{2}J_0\,\omega_M^2+\frac{1}{2}J_1\omega_{M1}^2 \qquad (2)$$

From equation 1 and 2: -

$$J=J_0+a_1^2J_1 \qquad (3)$$

Power at the loads and motor must be the same. If transmission efficiency of the gear be ή$_1$, then

$$T_l\omega_m=T_{l0}\omega_m+\frac{T_{l1}\omega_{m1}}{\acute{\eta}_1} \qquad (4)$$

Where Tl is the total equivalent torque referred to motor shaft.

From equation 1 and 4: -

$$T_l=T_{l0}+\frac{a_1T_{l1}}{\acute{\eta}_1} \qquad (5)$$

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, J_3………., J_m and gear teeth ratio of a_1, a_2……….a_m then

$$J=J_0+a_1{}^2J_1+a_2{}^2J_2+\text{……….}+a_m{}^2J_m \qquad (6)$$

If m loads with torques T_{l1}, $Tl_{2\ldots,}$ Tlm are coupled through gears with teeth ratios a_1, $a_{2\ldots}a_m$ and transmission efficiency $\acute{\eta}_1$, $\acute{\eta}_2$…., $\acute{\eta}_m$ in addition to one directly coupled, then

$$T_l=T_{l1}+\frac{a_1T_{l1}}{\acute{\eta}_1}+\text{……}+\frac{a_mT_{l2}}{\acute{\eta}_m} \qquad (7)$$

Loads with translational motion

Let us consider a motor driving two loads, one coupled directly to its shaft and other through a transmission system converting rotational motion to linear motion. Let moment of inertia of the motor and load directly coupled to it be J_0. load torque directly coupled to motor be T_{l0} and the mass, velocity and force of load with translational motion be M_1(kg), V_1(m/sec) and F_1 (Newtons), respectively.

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

$$\frac{1}{2}J\omega_M{}^2=\frac{1}{2}J_0\,\omega_M{}^2+\frac{1}{2}M_1v_1{}^2$$

$$J=J_0+M\left(\frac{V_1}{\omega_m}\right)$$

Similarly, power at the motor and load should be the same, thus if efficiency of transmission be $\acute{\eta}_1$

$$T_l\omega_m=T_{l0}\omega_m+\frac{f_1v_1}{\acute{\eta}_1}$$

$$T_l=T_{l0}+\frac{F_1}{\acute{\eta}_1}\left(\frac{V_1}{\omega_1}\right)$$

If in addition to one load directly coupled to the motor shaft, there are m other loads with translational motion with velocities V_1,V_2,……V_M and masses M_1,$M_{2,\ldots\ldots\ldots}M_m$, respectively, then

$$J=J_0+M_1\left(\frac{V_1}{\omega_m}\right)^2+\text{…….}+M_m\left(\frac{V_m}{\omega_m}\right)^2$$

$$T_l=T_{l0}+\frac{F_1}{\acute{\eta}_1}\left(\frac{V_1}{\omega_1}\right)+\text{……}+\frac{F_m}{\acute{\eta}_m}\left(\frac{V_m}{\omega_m}\right)$$

COMPONENTS OF LOAD TORQUES

(1) Friction torque T_f:

Friction will be present at the motor shaft and also in various parts of the load. T is equivalent value of various friction torques referred to the motor shaft.

(2) Windage torque T_W:

When a motor runs, wind generates a torque opposing the motion. This is known as windage torque.

(3) Torque required to do the useful mechanical work, T_L;

Nature of this torque depends on particular application. It may be constant and independent of speed; it may be some function of speed; it may depend on the position or path followed by load; it may be time invariant or time- variant; it may vary cyclically and its nature may also change with the load's mode of operation.

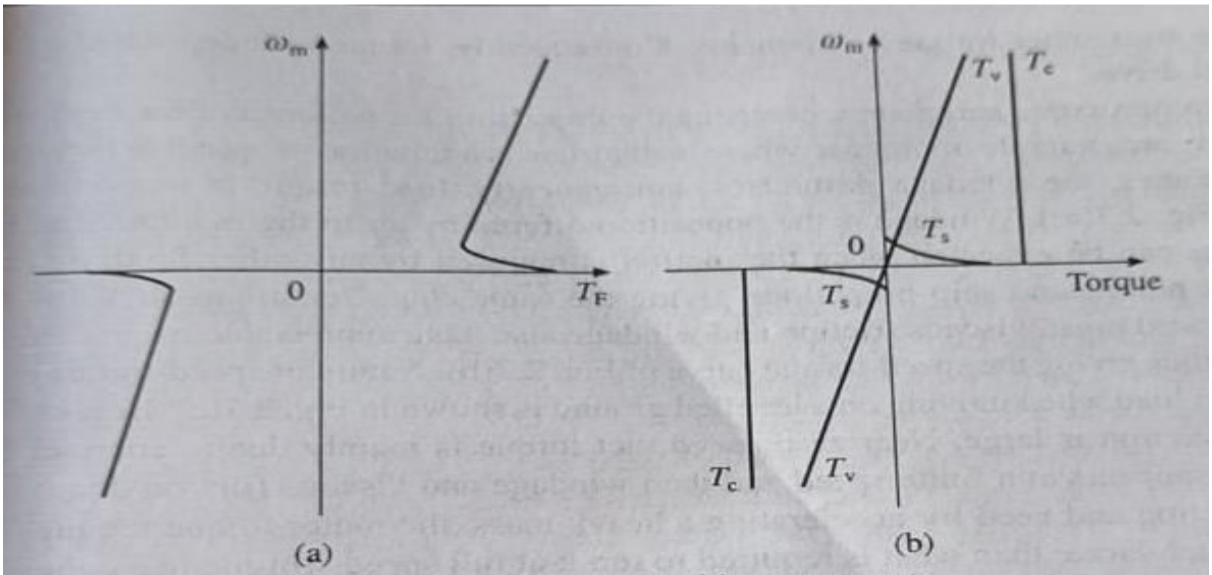
- Its value at standstill is much higher than its value slightly above zero speed. Friction at zero speed is called stiction or static friction. In order for drive to start, the motor torque should at least exceed stiction. Friction torque can be re resolved into three components. Components T_v which varies linearly with speed is called VISCOUS FRICTION and is given by;

  $$T_V = B\omega_m$$

  B is known as viscous coefficient.

- Another component T, which is independent of speed, is known as Coulomb friction. Third component T, accounts for additional torque present at standstill. Since T, is present only at standstill it is not taken into account in the dynamic analysis.
- Windage torque T_w which is proportional to speed squared, is given by

  $$T_w = C\omega^2$$, where C is a constant.



(a) (b)

Fig. 2.6 Friction torque and its components

For finite speed

$$T_l= T_l+B\omega_m+T_C+C\omega^2$$

In many applications (T_c+ $C\omega^2$) is very small compared to Boo and negligible compared to 7. In order to simplify the analysis, term (T_c+$C\omega^2$) is approximately accounted by updating the value of viscous friction coefficient, B.

$$T=J\frac{d\omega_m}{dt}+T_l+B\omega_m$$

If there is a torsional elasticity in shaft coupling the load to the motor, an additional component of load torque, known as coupling torque, will be present.

Coupling torque (T_e) is given by

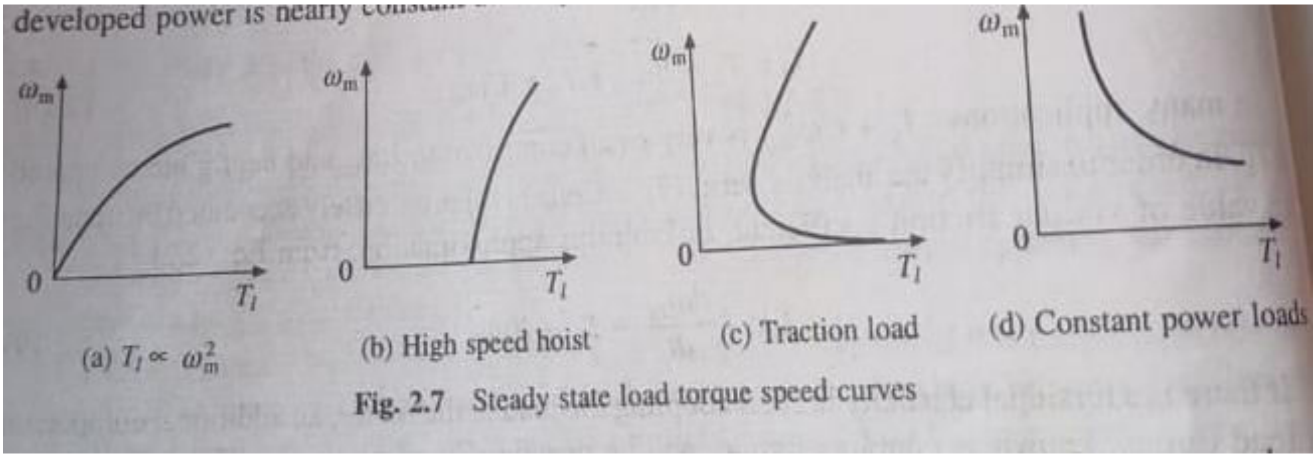
$$T_e=K_e\Theta_e$$

Θ_e is known as torsion angle of coupling (radians)

K_e is known as stiffness of the shaft (N-M/rad)

Nature and classification of load torques

developed power is nearly



(a) $T_l \propto \omega_m^2$ (b) High speed hoist (c) Traction load (d) Constant power loads

Fig. 2.7 Steady state load torque speed curves

Various load torques can be broadly classified into two categories: -

(1) active load torques

(2) passive load torques

- Load torques which have the potential to drive motor under equilibrium condition are called **active load**. Such load torques usually retain their sign when the direction of the drive rotation is changed.
- Load torque which always oppose the motion and change their sign on the reversal of motion are called **passive load torque.** Such torques are due to friction, windage, cutting.
- Electric drives always a dynamic condition.
- Dynamic conditions have two states: -
    (1) transient state
    (2) steady state
- starting, braking, speed change and speed reversal are transient operations.
- When T and T_l are constants or proportional to speed will be a first order linear differential equation. Then it can be solved analytically. When T or T_l is neither constant nor proportional to speed will be a non-linear differential equation. It could then be solved numerically by Runga Kutta method.
- Final speed is an equilibrium speed.

$$\text{dt} = \frac{jd\omega_m}{(T\omega_m)-(T_l\omega_m)}$$

where $T\omega_m$ and $T_l\omega_m$ indicate that the motor and load torque are function of drive speed ω_m.

Time taken for drive speed to change from ω_{m1} to ω_{m2} is obtained by integrating equation (1): -

$$\text{t} = \text{J}\int_{\omega_{m1}}^{\omega_{m2}} \frac{d\omega_m}{(T\omega_M)-(T_l\omega_m)}$$

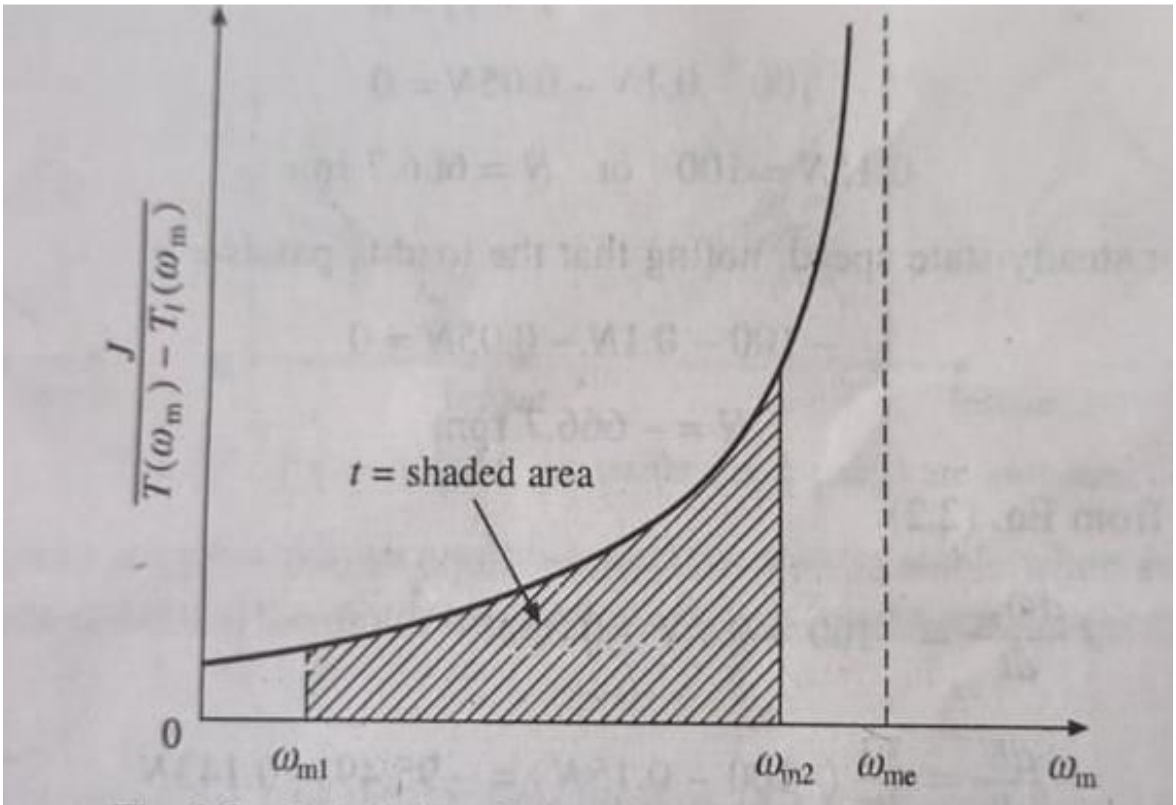


Fig. 2.8 Calculation of time during a transient operation

The transient time can be evaluated by measuring this area.

Energy dissipated in a motor winding during a transient operation is given by

$$E=\int_0^t Ri^2\, dt$$

Where R is known as motor winding

i is known as current flowing

Steady state stability

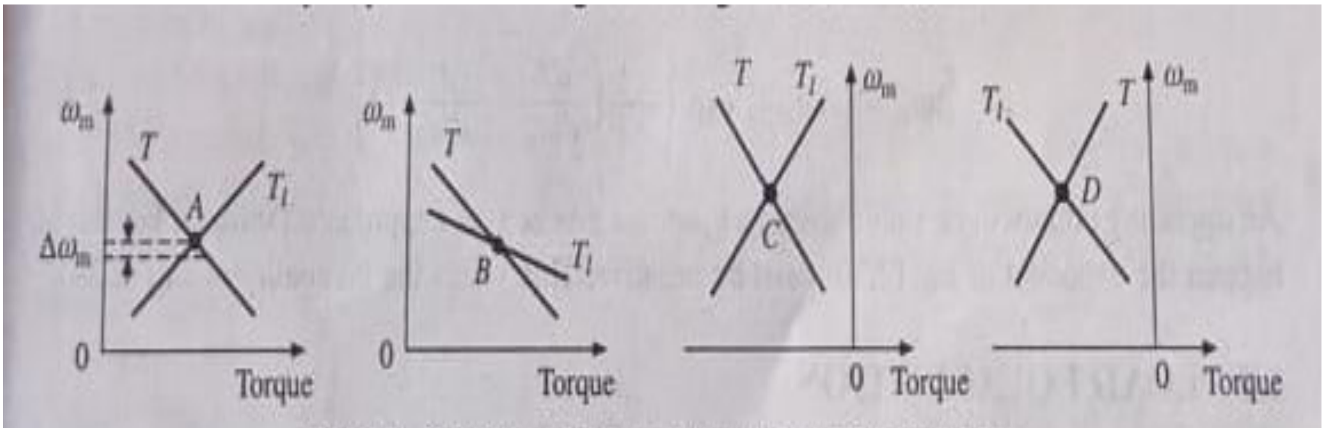


Fig. 2.9 Points A and C are stable and B and D are unstable

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:

$$\frac{dT_l}{d\omega_m} \rangle \frac{dT}{d\omega_m}$$

Let a small perturbation in speed, $\Delta\omega_m$ results in ΔT and ΔT_l perturbations in T and T_l respectively: -

$$T+\Delta T=(T_l+\Delta T_L)+J\frac{d(\omega_m+\Delta\omega_m)}{dt}$$

$$T+\Delta T=T_l+\Delta T_L+J\frac{d\omega_m}{dt}+J\frac{d\Delta\omega_m}{dt}$$

Subtracting this above two equations we get: -

$$J\frac{d\Delta\omega_m}{dt} = \Delta T- \Delta T_l$$

for small perturbations, the speed torque curves of the motor and load can be assumed to be straight lines. Thus

$$\Delta T= (\frac{dT}{d\omega_m})\ \Delta\omega_m$$

$$\Delta T_L = (\ \frac{dT_l}{d\omega_m}\ )\ \ \Delta\omega_m$$

Where $\frac{dT}{d\omega_m}$ and $\frac{dT_l}{d\omega_m}$ are respectively slopes of the steady-state speed torque curves of motor and load at operating point under consideration. Substituting this above two equations we get: -

$$J\frac{d\Delta\omega_m}{dt} + (\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m})\ \Delta\omega_m = 0$$

This is a first order linear differential equation. If initial deviation in speed at t=0 be $(\Delta\omega_m\ )0$ then the solution of equation will be

$$\Delta\omega_m\ = (\Delta\omega_m\ )0\ \exp\left\{-\frac{1}{J}\left(\frac{dT_l}{d\omega_m}\ -\ \frac{dT}{d\omega_m}\right)t\right\}$$

Load equalisation

- Motor is driving the load.
- There are two types of loads
  - Motor torque
  - Load torque
- Depending upon the motor torque, speed of motor is also being changes.
- Load is equalised by adding an additional arrangement called flywheel in series.

(load +flywheel)
⇓
(it increases the net inertia)
⇓
(control of speed & variation)
⇓
(control the torque)

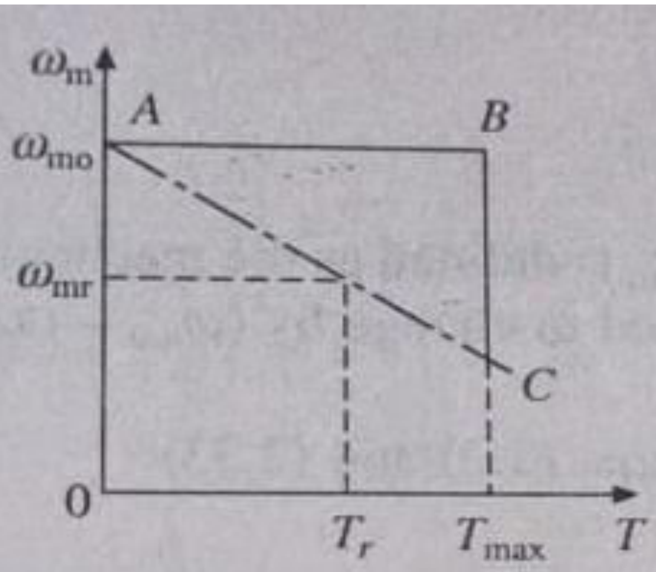
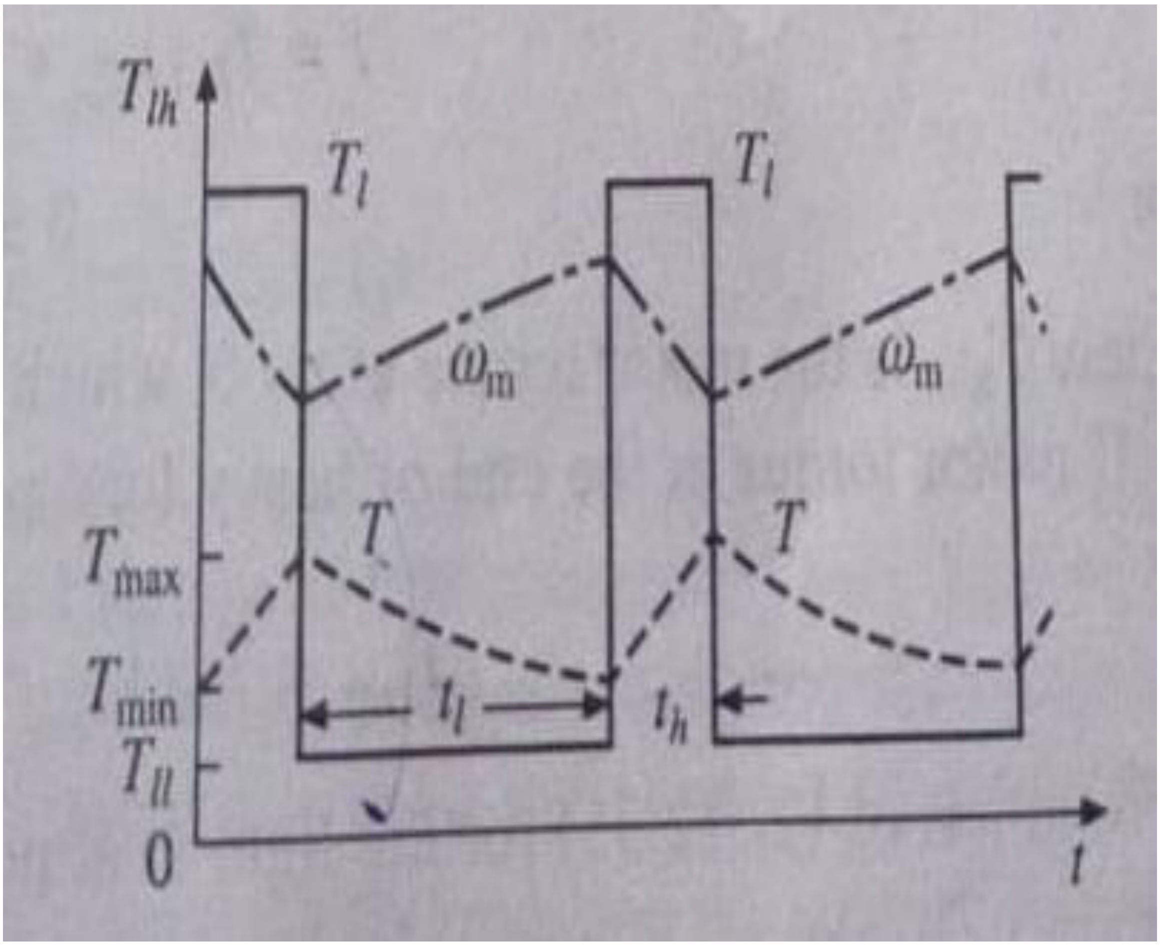


Fig. 2.10 Shapes of motor speed torque curves for fluctuating roads



Motor characteristics

$$\omega_m = \omega_{m0} - KT$$

Differentiating w.r.t time: -

$$\frac{d\omega_m}{dt} = \frac{d\omega_{m0}}{dt} - k\frac{dT}{dt}$$

$$\frac{d\omega_m}{dt} = - k\frac{dT}{dt}$$

Dynamic equation of a drives: -

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

$$- kJ \frac{dT}{dt} + T_L = T$$

$$kJ \frac{dT}{dt} + T = T_L$$

This is a 1st order equation. The solution of 1st order equation will be: -

$$T = T_{ini} + (T_{final} – T_{nitial})\ (1 – e\hat{}\ - (\frac{t}{\tau_m}))$$

$$\tau = \frac{t_h}{log_e \frac{(T_{lh} - T_{min})}{(T_{lh} - T_{max})}}$$

again $$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \left[\frac{t_h}{log_e \left\{ \frac{T_{lh} - T_{min}}{T_{lh} - T_{max}} \right\}} \right]$$

$$\tau_m = \frac{t_l}{log_e \left\{ \frac{(T_{max} - T_{l1})}{(T_{min} - T_{l1})} \right\}}$$

from this above two equations we get: -

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})} \left[\frac{t_l}{log_e \left\{ \frac{(T_{max} - T_{l1})}{(T_{min} - T_{l1})} \right\}} \right]$$

Moment of inertia of the flywheel required can be calculated from these equations: -

$$J = WR^2$$

Where w is the weight of the flywheel(kg) and R is the radius.

CLASSES OF MOTOR DUTY

Categorises various load time variations encountered in practice into eight standard classes of duty.

(I)Continuous duty.

(II) Short time duty.

(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:

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 in 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:

In this, time of drive operation is considerably less than the heating time constant and machine is allowed to cool off to ambient 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:

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 is sufficient to raise the temperature to a steady-state value, nor the rest period is long enough for the machine to cool off to ambient temperature. In this duty, heating of machine during starting and braking operations is negligible Some examples are pressing, cutting and drilling machine drives.

(iv)Intermittent Period Duty with Starting:

This is intermittent periodic duty where heat losses during starting cannot be ignored. Thus, it consists of a period of starting, a period of operation at a constant load and a rest period; with operating and rest periods being too short for the respective steady-state temperatures to be attained

In this duty, heating of machine during braking is considered to be negligible, because are used for stopping or motor is allowed to stop due to its own friction. Few examples are metal cutting and drilling tool drives, drives for fork lift trucks, mine hoist etc.

(v)Intermittent Periodic duty with Starting and braking:

This is the intermittent periodic duty where heat losses during starting and harking cannot be ignored. Thus, it consists of a period of starting, a period of operation with a combatant load, a braking period with electrical braking and a rest period; with operating and rest periods being too short for the respective steady state temperatures to be attained. some Billet mill drive, manipulator drive, ingot buggy drive, strapdown mechanism of blooming mill, several machine tool drives, drives for electric suburban trains and mine hoist are examples of this duty.

(vi) Continuous Duty with Intermittent Periodic Loading.

It consists of periodic duty cycles. each consisting of a period of running at a constant load and a period of running at no load, with normal voltage across the excitation winding, Again the load period and no-load period being too shown for the respective temperatures to be attained. This duty is distinguished from the intermittent periodic duty by the fact that a period of running at a constant load is followed by a period of running at no load instead of rest. Pressing, cutting, shearing and drilling machine drives are the examples.

(vii) Continuous Duty with Starting and Braking:

Consists of periodic duty cycle, each having a period of starting, a period of running at a constant load and a period of electrical braking: there is no period of rest. The main drive of a blooming mill is an example.

(vii) Continuous Duty with Periodic Speed Changes:

Consists of periodic duty cycle, each having a period of running at one load and speed, and another period of running at different speed and load; again, both operating periods are too short for respective steady-state temperatures to be attained. Further there is no period of rest.

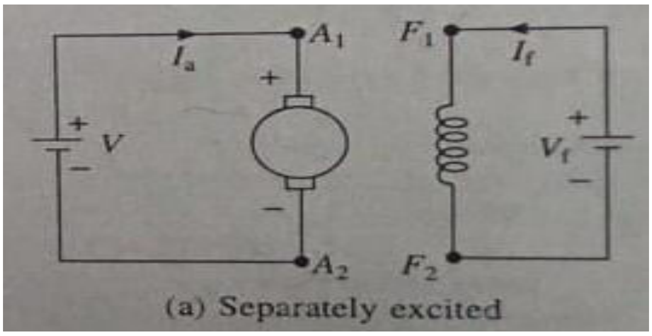
MODULE 2

DC MOTOR DRIVES: -

Commonly used dc motors are: -

- Separately excited
- Shunt
- Series
- Cumulatively compound

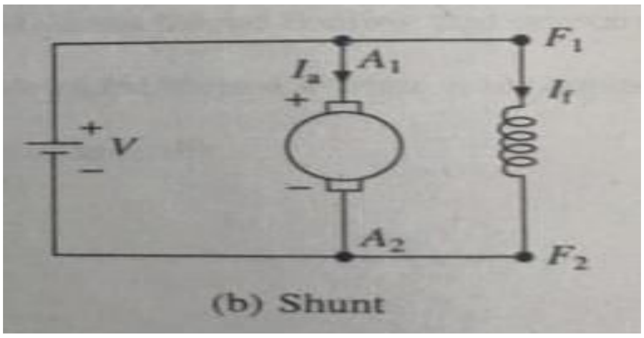
Separately excited: -



(a) Separately excited

The field and armature voltage can be controlled independent of each other.

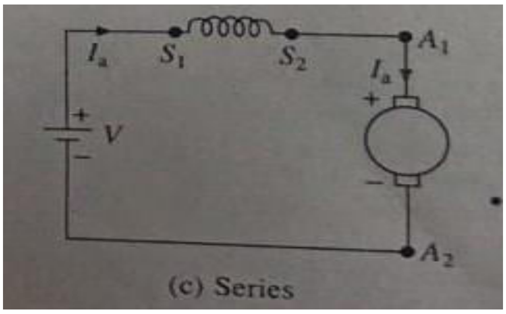
Shunt: -



(b) Shunt

In a shunt motor, field and armature are connected to a common source.

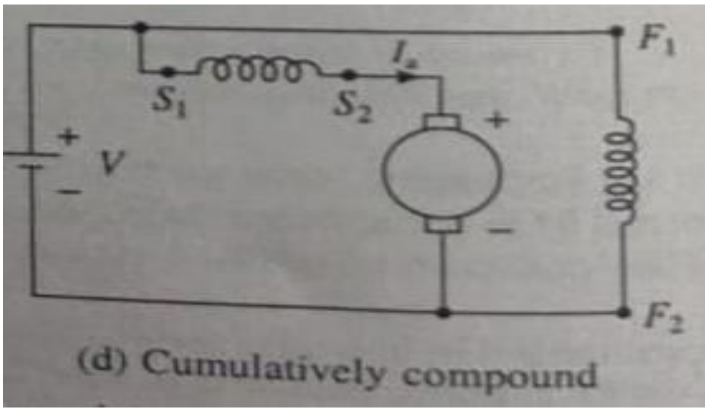
Series: -



(c) Series

In case of series motor, field current is same as armature current, and therefore, field flux is a function of armature current.

Cumulatively compound: -



(d) Cumulatively compound

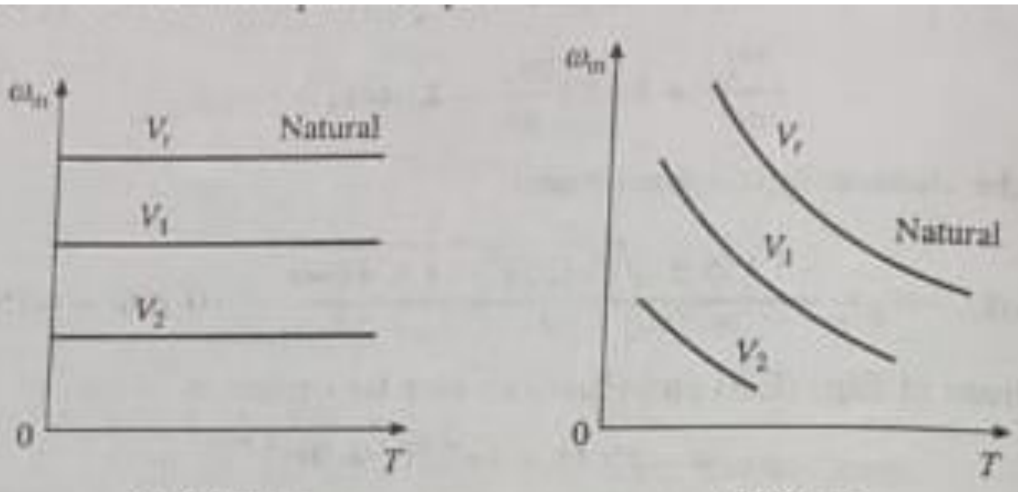
In a cumulatively compound motor, the magneto-motive force of the series field is a function of armature current and is in the same direction as mmf of the shunt field.

Speed control: -

There are three types of speed control: -

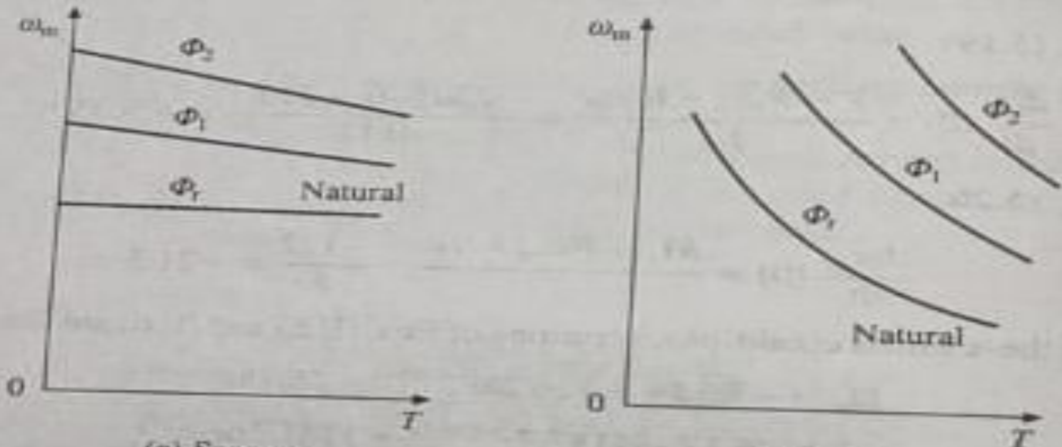
- Armature voltage control
- Field flux control
- Armature resistance control

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 the armature voltage cannot be allowed to exceed rated value. For speed control above base speed, field flux control is employed. In a normally designed motor, the maximum speed can be allowed up to twice rated speed and in specially designed machines it can be six times rated speed.



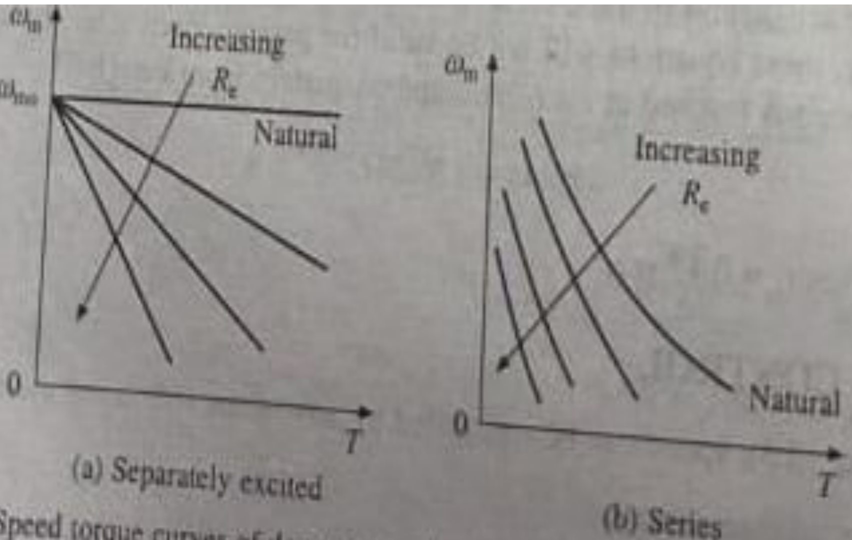
(a) Separate (b) Series

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

The maximum torque and power limitations of de drives operating with armature voltage control and full field below rated speed and flux control at rated armature voltage above rated speed are shown in Fig. 5.19. In armature voltage control at full field, Tx 1, consequently, the maximum torque that the machine can deliver has a constant value. In the field control at rated armature voltage, Pm 1, (because E = V = constant). Therefore, maximum power developed by the motor has a constant value.

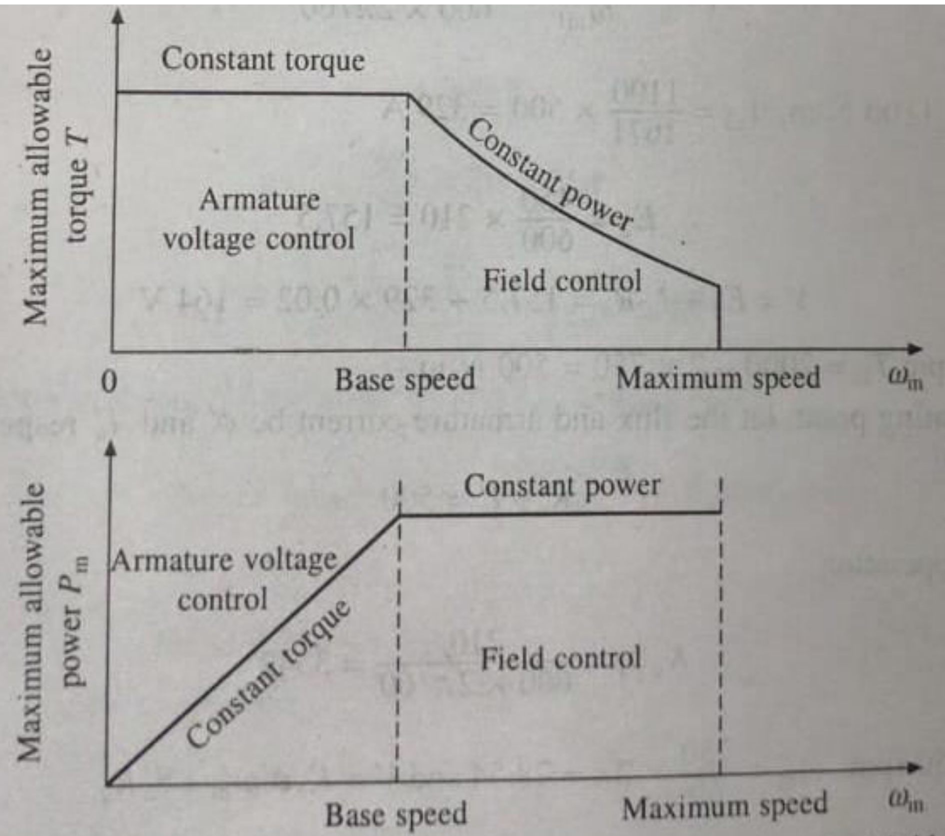


Fig. 5.19 Torque and power limitations in combined armature voltage and field control

In a separately excited motor, flux is controlled by varying voltage across field winding and in a series motor it is controlled either by varying number of turns in the field winding or connecting a diverter resistance across the field winding.

Methods of varying armature voltage

In armature resistance control, speed is varied by wasting power in external resistors that are connected in series with the armature. Since it is an inefficient method of speed control, it was used in intermittent load applications where the duration of low-speed operation forms only a small proportion of total running time, for example in traction. It has, however, been replaced by armature voltage control in all these applications.

BRAKING METHODS: -

- Brake is used to change the speed or make it halt.
- Braking is of two types: -
  Mechanical braking
  Electrical braking
- Disadvantages of mechanical braking is high friction.
- In case of electrical braking friction is vey less. Because there is no mechanical contact.
- Electrical braking is of three types: -

  (I)Regenerative braking
  (II)Dynamic braking
  (III)Plugging braking

- **Regenerative braking: -** It behaves itself as a generator i.e., generating the voltage. feeding back to the supply.
- **Dynamic braking: -** supply voltage needs to be disconnected.so voltage will be zero.so it becomes short-circuited.
- **Plugging braking:** -reversal of armature winding is there. So, the back emf is changed. So, torque is also changed and speed decreased.

Regenerative braking: -

Regenerative Braking, generated energy is supplied to the source.

$E > V$ and negative I_a

Field flux cannot be increased substantially beyond rated because of saturation. Therefore, 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. In series motor as speed increases, armature current, and therefore, flux decreases. Thus, regenerative braking is not possible.

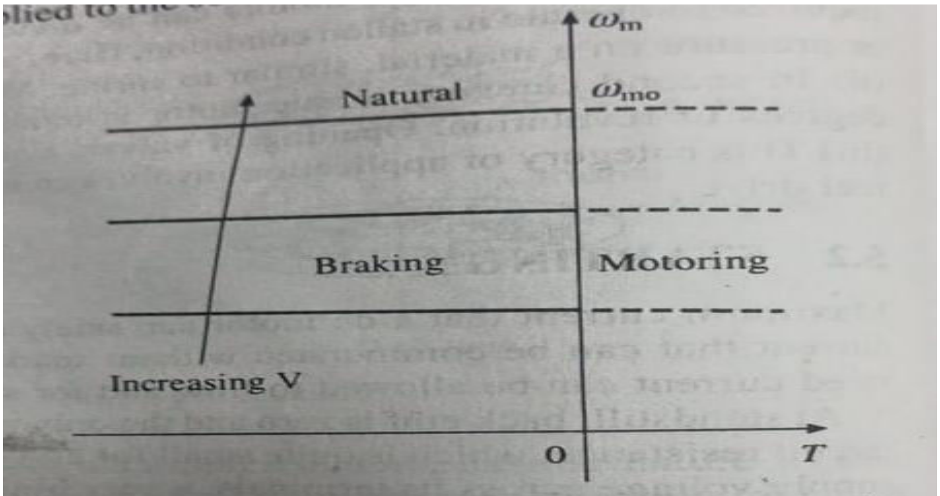
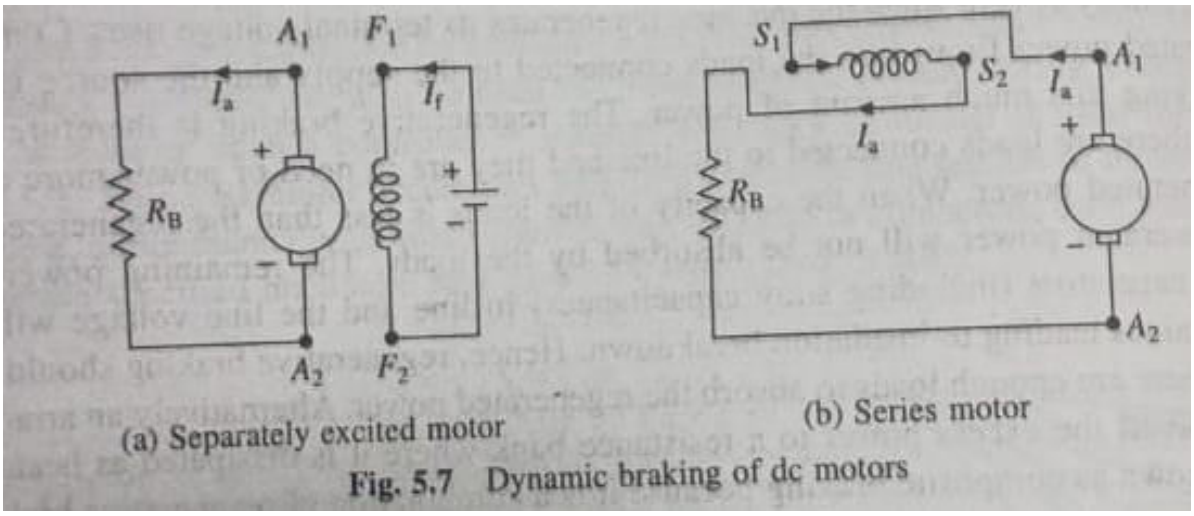


Fig. 5.6 Regenerative braking characteristics of a separately excited motor

Dynamic braking: -

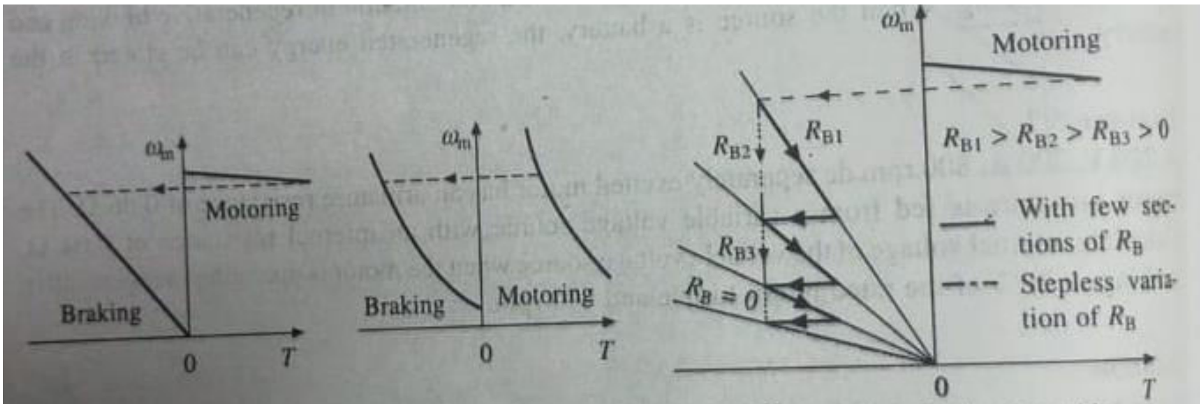
In dynamic braking, motor armature is disconnected from the source and connected across a resistance R_B. The generated energy is dissipated in R_B and Ra. Since series machine works as a self-excited generator, the field connection is reversed so that field assists the residual magnetism. These characteristics are obtained from equations for V=0. When fast braking is desired, Ry consists of a few sections. As the speed falls, sections are cut-out to maintain a high average torque for a separately excited motor.

During braking, separately excited motor can be converted as a self-excited generator. This permit braking even when supply fails.



(a) Separately excited motor (b) Series motor

Fig. 5.7 Dynamic braking of dc motors

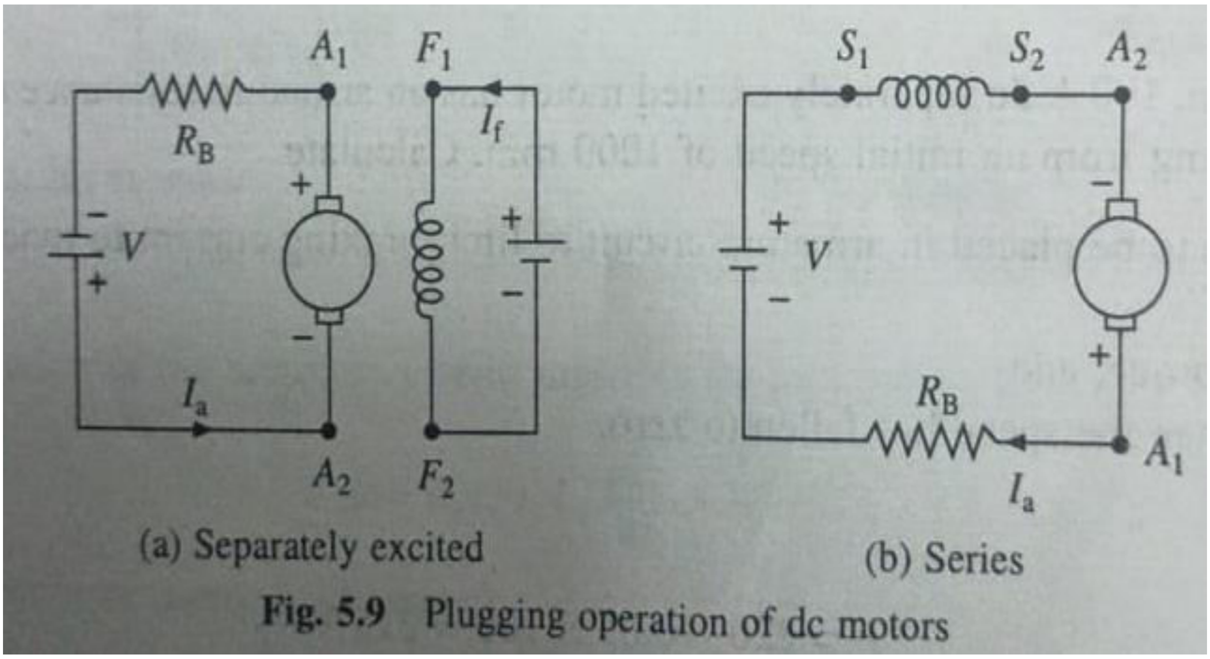


(a) Separately excited motor (b) Series motor (c) Separately excited motor with variable armature resistance

Fig. 5.8 Dynamic braking speed-torque curves

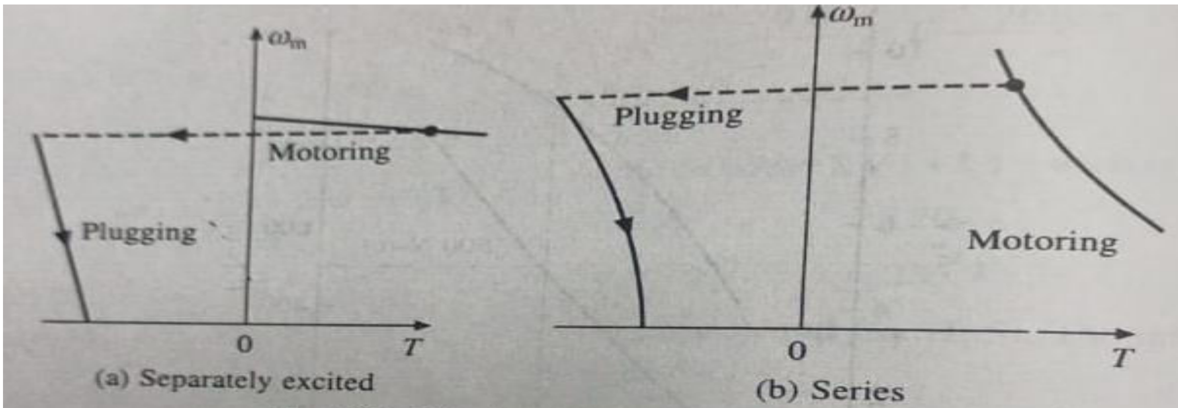
Plugging: -

For plugging, the supply voltage of a separately excited motor is reversed so that it assists the back 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 alone 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 hoist applications and the braking is then called counter-torque braking.



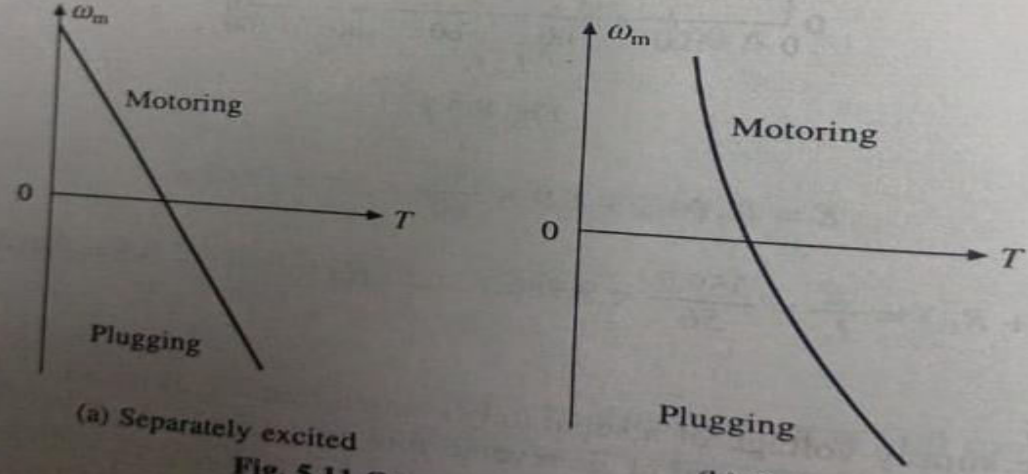
(a) Separately excited (b) Series

Fig. 5.9 Plugging operation of dc motors



(a) Separately excited (b) Series

Fig. 5.10 Plugging speed-torque curves



(a) Separately excited (b) Series

Fig. 5.11 Counter-torque braking

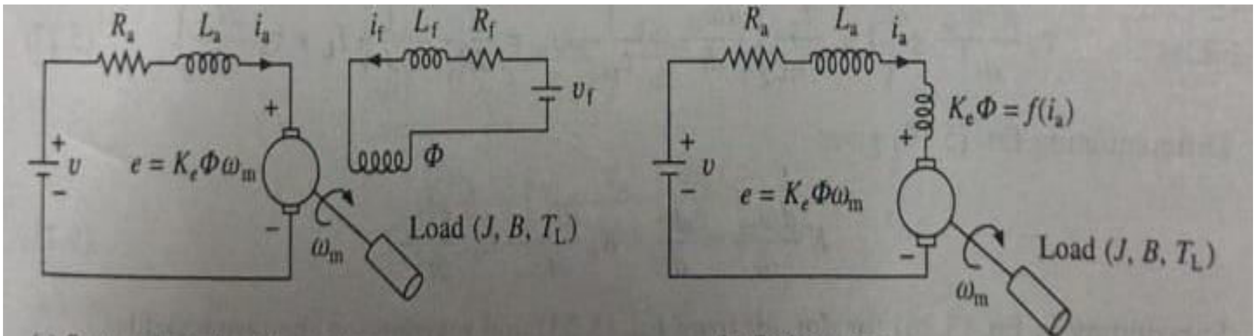
gives fast braking due to hi
Since to

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

Transient Analysis: -

Starting, braking, reversing, speed changing and load changing are the transient operations which commonly occur in an industrial drive. One is interested in knowing how current, torque and speed of the driving motor change with time when under these transient operations. One is also interested in knowing energy losses, particularly those responsible for heating of the motor, and time taken for the completion of the transient process. This information is needed by the designer for selecting suitable rating of the motor, nature and type of its control equipment and its operation schedule, and types of protective devices and their settings.

Dynamic equivalent circuits of de motors are shown in Fig. 5.12. Source voltage u motor armature current i, and back emf e are denoted by lower case letters to emphasize that these are instantaneous values of time varying quantities. B and J are respectively the coefficient of viscous friction in Nm/rad/sec and polar moment of inertia in kg-m² of the motor load system referred to the motor shaft.



(a) Separately excited dc motor

(b) Series motor

Fig. 5.12 Dynamic equivalent circuits of dc motors

Voltage equation of the armature circuit under transient is given by

$$V=R_a i_a + L_a\frac{di_a}{dt} + K_e\Phi\omega_m$$

From the dynamic of motor load system

$$J\frac{d\omega_m}{dt} = T - T_l - B\omega_m$$

For a series motor this equation can be solved numerically using 4th order Rungakutta method or predictor corrector method.

Transient analysis of separately excited motor with armature control: -

$$V=R_a i_a + L_a\frac{di_a}{dt} + K\omega_m \qquad (1)$$

$$J\frac{d\omega_m}{dt} = Ki_a - B\omega_m - T_l \qquad (2)$$

Differentiating both equations (1) and (2) we get: -

$$K\frac{di_a}{dt} = J\frac{d^2\omega_m}{dt^2} + B\frac{d\omega_m}{dt} + \frac{dt_l}{dt} \qquad (3)$$

Substituting in equation (1) for $\frac{di_a}{dt}$ from equation (3) and rearranging the term gives: -

$$T_a\frac{d^2\omega_m}{dt^2} + \left(1 + \frac{\tau_a}{\tau_{m1}}\right)\frac{d\omega_m}{dt} + \frac{1}{\tau_{m2}} = \frac{kv}{JR_a} - \frac{1}{J}\left(T_l + \tau_a\frac{dT_l}{dt}\right)$$

Differentiating equation (1): -

$$K\frac{d\omega_m}{dt}=\frac{dv}{dt}-R_a\frac{di_a}{dt}-L_a\frac{d^2i_a}{dt^2}$$

where $\tau_a=\frac{L_a}{R_a}$,armature circuit time constant

$$\tau_{m1}=\frac{J}{B}$$

$$\tau_{m2}=\frac{JR_a}{(BR_a+K^2)}$$

Transient analysis of starting of separately excited motor with armature control: -

$$I_l=\frac{T_l}{K}$$

When motor is connected to the supply, initial value of current is zero and due to armature circuit inductance, it takes some time to reach the value. During whole of this period, which will be termed as first interval of the transient response, motor remains at standstill and so its back emf remains zero. Motor behaves like a simple R_a -L_a, load. Hence its current is given by

$$I_a=\frac{V}{R_a}\left(1-e^{-t/\tau_a}\right)$$

Second interval of transient response starts after current reaches the value 4. Since V and T are constants, dv/dt and dT/dt will be zero.

$$T_a\frac{d^2\omega_m}{dt^2}+\left(1+\frac{\tau_a}{\tau_{m1}}\right)\frac{d\omega_m}{dt}+\frac{1}{\tau_{m2}}=\frac{K_1}{\tau_{m2}}$$

$$T_a\frac{d^2i_a}{dt^2}+\left(1+\frac{\tau_a}{\tau_{m1}}\right)\frac{di_a}{dt}+\frac{1}{\tau_{m2}}i_a=\frac{K_2}{\tau_{m2}}$$

Where $K_1=\frac{\tau_{m2}(KV-R_aT_l)}{JR_a}$

$$K_2=\frac{\tau_{m2}(BV-KT_l)}{JR_a}$$

K_1 and K_2 represent the steady state values of speed and current respectively with load torque equal to $T_{l.}$

Initial condition needed for the solution: -

$$W_m\ (0)=0\ ia\ (0)=I_l$$

Since the braking of this interval, motor is equal to load torque

$$\frac{d\omega_m}{dt}(0)=0$$

$$\frac{di_a}{dt}(0) = \frac{V - R_a I_l}{L_a}$$

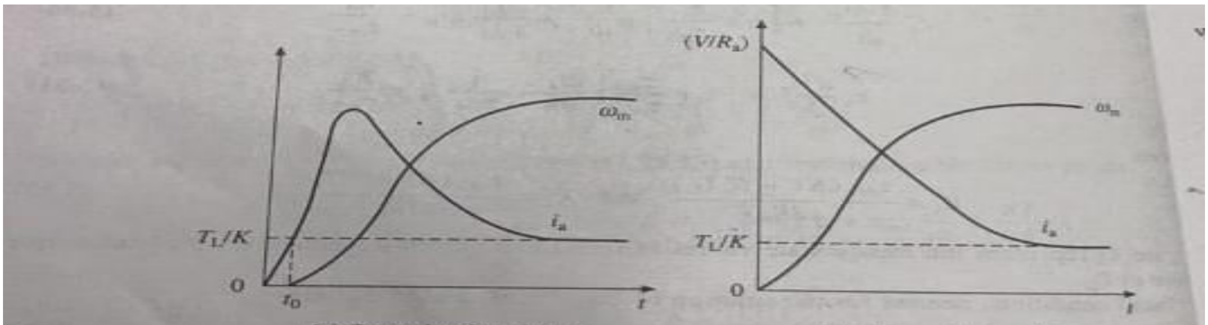
Solutions of these equations with the initial conditions will have the form:

$$W_m = \frac{\propto_2 K_1}{\propto_1 - \propto_2} e^{-\propto_1 t} + \frac{\propto_2 K_1}{\propto_2 - \propto_1} e^{-\propto_2 t} + K_1$$

and

$$i_a = \frac{V - \propto_2 L_a K_2 + (\propto_2 L_a - R_a) I_l}{L_a(\propto_2 - \propto_1)} e^{-\propto_1 t} + \frac{V - \propto_1 L_a K_2 + (\propto_1 L_a - R_a) I_l}{L_a(\propto_1 - \propto_2)} e^{-\propto_2 t} + K_2$$

where $\propto_1$ and $\propto_2$ are roots of characteristics equation and are given by



(a) Second order model (b) First order model

Fig. 5.13 Transient response of dc separately excited motor during starting with constant applied voltage

Transient analysis of dynamic braking of separately excited motor: -

It is assumed that a constant active load torque T_l is acting on the motor shaft. Transient speed and current equations can be obtained by substituting new value for armature circuit resistance and V=0. This gives

$$\tau_a \frac{d^2\omega_m}{dt^2} + \left(1 + \frac{\tau_a}{\tau_{m1}}\right) \frac{d\omega_m}{dt} + \frac{1}{\tau_{m2}} \omega_m = \frac{K_3}{\tau_{m2}}$$

$$\tau_a \frac{d^2 i_a}{dt^2} + \left(1 + \frac{\tau_a}{\tau_{m1}}\right) \frac{di_a}{dt} + \frac{1}{\tau_{m2}} i_a = \frac{K_4}{\tau_{m2}}$$

Where $K_3 = \frac{\tau_{m2} T_l}{J}$ and $K_4 = \frac{\tau_{m2} K T_l}{J R_a}$

Here also $-K_3$, and K_4, represent the steady state values of speed and current, respectively. This steady state running will occur when active load torque T_l is allowed to drive the motor in reverse direction. Initial conditions needed for the solution these equations are obtained as: It is assumed that at the initiation of breaking the motor was running in steady state with load torque T_l.

Substituting V=0, I_a=0, and $\omega_m = K_1$

$$\frac{di_a}{dt}(0) = -\frac{KK_1}{L_a}$$

$$\frac{d\omega_m}{dt}(0) = -\frac{BK_1+T_l}{L_a}$$

Solutions of these above two equations with the initial conditions will have the form

$$\omega_m = \frac{(J\propto_2-B)(K_1)-(T_l-J\propto_2K_3)}{J(\propto_2-\propto_1)}\, e^{-\propto_1 t} + \frac{(J\propto_1-B)(K_1)-(T_l-J\propto_1K_3)}{J(\propto_1-\propto_2)}\, e^{-\propto_2 t} - K_3$$

$$I_a = K_4 - \frac{KK_1+\propto_2 L_a K_4}{L_a(\propto_2-\propto_1)}\, e^{-\propto_1 t} - \frac{KK_1+\propto_1 L_a K_4}{L_a(\propto_1-\propto_2)}\, e^{-\propto_2 t}$$

Transient analysis of separately excited motor with field control: -

Let the armature voltage be maintained constant. Now

$$V_f = R_f i_f + L_f \frac{di_f}{dt}$$

$$V = R_a i_a + L_a \frac{di_a}{dt} + K_e \Phi \omega_m$$

$$J\frac{d\omega_m}{dt} = K_e \Phi i_a - T_l - B\omega_m$$

Here Φ *is a non linear* function of i_f. If saturation is neglected and Φ is assumed to be proportional to i_f. then can be written as

$$V = R_a i_a + L_a \frac{di_a}{dt} + K'_{i_f} \omega_m$$

$$J\frac{d\omega_m}{dt} = K'_{i_f} i_a - T_l - B\omega_m$$

Because of the terms $K'_{i_f}\omega_m$ and $K'_{i_f} i_a$ which involve product of two variables are nonlinear equations, even though the saturation has been neglected. Thus, this analysis can be carried out using numerical methods of solving non-linear differential equations such as 4th order Runge-Kutta and Predictor-Corrector Methods.

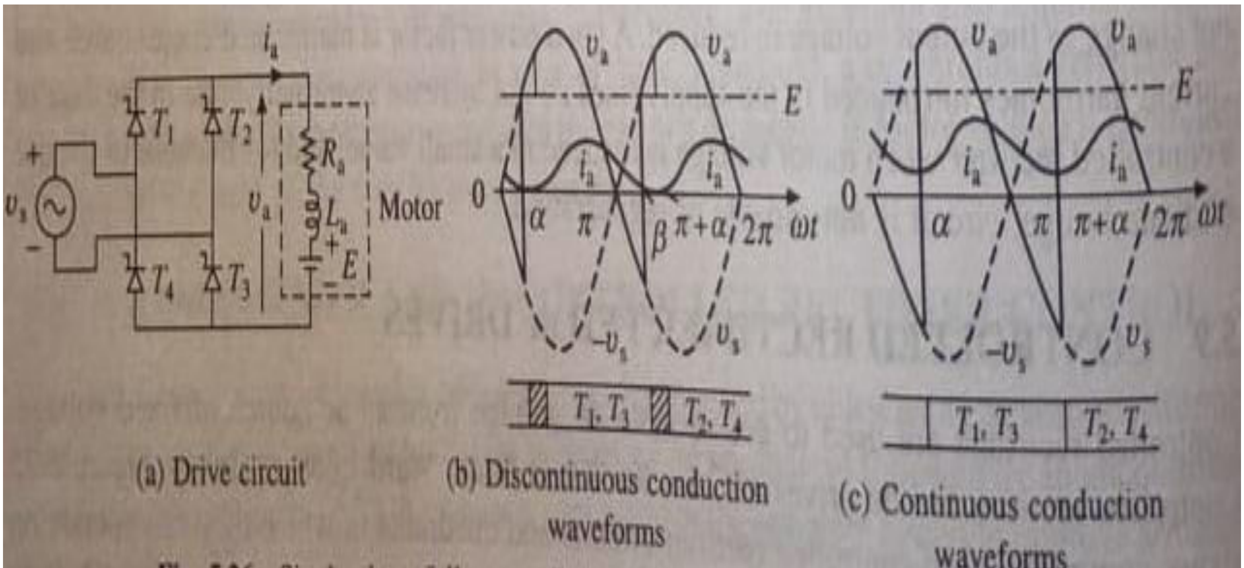
$$J\frac{d\omega_m}{dt} = K'_{i_f} - T_l - B\omega_m$$

Where $K_a = K_e K_\Phi I_a$ and I_a is the armature current.

$$J\tau_f \frac{d^2\omega_m}{dt} + (\tau_a + J)\frac{d\omega_m}{dt} + B\omega_m = \frac{K_f V_f}{R_f} + \tau_f \frac{dT_l}{dt} + T_l$$

The motor can be analysed for its transient response provided the initial conditions are known. The initial value of com will be known from the steady state operating point immediately before the transients and the initial value of dω_m/dt is calculated.

SINGLE-PHASE FULLY-CONTROLLED RECTIFIER CONTROL OF de SEPARATELY EXCITED MOTOR: -



(a) Drive circuit (b) Discontinuous conduction waveforms (c) Continuous conduction waveforms

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

V_s=V_m sin ωt

In a cycle of source voltage, thyristors T_1 and T_3, are given gate signals from a to л, and thyristors T_2 and T_4 are given gate signals from (∏+a) to 2∏. When armature current does not 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 considered.

Discontinuous conduction: -

In a cycle of motor terminal voltage $V_{a,}$ the drive operates in two intervals: -

- Duty interval (∝≤ωt≤в) when motor is connected to the source and V_a=V_b
- Zero current interval (в≤ωt≤∏+∝) when i_a=0 and V_a=E

Drive operation interval by the following equations:

$$V_a=R_a i_a+L_a \frac{di_a}{dt}+E=V_m \sin\omega t, \text{ for } \propto\leq \omega t \leq\beta \qquad (1)$$

$$V_a=E \text{ and } i_a=0 \text{ for } \beta \leq \omega t \leq \prod+\propto \qquad (2)$$

Solutions of eq. (1) has two components – one due to the ac source $\frac{v_m}{z}$ sin $(\omega t-\Phi)$, and other due to back emf $\left(-\frac{E}{R_a}\right)$.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

$$I_a(\omega t) = \frac{V_m}{Z}\sin(\omega t-\Phi) -- \frac{E}{R_a} + K_1 e^{-t/\tau_a} \quad \text{for } \propto \leq \omega t \leq \beta$$

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

$$\Phi = tan^{-1}(\omega L_a/R_a) \quad \text{M}$$

Constant K_1 can be evaluated to the initial condition $i_a(\propto)=0$. Substituting value of $K_{1.}$

$$\boldsymbol{I_a(\omega t) = \frac{V_m}{Z}[\sin(\omega t-\Phi) - sin(\propto-\Phi)e^{-(\omega t-\propto)cot\Phi}] - \frac{E}{R_a}\left[1-e^{-(\omega t-\propto)cot\Phi}\right]}$$

for ∝≤ωt≤β

Since $i_a(\beta)=0$,

$$\frac{V_m}{Z}\sin(\beta-\Phi) - \frac{E}{R_a} + \left[\frac{E}{R_a} - \frac{V_m}{Z}\sin(\propto-\Phi)\right]\boldsymbol{e^{-(\beta-\propto)cot\Phi}=0}$$

β can be evaluated by iterative solution

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

$$V_{a=}\text{E} + I_a R_a$$

$$V_a = \frac{1}{\pi}\left[\int_\alpha^\beta V_m sin\omega t d(\omega t) + \int_\beta^{\pi+\alpha} Ed(\omega t)\right]$$

$$= \frac{V_m(cos\alpha - cos\beta)+(\pi+\alpha-\beta)E}{\pi}$$

Armature current consists of dc component II_a and harmonics. When flux is constant, only dc component produces steady torque. Harmonics produce alternating torque components, average value of which is zero.

$$\omega_{m=}\frac{V_m(cos\alpha-cos\beta)}{K(\beta-\alpha)} - \frac{\pi R_a}{K^2(\beta-\alpha)}T$$

Boundary between continuous and discontinuous conduction is reached when $\beta=\pi+\alpha$,Substituting $\beta=\pi+\alpha$ gives the critical value of speed ω_m which separates continuous conduction from discontinuous conduction for given α as

$$\omega_m = \frac{R_a V_m}{ZK} sin(\propto-\Phi)\frac{1+e^{-\Pi cot\Phi}}{e^{-\Pi cot\Phi}-1}$$

Continuous conduction: -

$$V_a = \frac{1}{\pi}\int_{\propto}^{\Pi+\propto} V_m \sin \omega t \; d(\omega t) = \frac{2V_m}{\pi}\cos \propto$$

From above equations we get: -

$$\omega_m = \frac{2V_m}{\prod K}\cos \propto - \frac{R_a}{K^2}T$$

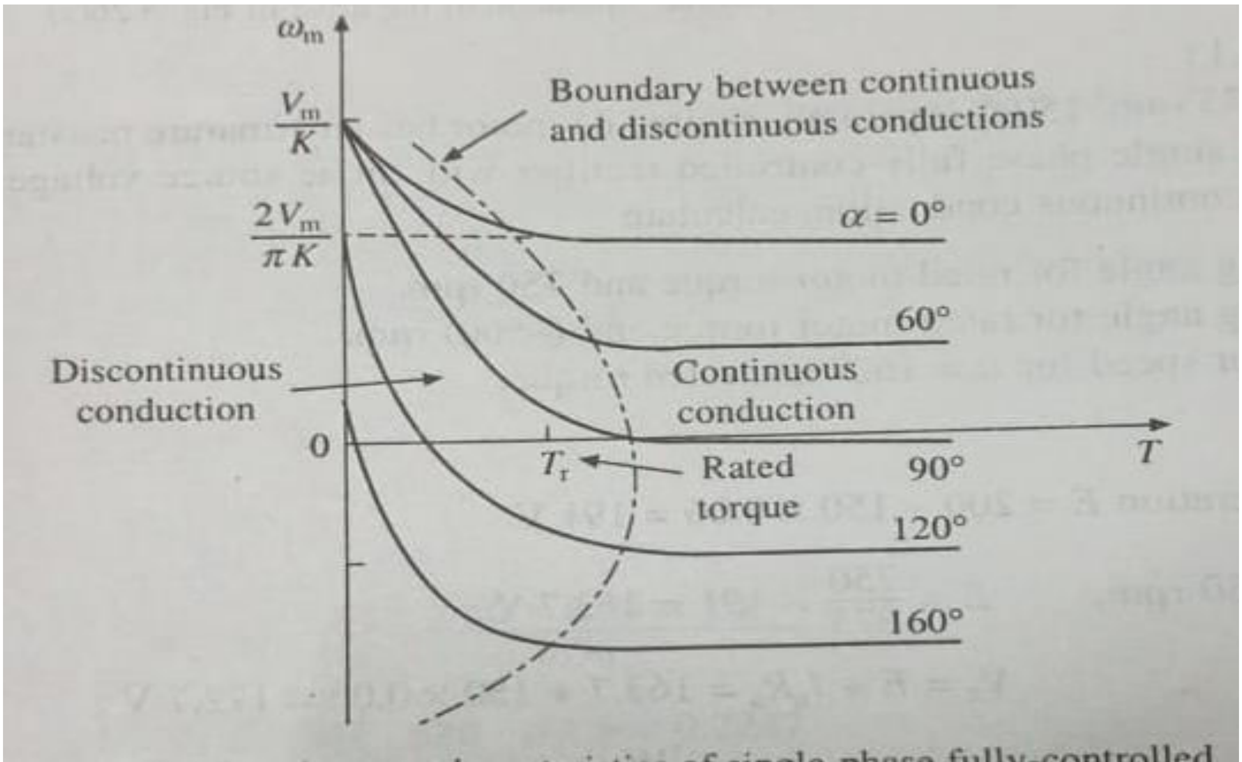
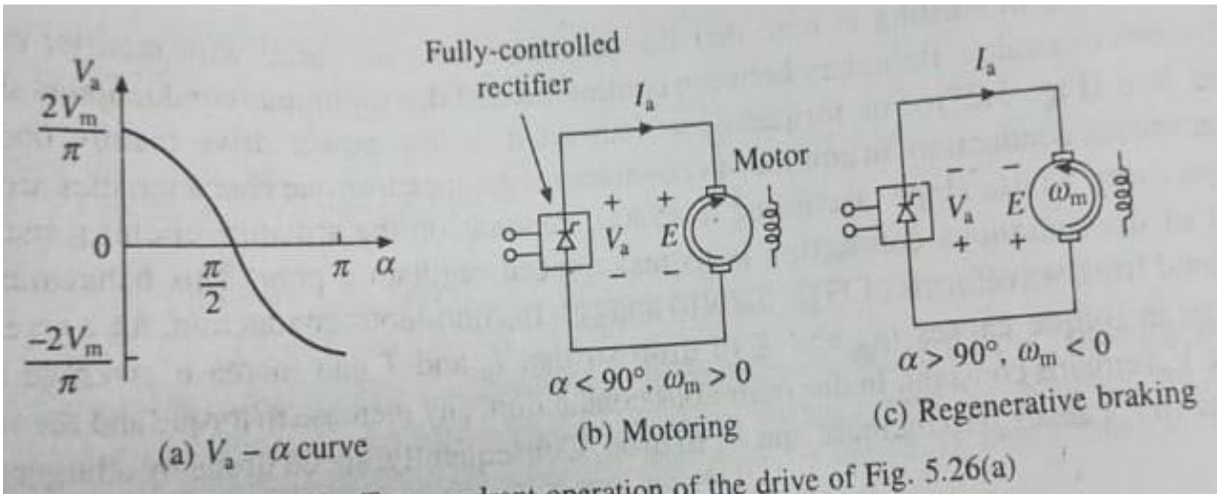


Fig. 5.27 Speed torque characteristics of single-phase fully-controlled rectifier fed dc separately excited motor

The drive operates in quadrants I (forward motoring) and IV (reverse regenerative braking). These operations can be explained as follows:

under the assumption of continuous conduction, de output voltage of rectifier varies with $\propto$ as shown in Fig. When working in quadrant I, ω_m is positive and $\propto \leq 90°$; and polarities of V_a, and E are shown in Fig. For positive I_a, this causes rectifier to deliver power and the motor to consume it, thus giving forward motoring. Polarities of E, I_a, and V_a, for IV operation are shown in Fig. E has reversed due to reversal of ω_m. Since I_a is still in same direction, machine is working as a generator producing braking torque. Further due to $\propto > 90°$, V_a, is negative, suggesting that the rectifier now takes power from de terminals and transfers it to ac mains. This operation of rectifier is called inversion and the rectifier is said to operate as an inverter. Since generated power is supplied to the source in this operation, it is regenerative braking.

Two quadrant operation capability of the drive can be utilised only with overhauling loads or other active loads which can drive the motor in reverse direction. In a normal two quadrant operation of a motor one needs forward motoring (quadrant I) and forward braking (quadrant II) which cannot be provided by the drive of Fig.



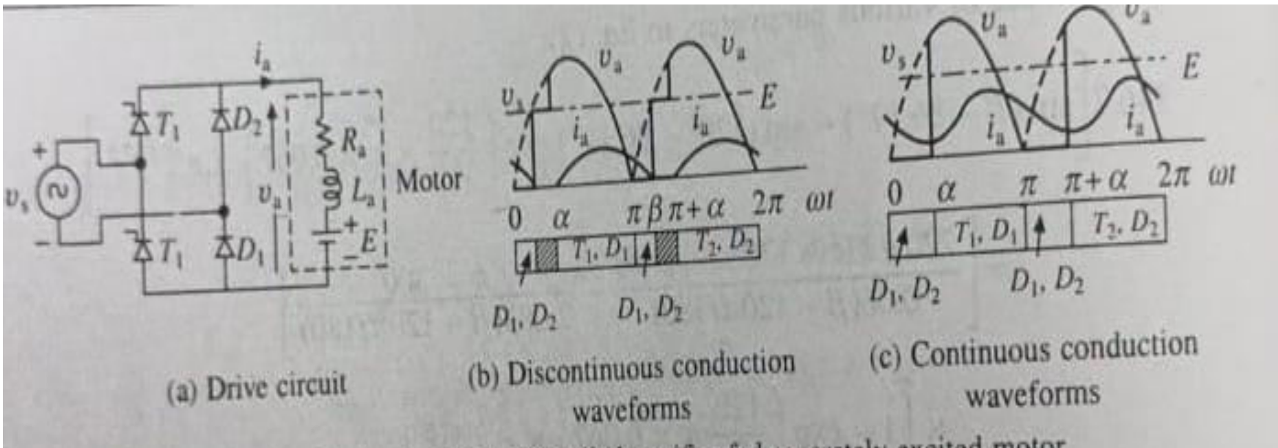
(a) $V_a - \alpha$ curve (b) Motoring (c) Regenerative braking

Fig. 5.28 Two-quadrant operation of the drive of Fig. 5.26(a)

SINGLE-PHASE HALF-CONTROLLED RECTIFIER CONTROL OF de SEPARATELY EXCITED MOTOR: -

Discontinuous conduction: -

A cycle of motor terminal voltage consists of three intervals:-



(a) Drive circuit (b) Discontinuous conduction waveforms (c) Continuous conduction waveforms

Fig. 5.29 Single-phase half-controlled-rectifier fed separately excited motor

- **Duty interval (∝≤ωt≤∏+∝):** -substitution of ωt=∏ in armature equation gives i_a (∏).
- **Freewheeling intervals (∏≤ωt≤β):** -operation is governed by the following equation:

$$i_a R_a + L_a \frac{di_a}{dt} + E = 0$$

$$i_a(\omega t) = \frac{V_m}{Z}\left[\sin\Phi . e^{-(\omega t-\prod)\cot\Phi} - sin(\propto -\Phi)e^{-(\omega t-\prod)\cot\Phi}\right] - \frac{E}{R_a}\left[1-. e^{-(\omega t-\prod)\cot\Phi}\right]$$

- **Zero current interval (β≤ωt≤∏+∝):**

INDUCTION MOTOR: -

Speed Control: -

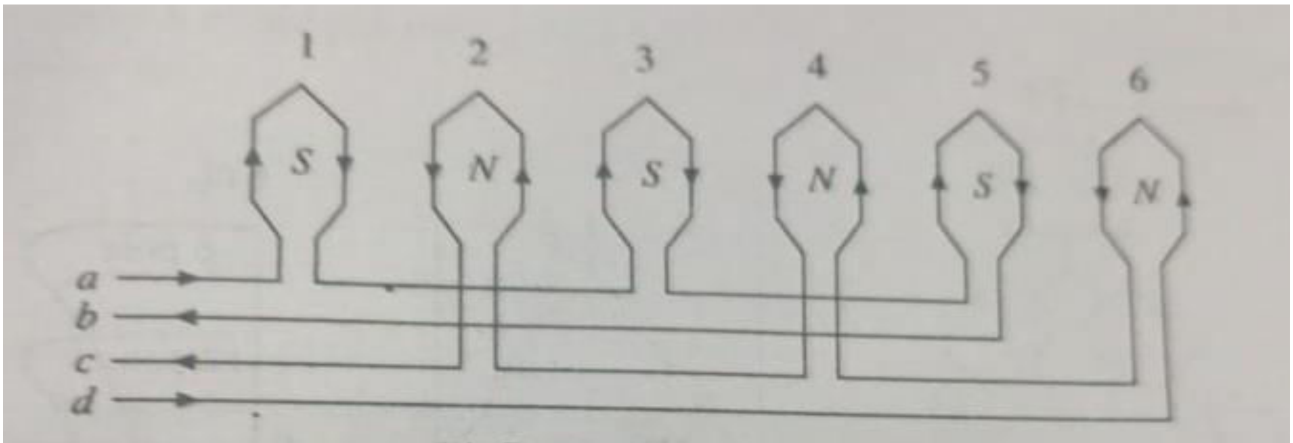
Following methods are employed for speed control of induction motors: -

- Pole changing
- Stator voltage control
- Supply frequency control
- Eddy current coupling
- Rotor resistance control
- Slip power recovery

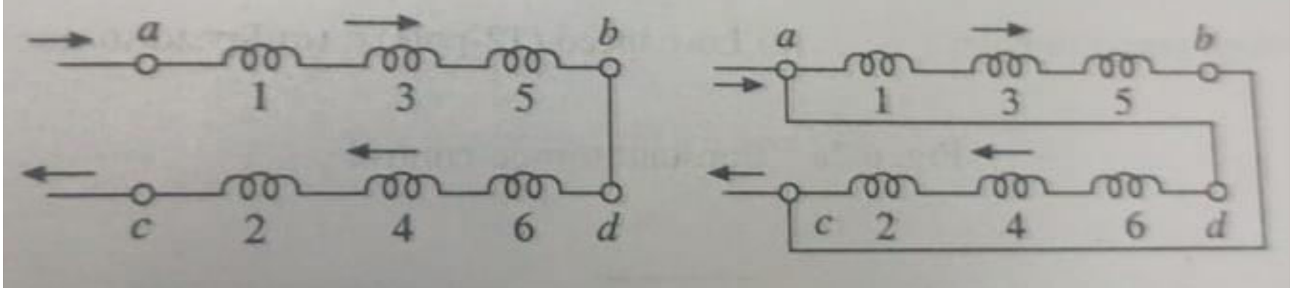
Pole changing: -

For a given frequency, the synchronous speed is inversely proportional to the number of poles. Synchronous speed, and therefore, motor speed can be changed by changing the number of poles. Provision for changing the number of poles has to be incorporated at the manufacturing stage and such machines are called, 'pole changing motors' or 'multi-speed motors.

Squirrel-cage rotor is not wound for any specific number of poles. It produces the same number of poles as stator winding has. Therefore, in a squirrel-cage motor, an arrangement is required only for changing the number of poles in stator. In wound-rotor motor, arrangement for changing the number of poles in rotor is also required, which complicates the machine. Therefore, this method of speed control is only used for squirrel-cage motors.



(a) Connection for 6 poles



(b) Series connection

(c) Parallel connection

Fig. 6.24 Stator phase connection for 6-poles

Stator voltage control: -

Pole changing method allows a change of speed by a factor 2. In some applications, speed change is required only by a small amount, e.g., some fan and pump drives require speed reduction to reduce power output at the most to half of rated. Since, torque is proportional to speed squared in a fan drive, power is proportional to (speed). Half of rated power is obtained when speed is reduced approximately by 20%. Such a small change in speed is possible by pole amplitude modulation.

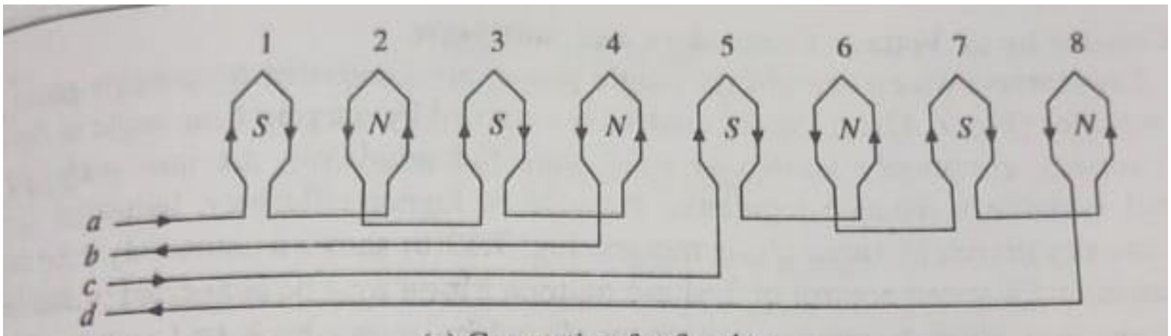
The mmf distribution in air-gap owing to stator winding of a three-phase induction motor may be written generally as

$$F_A = F_{mA} \sin p\Theta$$

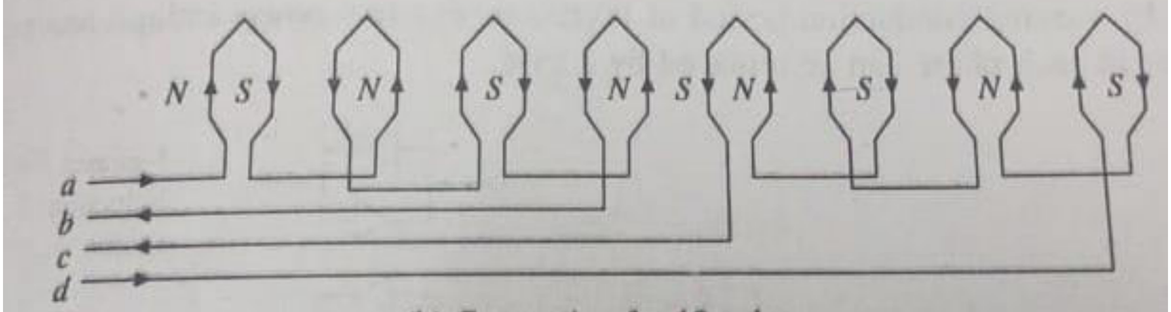
$$F_B = F_{mB} \sin (p\Theta - 2\pi/3)$$

$$F_C = F_{mC} \sin (p\Theta - 4\pi/3)$$

Where Θ is the mechanical energy.



(a) Connection for 8 poles



(b) Connection for 10 poles

Fig. 6.30 Pole amplitude modulation by coil inversion

suffer from harmonic currents and voltages, and have lower power factor and efficiency than pole changing motors described in the earlier section. They find applications in fan, blower and pump drives.

Stator voltage control: -

By reducing stator voltage, speed of a high-slip induction motor can be reduced by an amount which is sufficient for the speed control of some fan and pump drives). While torque is proportional to voltage squared, current is proportional to voltage. Therefore, as voltage is reduced to reduce speed, for the same current motor develops lower torque. Consequently, method is suitable for applications where torque demand reduces with speed, which points towards its suitability for fan and pump drives.

If stator copper loss, core loss, and friction and windage loss are ignored, then

$$\eta = \frac{p_m}{p_g} = 1 - s$$

The equation shows that the efficiency falls with decrease in speed. The speed control is essentially obtained by dissipating a portion of rotor input power in rotor resistance. Thus, not only the efficiency is low, the power dissipation occurs in the rotor itself, which may overheat the rotor. Because of these rating and for narrow speed range. Variable voltage for speed control is obtained using ac voltage controllers.

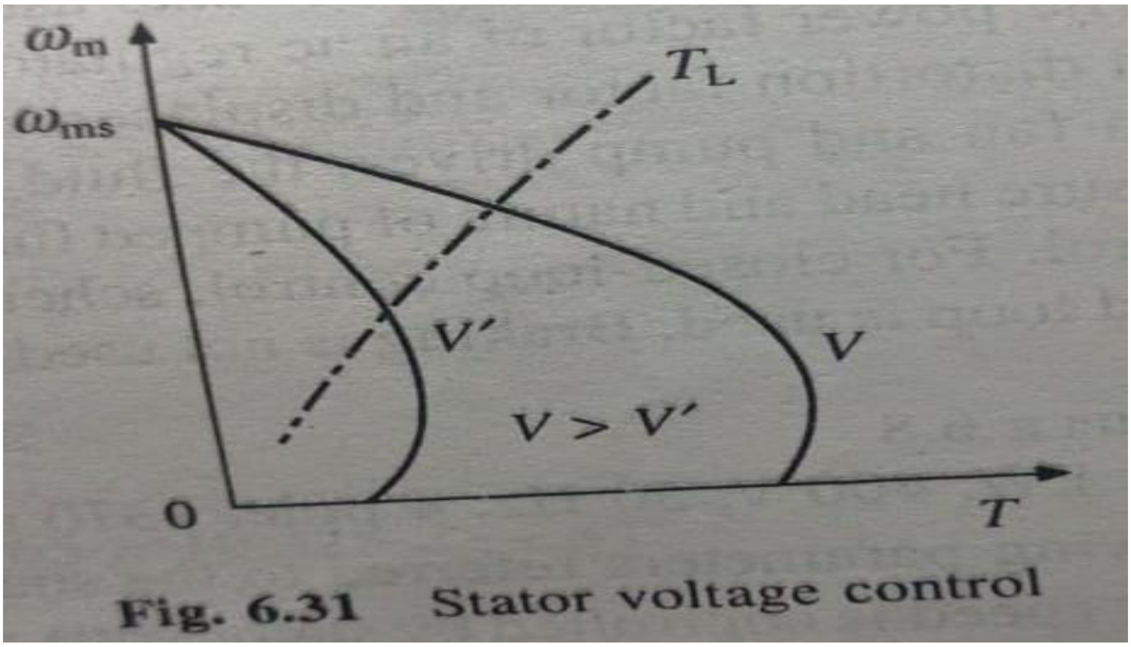


Fig. 6.31 Stator voltage control

Control by ac Voltage Controllers and Soft Start: -

Domestic fan motors, which are always single-phase, are controlled by a single-phase triac voltage controller. Speed control is obtained by varying firng angle of the triac. These controllers, commonly known as solid state fan regulators, are now preferred over conventional variable resistance regulators because of higher efficiency. Industrial fans and pumps are usually driven by three-phase motors. shows a commonly used thyristor voltage controller for speed control of 3-phase motors. Motor may be connected in star or delta. In delta connection, third harmonic voltage produced by motor back emf causes circulating current through the windings which increases losses and thermal loading of motor. Speed control is obtained by varying conduction period of thyristors. For low power ratings, anti-paralleled thyristor pair in each phase can be replaced by a triac.

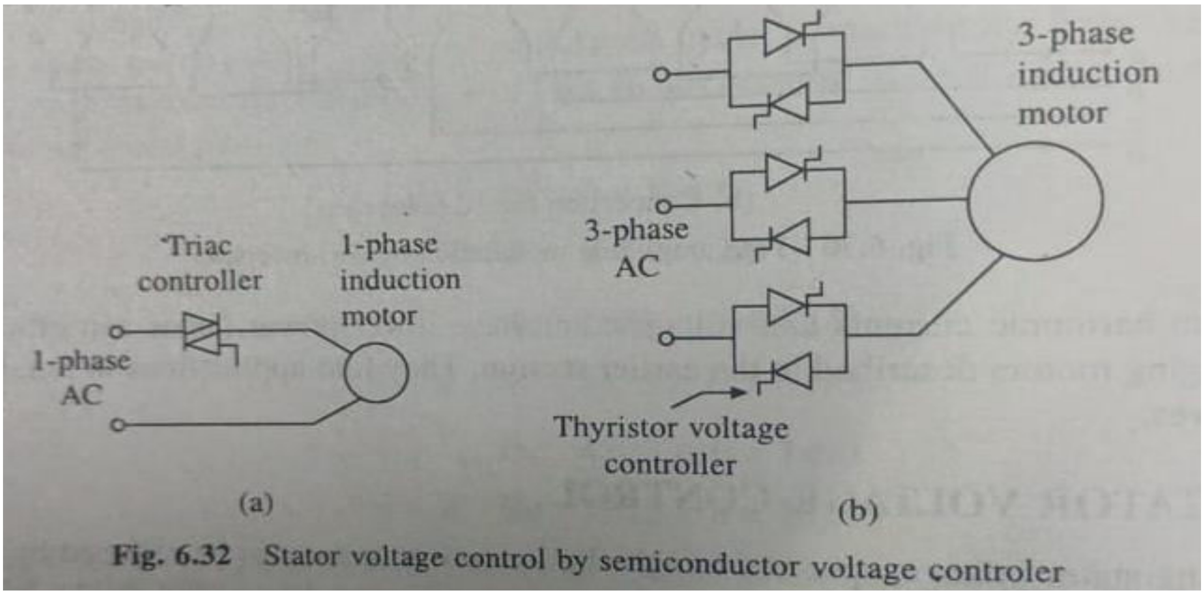


Fig. 6.32 Stator voltage control by semiconductor voltage controler

Since voltage controllers, both single- and three-phase, allow a stepless control of voltage from its zero value, they are also used for soft start of motors. The power factor of an ac regulator is defined.

With increase in firing angle, both distortion factor and displacement factor reduce, giving a low power factor.

In fan and pump drives, the fluid flow has to be maintained constant against variations in pressure head and nature of pumped fluid. Therefore, it is always operated with closed-loop speed control. For closed-loop control, consisting of inner current loop and outer speed loop is used. Braking is not used because fluid pressure provides adequate braking torque.

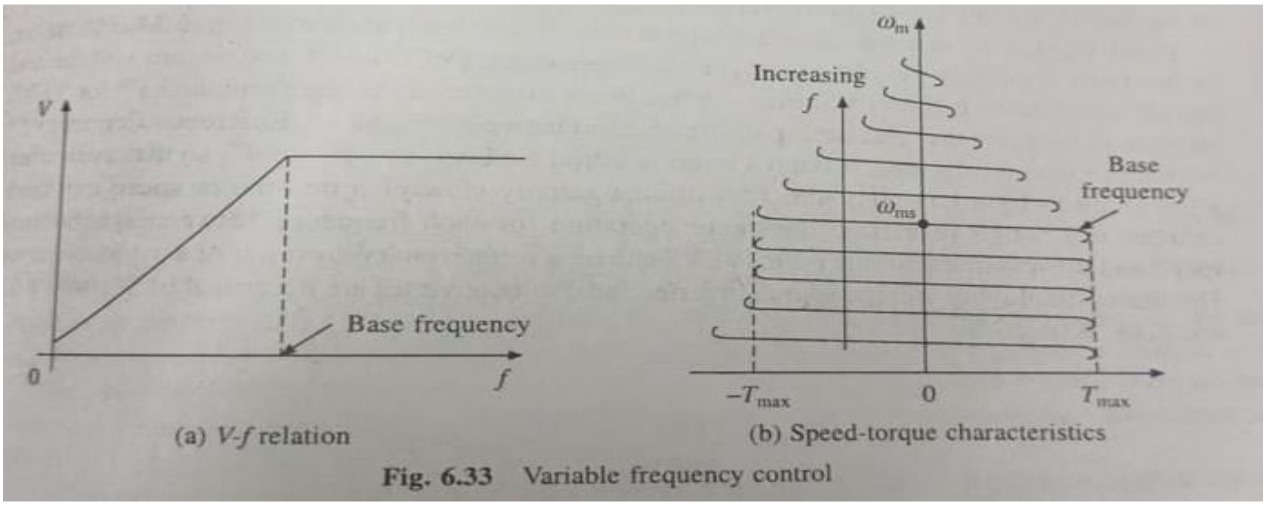
VARIABLE FREQUENCY CONTROL FROM VOLTAGE SOURCES:

Variable Frequency Control of an Induction Motor

Synchronous speed, therefore, the motor speed can be controlled by varying supply frequency. Voltage induced in stator is proportional to the product of supply frequency and air-gap flux. If stator drop is neglected, terminal can be considered proportional to the product of frequency and flux.

Any reduction in the supply frequency, without a change in the terminal voltage, causes an increase in the air-gap flux. Induction motors are designed to operate at the knee point of the magnetization characteristic to make full use of the magnetic material. Therefore, the increase in flux will saturate the motor. This will increase the magnetizing current, distort the line current and voltage, increase the core loss and the stator copper loss, and produce a high-pitch acoustic noise. While an increase in flux beyond the rated value is undesirable from the consideration of saturation effects, a decrease in flux is also avoided to retain the torque capability of the motor. Therefore, the variable frequency control below the rated frequency is generally carried out at rated air-gap flux by varying terminal voltage with frequency so as to maintain (V/f) ratio constant at the rated value.

$$T_{max} = \frac{K\left(\frac{V}{f}\right)^2}{\frac{R_S}{f}+\left[\left(\frac{R_S}{f}\right)^2+4\prod^2\left(L_S+L_r'\right)^2\right]^2}$$



(a) V-f relation

(b) Speed-torque characteristics

Fig. 6.33 Variable frequency control

A given torque is obtained with a lower current when the operation at any frequency is restricted between the synchronous speed and the maximum torque point, both for motoring and braking operations. Therefore, the motor operation for each frequency is restricted between the synchronous speed and maximum torque point as shown by solid lines.

The variable frequency control provides good running and transient performance because of the following features:

- Speed control and braking operation are available from zero speed to above base speed.
- During transients (starting, braking and speed reversal) the operation can be carried out at the maximum torque with reduced current giving good dynamic response.
- Copper losses are low, and efficiency and power factor are high as the operation is restricted between synchronous speed and maximum torque point at all frequencies.
- Drop in speed from no load to full load is small.

The most important advantage of variable frequency control is that it allows a variable speed drive with above-mentioned good running and transient performance to be obtained from a squirrel cage induction motor. The squirrel cage motor has a number of advantages over a de motor. It is cheap, rugged, reliable and longer lasting. Because of the absence of commutator and brushes, it requires practically no maintenance, it can be operated in an explosive and contaminated environment, and can be designed for higher speeds, voltage and power ratings. It also has lower inertia, volume and weight. Though the cost of a squirrel cage motor is much lower compared to that of a de motor of the same rating, the overall cost of variable frequency induction motor drives, in general are higher. But because of the advantages listed above, variable frequency induction motor drives are preferred over de motor drives for most applications. In special applications requiring maintenance free operation, such as underground and underwater installations, and also in applications involving explosive and contaminated environments, such as in mines and chemical industry, variable frequency induction motor drives are a natural choice. They have several other applications such as traction, mill run out tables, steel mills, pumps, fans, blowers, compressors, spindle drives, conveyers, machine tools, and so on.

Slip Speed Control: -

Let V and f denote the rated voltage and frequency of the machine. When the motor is operated below the base speed with constant (V/f) control, for a frequency, kf, the terminal voltage will be kV, where k is a factor such that, 0 ≤ k ≤1. Thus, as frequency is changed from 0 to f, k changes from 0 to 1 and voltage changes from 0 to V.

Substituting for voltage kV and for frequency kf and neglecting stator resistance drop,

$$I_r = \frac{V}{\sqrt{\left(\frac{R_s'}{Ks}\right)^2 + \left(X_s + X_r'\right)^2}}$$

$$\mathrm{T} = \frac{3}{\omega_{ms}}\left[\frac{\frac{V^2 R_r'}{ks}}{(R_r'/K_s)^2 + (X_s + X_r')^2}\right]$$

According to above discussion, for a gives slip speed, motor current and torque have same values at all frequencies. Thus, motor current and torque can be controlled by controlling the slip speed. Further the motor current can be restricted within a safe limit by limiting the slip speed. This behavior is utilized in closed loop speed control for limiting the current within a permissible limit.

$$I'_r = \frac{V}{\sqrt{\left(R_s + \frac{R_s'}{Ks}\right)^2 + K^2\left(X_s + X_r'\right)^2}}$$

EDDY CURRENT DRIVES: -

Drive consists of an eddy current clutch placed between an induction motor running at a fixed speed and the variable speed load. Speed is controlled by controlling de excitation to magnetic circuit of the clutch. Since motor itself runs at a fixed speed it can be fed directly from ac mains.

An eddy-current clutch is identical in principle to an induction motor in which both stator and rotor are allowed to rotate. Stator, which is coupled to driving induction motor, has de winding which produces magnetic field rotating at the speed of stator. Rotor has a metal drum coupled to the load. Eddy currents are induced in rotor drum by stator magnetic field. Interaction between the stator field and eddy currents produces a torque which causes rotor to move with stator with a slip. Slip, and therefore, the load speed, can be controlled by controlling de current through stator winding. Speed-torque characteristics are identical to an induction motor. Slip is given by

$$\mathrm{S} = \frac{\omega_{ms} - \omega_{mr}}{\omega_{ms}}$$

where and or are respectively the stator and rotor speeds. Since torque on either side of eddy current clutch is the same, ratio of output power Pm to input power P_{in} is given by

$$\frac{P_m}{P_{in}} = \frac{\omega_{mr}}{\omega_{ms}}=1\text{-s}$$

$$P_{in} - P_m = sP_{in}$$

Rotor Resistance Control: -

Speed-torque curves for rotor resistance control are given in Fig. 6.50. While maximum torque is independent of rotor resistance, speed at which the maximum torque is produced changes with rotor resistance. For the same torque, speed falls with an increase in rotor resistance. Advantage of rotor resistance control is that! motor torque capability remains unaltered even at low speeds. Only other method which has this advantage is variable frequency control. However, cost of rotor resistance control is very low compared to variable frequency control. Because of low cost and high torque capability at low speeds, rotor resistance control is employed in cranes, Ward Leonard Iinear Drives, and other intermittent load applications. Major disadvantage is low efficiency due to additional losses in resistor connected in the rotor circuit. As the losses mainly take place in the external resistor they do not-heat the motor.

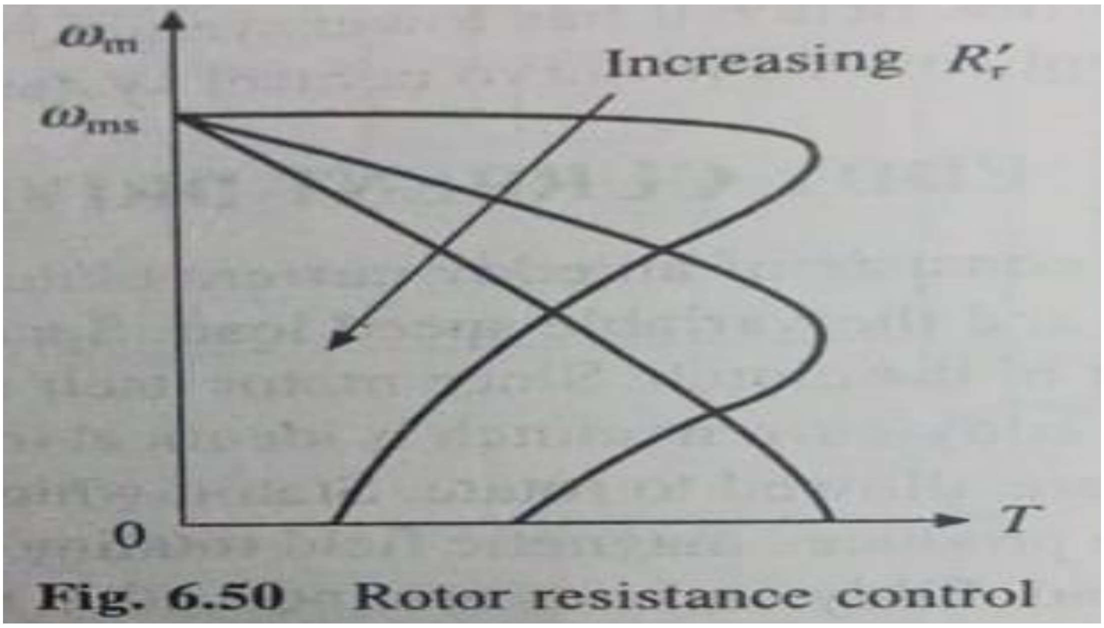
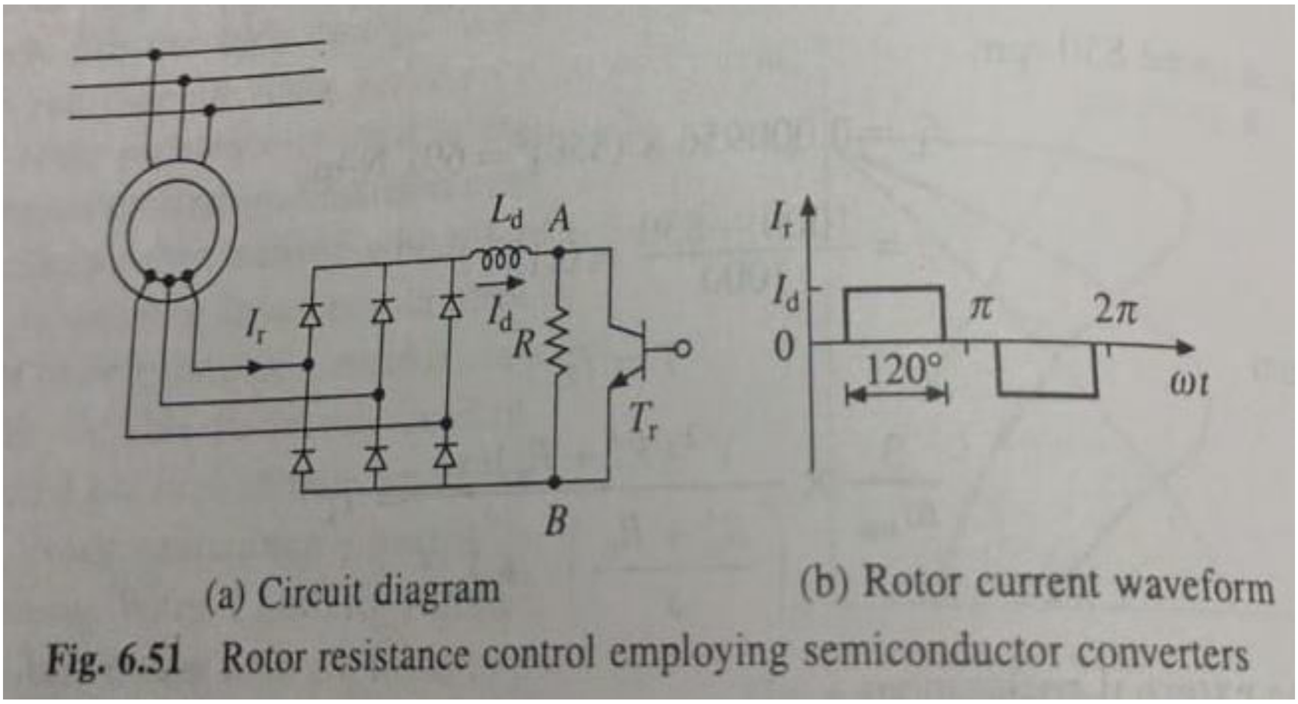


Fig. 6.50 Rotor resistance control

Rotor Resistance Control: -

Rotor resistance can also be varied steplessly using circuit of Fig. The ac output voltage of rotor is rectified by a diode bridge and fed to a parallel combination of a fixed resistance Rand a semiconductor switch realised by a transistor T_r. Effective value of resistance across terminals A and B. RAB. is varied by varying duty ratio of transistor T_r, which in turn varies rotor circuit resistance. Inductance L is added to reduce ripple and discontinuity in the de link current I Rotor current waveform will be as same as when the ripple is neglected. Thus, rms rotor current will be

$$I_r = \sqrt{\frac{2}{3}}\, I_d$$



(a) Circuit diagram (b) Rotor current waveform

Fig. 6.51 Rotor resistance control employing semiconductor converters

Resistance between terminals A and B will be zero when transistor is on and it will be R when it is off. Therefore, average value of resistance between the terminals is given by

$$R_{AB}=(1-б)R$$

Where б is the duty ratio of the transistor.

A closed-loop speed control scheme with inner current control loop is shown in Fig. 6.52. Rotor current 1, and therefore, la has a constant value at the maximum torque point, both during motoring and plugging. If the current limiter is made to saturate at this current, the drive will accelerate and decelerate at the maximum torque, giving very fast transient response. For plugging to occur, arrangement will have to be made for reversal of phase sequence.

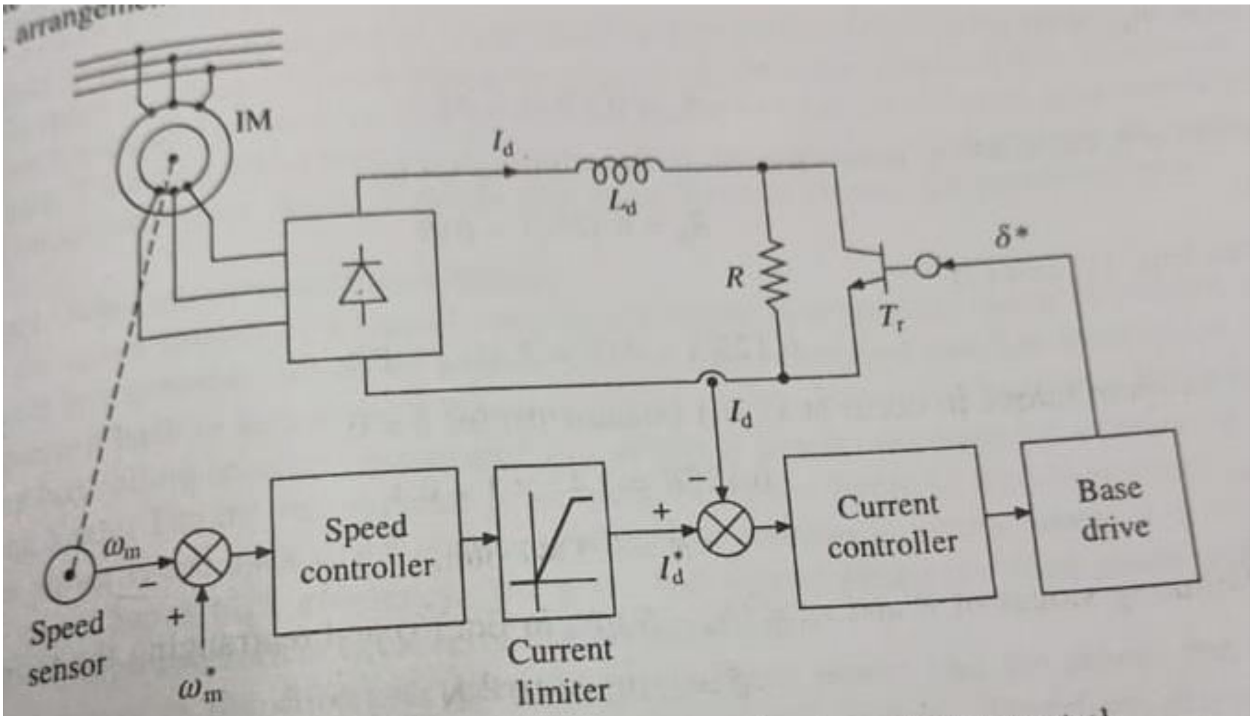


Fig. 6.52 Closed-loop speed control with static rotor resistance control

Compared to conventional rotor resistance control, static rotor resistance control has several advantages such as smooth and stepless control, fast response, less maintenance, compact size. simple closed-loop control and rotor resistance remains balanced between the three phases for all operating points.

Slip power recovery: -

An equivalent circuit of a wound-rotor induction motor with voltage V, injected into its rotor, assuming stator-to-rotor turns ratio unity. When rotor copper loss is neglected

$$P_m = P_s - P_r$$

where P, is the power absorbed by the source V_r. The magnitude and sign of P_r can be controlled by controlling the magnitude and phase of V_r When P_r, is zero, motor runs on its natural speed torque characteristic. A positive P_r, will reduce P_m and therefore, motor will run at a lower speed for the same torque. When P_r, is made equal to P_g then P_m, and consequently speed will be zero. Thus, variation of P_r, from 0 to P_g will allow speed control from synchronous to zero speed. Polarity of V_r, for this operation by a continuous line.

When P, is negative, i.e. V_r, acts as a source of power. Pm will be larger than P_g, and motor will run at a speed higher than synchronous speed. Polarity of V_r, for speed control above synchronous speed is shown by a dotted line.

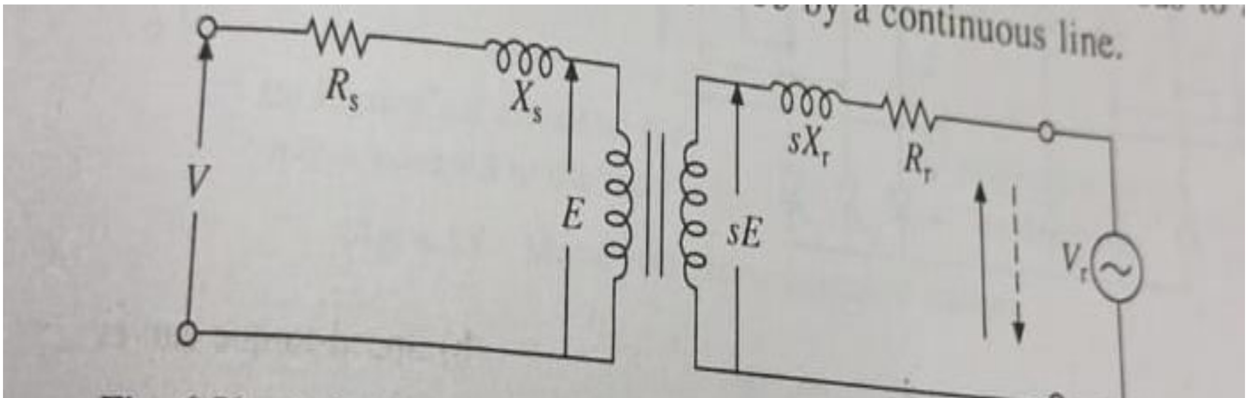


Fig. 6.53 Induction motor operation with an injected voltage in its rotor

When rotor copper loss is neglected, P, is equal to slip power, SP. Speed control below synchronous speed is obtained by controlling the slip-power, the same approach was adopted in rotor resistance control. However, instead of wasting power in external resistors, it is usefully employed here. Therefore, these methods of speed control are classified as slip power recovery schemes. Two such schemes, Static Sherbius and Static Kramer Drives, are described here.

MODULE – 3

SYNCHRONOUS MOTOR VARIABLE SPEED DRIVES

Variable Frequency Control: -

Synchronous speed is directly proportional to frequency. Motor speed can be controlled by varying the frequency. As in case of an induction motor, constant flux operation below base speed is achieved by operating the motor with a constant (V/f) ratio; which is increased at low speeds to compensate for the stator resistance drop. for all types of synchronous motors this gives operation with a constant pull-out torque. Rated voltage is reached at the base speed. For higher speeds, the machine is operated at a rated terminal voltage and variable frequency, and the pull-out torque decreases with an increase in frequency.

Modes of Variable Frequency Control: -

Variable frequency control may employ any of the two modes:

- true synchronous mode
- self-controlled mode, also known as self-synchronous mode.

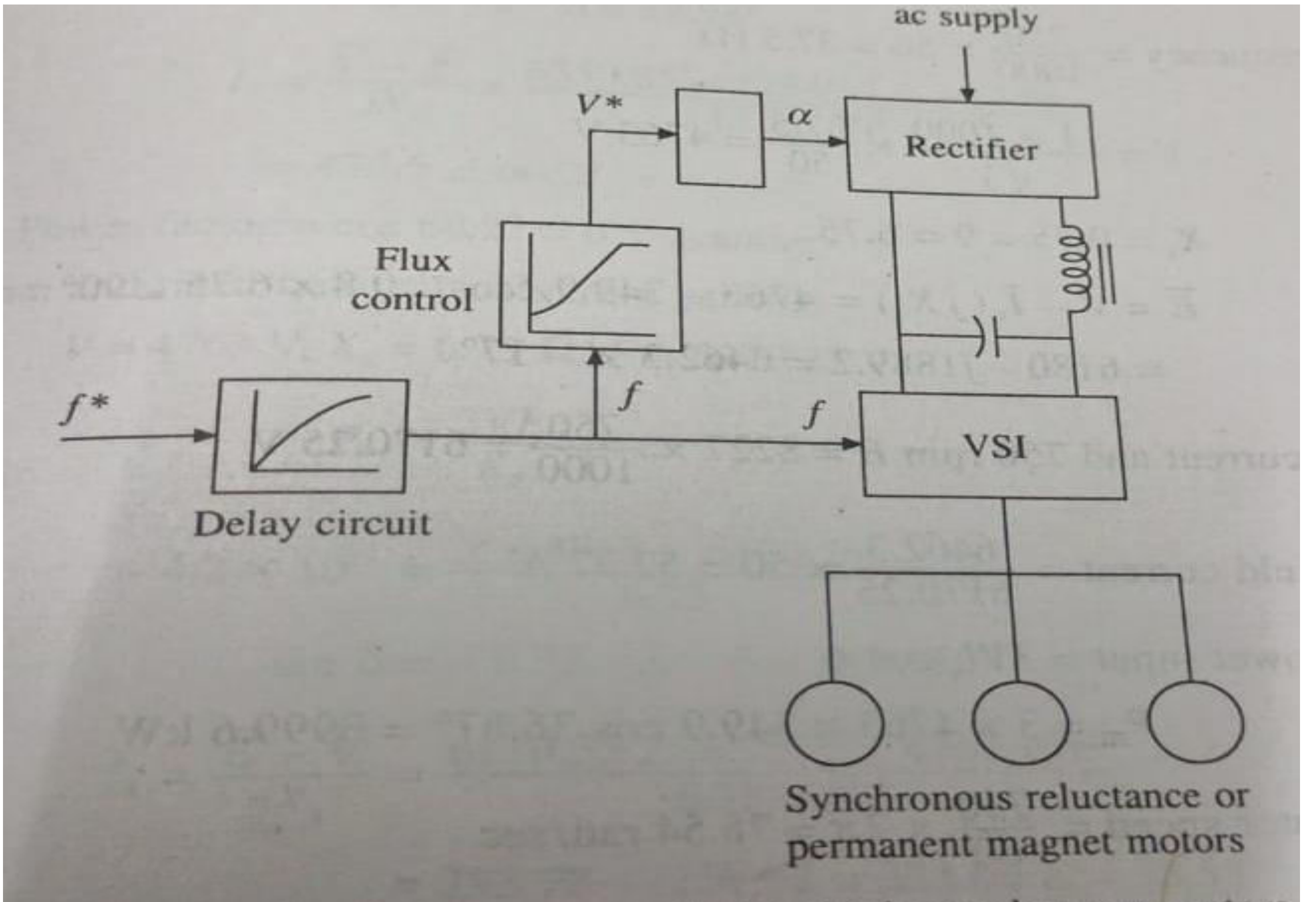
In true synchronous mode, the stator supply frequency is controlled from an independent oscillator. Frequency from its initial to the desired value is changed gradually so that the difference between synchronous speed and rotor speed is always small. This allows rotor speed to track the changes in synchronous speed. When the desired synchronous speed (or frequency) is reached the rotor pulls into step, after hunting oscillations. Variable frequency control not only allows the speed control, it can also be used for smooth starting and regenerative braking, as long as it is ensured that the changes in frequency are slow enough for rotor to track changes in synchronous speed. A motor with damper winding is used for pull-in to synchronism.

In self-control mode, the stator supply frequency is changed so that synchronous speed is the same as rotor speed. This ensures that rotor runs at synchronous speed for all operating points. Consequently, rotor cannot pull-out of step and hunting oscillations are eliminated. For such applications, the motor may not require a damper winding.

In self-control mode, the stator supply frequency is changed in proportion to the rotor speed so that the rotating field produced by the stator always moves at the same speed as the rotor (or rotor field). Since, the voltage induced in the stator phase has a frequency proportional to rotor speed, self-control can be realized by making the stator supply frequency to track the frequency of induced voltage. Alternatively, sensors can be mounted on the stator to track the rotor position. These sensors are called rotor position sensors. The frequency of signals generated by these sensors is proportional to rotor speed. Hence, the stator supply frequency can be made to track the frequency of these signals.

VARIABLE FREQUENCY CONTROL OF MULTIPLE SYNCHRONOUS MOTORS –

A drive operating in true synchronous mode. Frequency command f* is applied to a voltage source inverter through a delay circuit so that rotor speed is able to track the changes in frequency. A flux control block changes stator voltage with frequency to maintain a constant flux below rated speed and a constant terminal voltage above rated speed. This scheme is commonly used for the control of multiple synchronous reluctance or permanent magnet motors in fiber spinning, textile and paper mills where accurate speed tracking between the motors is required.



ig. 7.9 Variable frequency control of multiple synchronous motors

TRACTION DRIVES: -

ELECTRIC TRACTION SERVICES: -

Electrical traction services can be broadly classified as:

- Electric Trains
- Electric buses, trams (or treamways) and trolleys.
- Battery driven and solar powered vehicles.

Electric Trains: -

Electrical trains run on fixed rails. They are further classified as main line trains and suburban trains.

Main-line Trains: -

Intercity passenger and goods trains which come under this category have trailer coaches carrying men and material driven by locomotives carrying driving motors. Since driving motors travel with locomotive, power supply to the motors is arranged in two ways from overhead transmission line in electrical locomotive and from diesel generator set mounted on the locomotive in a diesel electric locomotive.

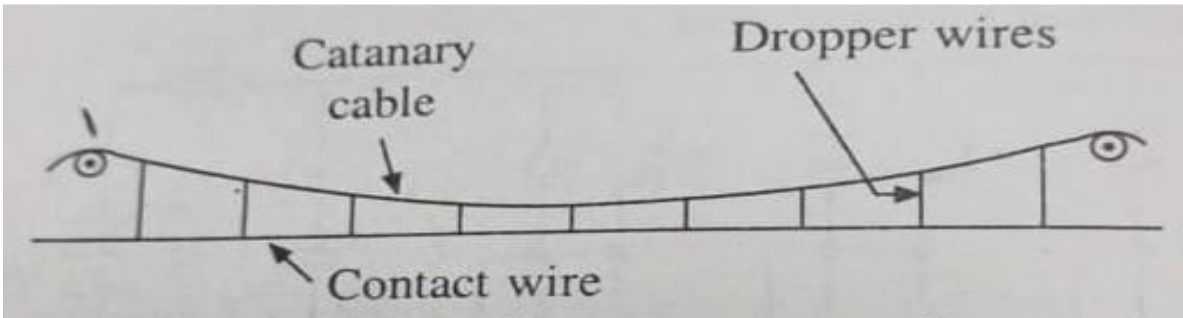


Fig. 10.1 Transmission arrangement (catanary)

Suburban Trains: -

They are employed for transporting men within a city or between cities located at small distances. The main difference being that the distance between consecutive stops (or stations) is much smaller for suburban trains than the main line. The suburban trains are also known as local trains. Because of shortage of land in cities, they are often run through underground tunnels and are called subway trains, metros or simply underground trains. Suburban trains are driven by motor (or motorized) coaches, instead of locomotives.

Electric Buses, Trams and Trolleys: -

Because of lower running expenses and complete absence of pollution, electric buses are preferred over diesel engine driven buses for city services and are quite popular in Europe and Canada. Their main disadvantage is the need for elaborate supply network, which makes their capital cost very high (though total expenses are lower) and makes them unsuitable for intercity services. The electric buses, also known as electric cars, usually consists of single motor driven coach. The supply isgenerally low voltage de overhead line running along the road.

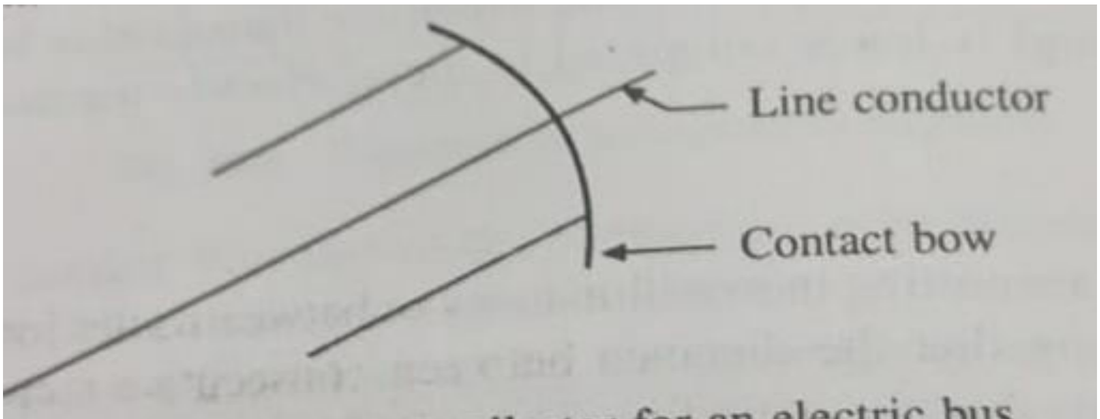


Fig. 10.3 Current collector for an electric bus

NATURE OF TRACTION AND LOAD: -

When the train runs at a constant velocity on level track, a number of frictional forces oppose its motion. The friction at bearings, guides etc. is classified as internal friction. The rolling friction between wheels and rails, and friction between V wheel-flanges and rails is termed as external friction. A third category consists of air friction which is independent of weight of train but depends upon its size and shape, and velocity and relative direction of wind. All these frictional forces together are known as train resistance. Variation of train resistance (F_r) with speed (V) is shown in Fig. load torque vs speed curve will have similar nature. The train resistance (or load torque) can also be identified in terms of common classification of friction such as windage, viscous friction, coulomb friction and stiction. Stiction has a large value and the influence of air friction, which varies as the square of speed, is quite prominent at high speeds. When deciding torque requirements of driving motors, the torque components required to provide acceleration and to overcome gravity must also be considered.

Owing to large inertia, particularly of electric trains, accelerating torque forms major proportion of the total torque in accelerating range. Because of large values of stiction and accelerating torque, the torque requirement at start and during acceleration is much higher than the torque needed for running at the highest speed. Therefore, only those drives which develop large torque from zero to the base speed are suitable for traction application.

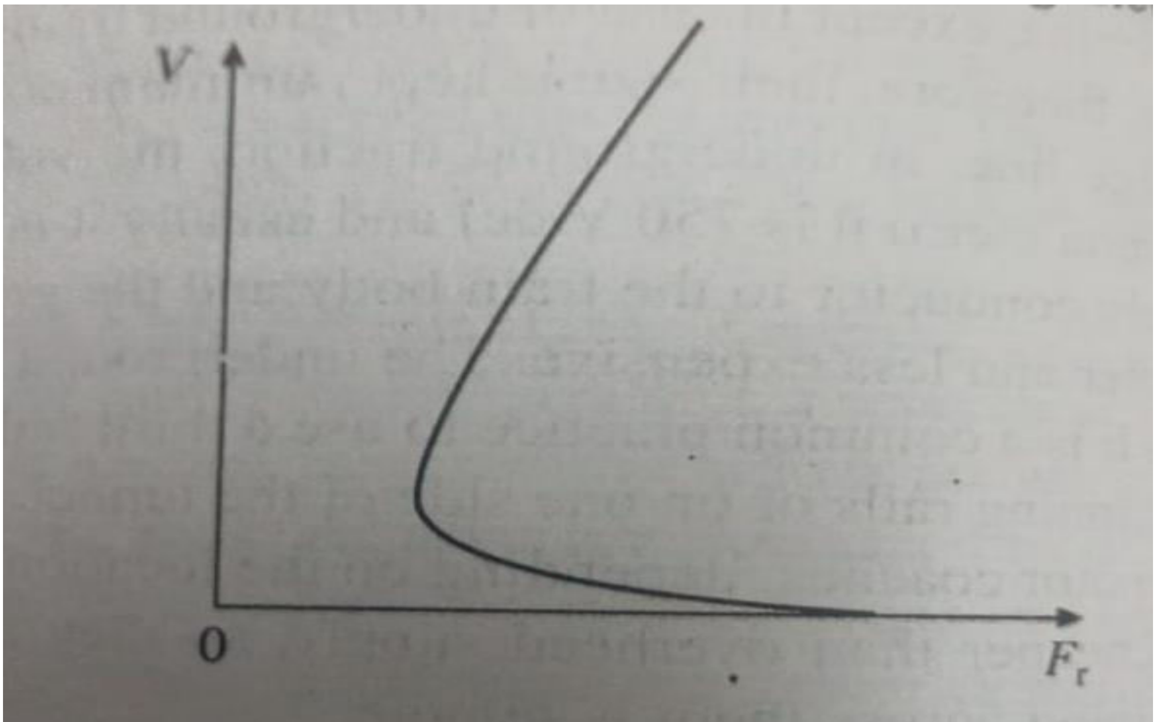


Fig. 10.4 Relation between speed V and train resistance F_r

Coefficient of Adhesion (C_A): -

In traction, the task of driving equipment consists of pushing the carriage on which it is mounted and pulling coaches and wagons behind it. Wheels coupled to the motors, either directly or through a reduction gear, are known as driving wheels. When motors run, driving wheels in their effort for rotation, exert a frictional force on the track tangentially backward at points of contact between the driving wheels and track. As a result, driving wheels experience a reaction in the forward direction, consequently wheels and the carriage move in forward direction. If at the points of contact between driving wheel and the track, force applied is large, the wheels may slip, then the wheels turn but carriage remains stationary.

A very important factor in traction drives, coefficient of adhesion (u_a), provides a quantitative measure of the tendency of wheels to slip and is defined as:

$$U_a = \frac{\text{Maximum tractive effort that can be applied without slipping of wheels}}{\text{weight on the driving axles}}$$

Weight on the driving axles is also the weight on driving wheels. It is also known as adhesive weight. Tractive effort is the total force at rims of driving wheels, and therefore, it is proportional to the motor torque. Value of the coefficient of adhesion depends on the condition of surfaces of driving wheels and track at the point of contact. The coefficient of adhesion is somewhat analogous to coefficient of friction; while latter depends on conditions at one point of contact, the former depends on conditions at several points of contact. for a given value of the coefficient of adhesion, there is a maximum value of torque that can be applied without the slipping of driving wheels; this in turn places restriction on the maximum value of acceleration.

The coefficient of adhesion depends on many factors such as

- Type and condition of surfaces at the point of contact
- Nature of motor speed-torque characteristic
- Vehicle speed.
- Motor connections.
- Type of power modulator

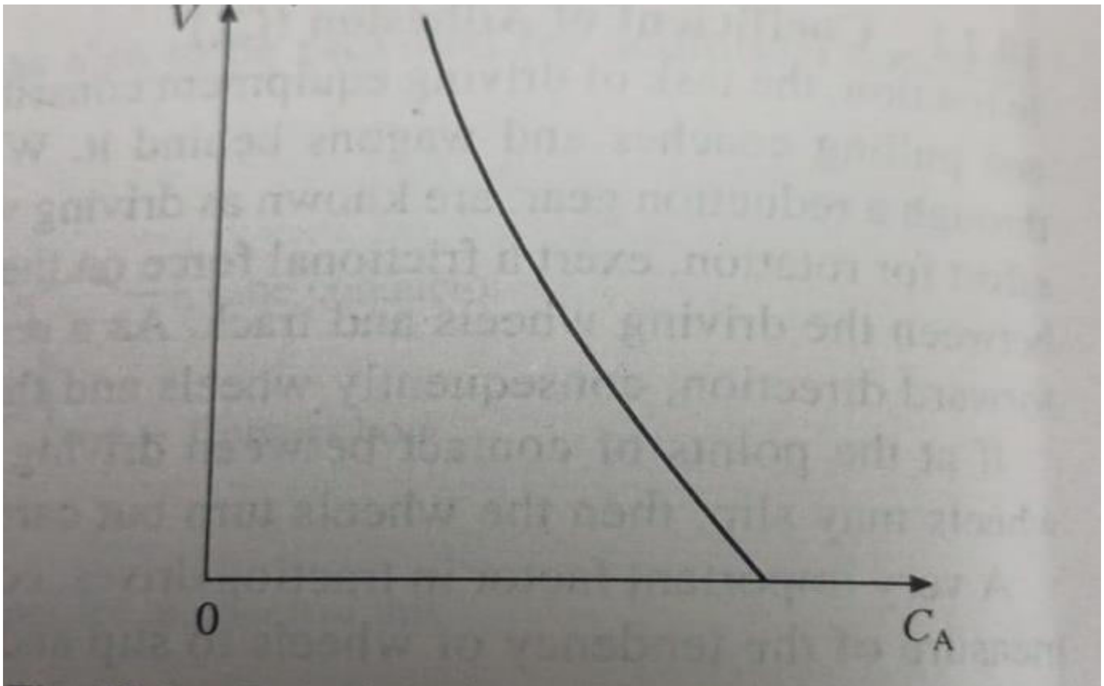


Fig. 10.5 Relation between train speed V and coefficient of adhesion C_A

Duty Cycle of Traction Drives: -

The duty cycle of electric trains is explained with the help of speed-, torque- and power-time diagram which are drawn for travel between two consecutive stations on a levelled track. The train is accelerated at the maximum permissible torque, giving constant maximum acceleration. The power increases linearly with speed. At time, the base speed and the maximum allowable power is reached. Further acceleration occurs at constant power. Torque and acceleration decrease inversely with speed. At time t_2, the drive torque equals the load torque and steady speed is reached. The acceleration time (0 to t_2) has two parts:

acceleration at a constant torque (0 to 1) and acceleration at a constant power (t_1 to 12). From 12 to 13, train runs at a constant speed and constant drive power. This duration is known as free running. At 13, supply to the motor is turned off, reducing the drive torque to zero. Now the train coasts due to its own inertia. At a suitable time 14, brake is applied to stop the train at the next station. The area beneath the speed- time, curve gives the distance covered. Thus, larger the area beneath the speed-time curve, greater will be the distance covered in a given time or lesser will be the time taken to cover a given distance.

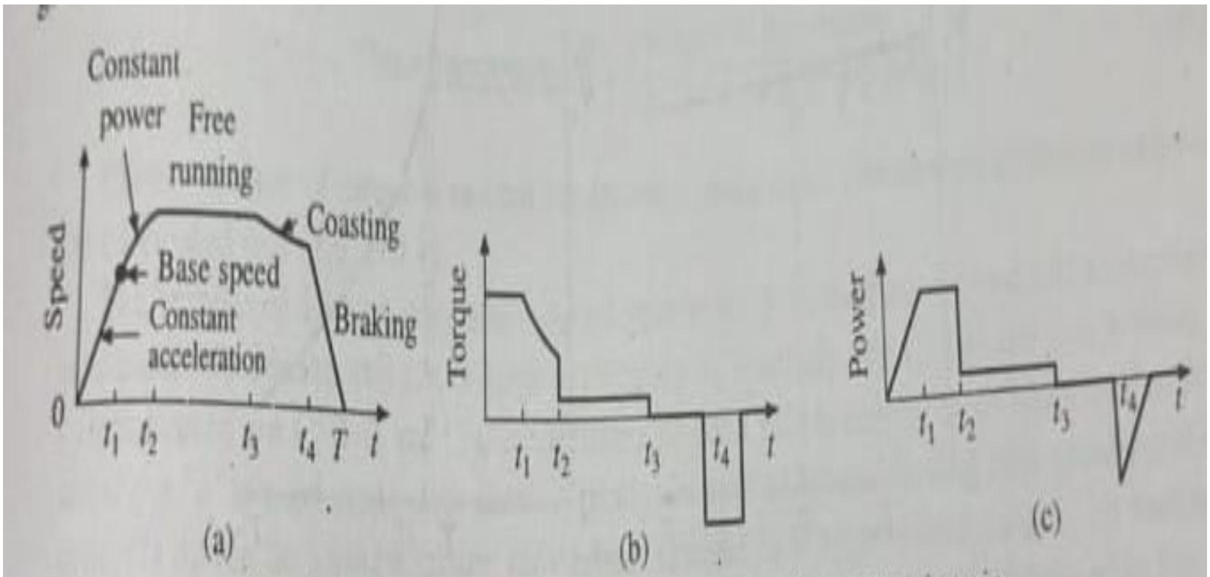


Fig. 10.6 Speed-, torque- and power-time curves for an electric train

CALCULATIONS OF TRACTION DRIVE RATING AND ENERGY CONSUMPTION: -

The speed-time curve of Fig is reproduced for simplification in calculations. is approximated by a trapezoidal curve having constant values for acceleration and deceleration. As the area beneath curve represents distance covered, the area of trapezoidal curve is chosen equal to the area of actual curve. Let D be the distance in km, T the time taken by train to move from A to D in sec, Vm the free running speed of trapezoidal curve in km/hr (kmph) and

$\propto$, β = acceleration/deceleration in km/hr/sec (kmphps).

Then V_{av} = Average speed of the train, Kmph

$$V_{av}=\frac{distance\ between\ the\ stops,km}{Acutual\ line\ of\ run,hours}=\frac{3600\ D}{T}$$

V_d = Scheduled speed of the train, Kmph

$$=\frac{distance\ between\ the\ stops,km}{Acutual\ line\ of\ run,hours+Time\ of\ stop,hours}$$

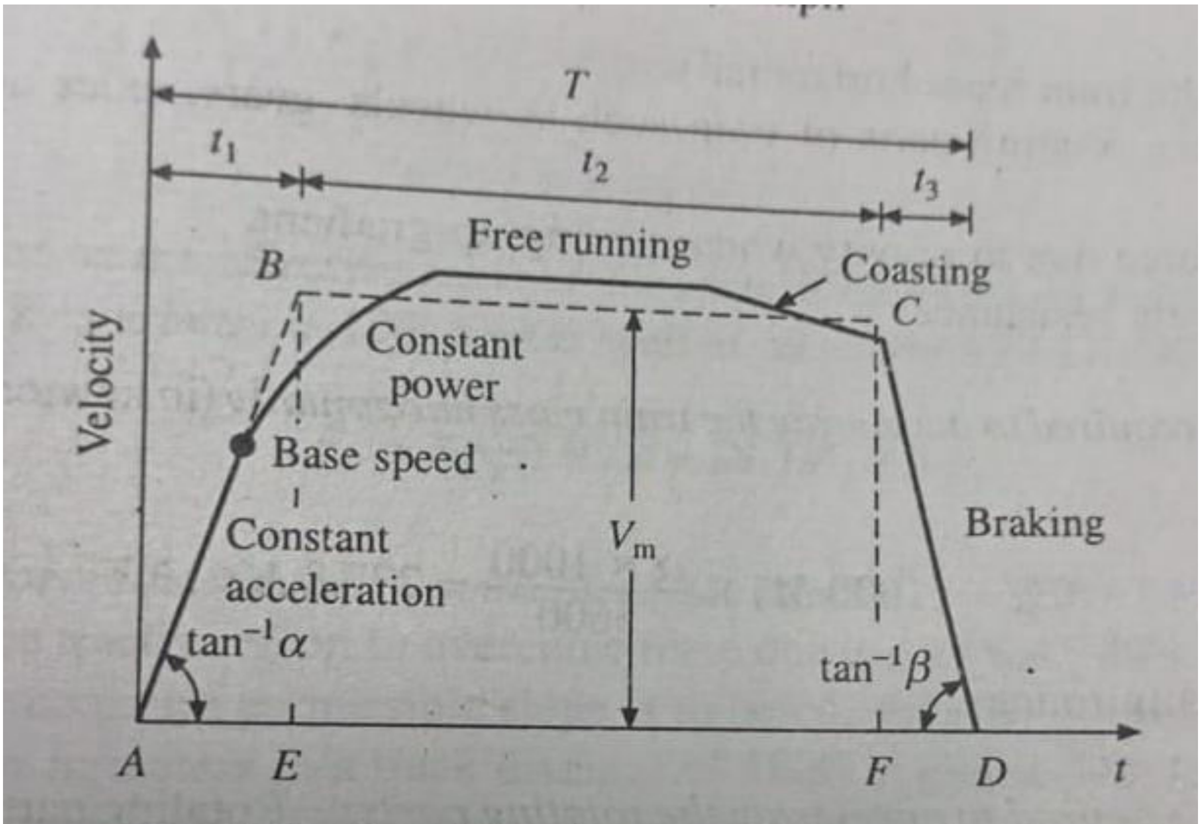


Fig. 10.9 Speed-time curve and its approximation

From the trapezoidal curve,

$t_1 = \frac{v_m}{\propto}$, sec and $t_3 = \frac{v_m}{\beta}$,sec

D=Area of trapezoidal curve = $\frac{V_m}{3600}\left(\frac{1}{2}t_1 + t_2 + \frac{1}{2}t_3\right)$

$$= \frac{V_m}{7200}\left[2T - (t_1 + t_3)\right]$$

$$= \frac{V_m}{7200}\left[2T - \left(\frac{V_m}{\propto} + \frac{V_m}{\beta}\right)\right]$$

Tractive Effort and Drive Ratings: -

Tractive effort is the force developed at the rims of driving wheels for moving train. In main line trains it is caused by locomotive and in suburban by motor coaches. Draw bar pull is the force exerted by locomotive through draw bar for moving train. Thus, draw bar pull is less than tractive effort by the force required to move the locomotive. The tractive effort has to perform following functions:

- Accelerate the train mass horizontally
- Accelerate the rotating parts of train such as wheels, gears, axles and the rotor of the motor.
- Overcome force due to gravity when moving up-gradient.
- Overcome train resistance.

(a) Tractive effort required to accelerate the train mass horizontally (in newtons) at an acceleration of ∝ kmphps is

$$F_{al} = (1000\,M) * \frac{\propto * \; 1000}{3600} = 277.8\,M \propto, N$$

where M is the mass in tonnes.

(b) Tractive effort required to accelerate the rotating parts:

Rotating parts consists of wheels axles, gears and rotor of the motor. The inertia of gears and axles can be ignored in comparison to that of wheels. Moment of inertia of wheels

$J=2N_x J_w$

where J_w is the moment of inertia of one wheel, kg-m² and N, the number of axles on the train.

Let N= number of driving motors

n_1 = teeth on motor gear wheel

n2= teeth on axle gear wheel

a=$\frac{n_1}{n_2} = \frac{wheel\ speed}{motor\ speed}$

R= radius of the wheel, m

J_m= moment of inertia of one motor, kg-m2

Then moment of inertia of motors referred to wheels

$J_2 = N\,Jm/\,a^2$

Acceleration (in meters/second²) = ∝x 1000 /3600, mpsps

Acceleration in rad/sec² =∝ x 1000/3600 R, rpsps

Tractive effort for driving rotating parts

$$F_a = (J_1 + J_2)\frac{\propto * \; 1000}{3600} = \left(2\,N_x J_w + \frac{NJ_m}{\propto^2}\right) * \frac{\propto}{3.6\,R^2}$$

Total tractive effort required for accelerating the train on a level track (in newtons).

$$F_1 = F_{al} + Fa2 = 277.8M\alpha + (2\,N_x J_w + \frac{NJ_m}{\propto^2})\,\frac{\propto}{3.6\,R^2}$$

$$= 277.8\,M_e\propto,\,N$$

where M. is defined as the effective mass of the train. It accounts for rotating parts in addition to the train mass. It is around 8-15% higher than can also be written as

(iii) **Tractive effort required to overcome force due to gravity:**

When moving up-gradient, the drive has to produce tractive effort to overcome force due to gravity. When deciding drive rating. gradient with the maximum permissible slope is to be considered. In railway practice, gradient is expressed as rise in meters in a track distance of 1000 m and is denoted by G. Now, tractive effort required to overcome force due to gravity will be

$$F_g = 1000M * \frac{G}{1000} * g, N$$

$$= 9.81MG, N$$

$$= MG, kg$$

(iv) **Tractive effort required to overcome train resistance:**

Variation of train resistance with speed is shown in Fig. 4. It is not possible to accurately represent it analytically. Among several empirical relations proposed, the simplest is based on the understanding the train resistance is due to various kinds of frictions. Therefore, it will have three basic components: one due to coulomb friction which is independent of speed, and third because of air friction which is proportional to speed squared.

Thus, $F_1 = A + BV + CV^2$, N

Where V is the speed of the train and A,B,C are constants. The above equation suggests that it is difficult to estimate the train resistance. Since it is quite small compared to F_a can be used and is often assumed as r newtons per tonne weight of the train. Thus,

$$F_r = rM, N$$

$$= \frac{rM}{9.81}, kg$$

For calculating drive rating, r is chosen to be 20 N/tonne.

(v) Total tractive effort required to move the train:

$$F_t = F_a + F_g + F_r$$

$$= 28.3\ M_e \propto \pm MG + \frac{rM}{9.81}, kg$$

$$= 277.8\ M_e \propto \pm MG + Mr_1, N$$

The positive sign is used for the train movement up-gradient and negative for down the gradient,

(vi) Motor torque rating:

Total torque at the rims of driving wheels = Total tractive effort (in newtons) x R

$$= RF_t, N\text{-}m$$

Where R is the radius of the driving wheel in meter.

Total torque referred to the motor shaft

$$T_1 = \frac{aRF_1}{\eta_1}, \text{ N-m}$$

When η_1 is the efficiency of transmission.

Torque per motor

$$T_m = \frac{aRF_1}{\eta_1}, \text{ N-m}$$

Where N is the numbers of motors.

When deciding motor rating, maximum gradient allowed while laying down the track should be considered.

MODULE-IV

Drives for Specific Applications

Steel Mill:

The major function of rolling of steel mill is to reduce the cross section of the metal s while increasing the length proportionally. Steel mill usually produce blooms, slabs, rails, sheets, strips, beams, bar and angles.

Technologically steel mill is divided into four categories:

- Continuous cold rolling mills
- Reversing cold rolling mills
- Continuous hot rolling mills
- Reversing hot rolling mills

In reversing mill there is only one stand carrying the rolls that press the metal and metal is passed through this stand alternately forward and backward several times in order to reduce it to desired size. Each motion or travel is known as pass. A continuous mill consists of several stands, each one of them carrying pressing rolls. The metal passes through all the stands in only one direction and gets rolled.

Drives used in steel mills:

Dc motors is usually used in both reversible and continuous mills. Motor for reversing mills must have high starting torque, wide speed range, precise speed control, be able to withstand overload and pull out torque. Acceleration from zero to base speed and then to top speed and subsequent reversal from top speed backward to top speed forward must be achieved in few second. The moment of inertia of armature must be as small as possible and motors are enclosed and force ventilated. Ward-Leonard method for speed control is used. However, the speed control is replaced by thyristorised converter.

Paper Mills:

Pulp making and paper making are the two main important job for paper mills. The drive required each of them is quite different.

Pulp Making:

Pulp making requires grinding machines which almost run at constant speed that is acquired by synchronous motor. Motors run at speed of 200-300 rpm. However, pulp by mechanical means, the motor runs at speed of 2000-3000 rpm for large grinder. Pulp is made by cutting the logs into several pieces and treated with alkalies and grass, rags etc. During the chemical treatment the material is continually beaten by the beater. Beater requires speed less than 200 rpm so, slip ring induction motor is used. The end product of the beater is passed to chipping and refining .so, synchronous motor is used.

Paper making:

The machine that makes the paper from pulp has to perform several jobs from five sections.

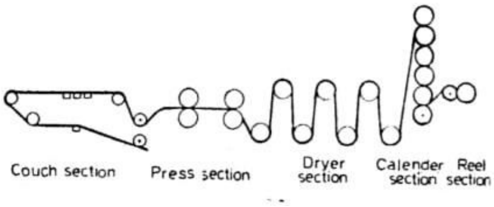
i)Couch section(Wire section)

ii) Press section

iii) Dryer section

iv) Calender section

v) Reel sectioN



Drive Requirement:

- Speed should be adjustable over a range of as large as 10:1
- In the wet end of paper machine, the speed section should be independently adjustable.
- In the last two sections, speed control circuit must be good enough for tension control.
- Control system employed should be flexible in nature.

Textile Mills:

From the raw material to finishing of cloths the mill has to perform several processes such as cotton to slivers, spinning, weaving and finishing.

Cotton to slivers: The process by which the seeds are separated from cotton is called ginning. The cottons are converted into slivers and then processed by drawing machine. The slivers are then made lap form.

Spinning: In this process, the slivers are made yarn is made of sufficient strength. This yarn is wound on bobbins by winding machine.

Weaving: The yarn is made in uniform layers. Weaving consists of two sets of threads, one which extends throughout the length of the fabric and other whose thread go across. This process is done in a loom.

Finishing: This consists a number of processes such as bleaching, dying, printing, calendaring, stamping and packing. The impurities like oil and grease are removed and the fabric is made white by bleaching.