ATME College of Engineering

Industrial Drives and Applications-BEE702

Module-1
Electrical Drives
Dynamics of Electrical Drives
Control of Electrical Drives

Presented By,
KAVYASHREE S
Assistant Professor
Department of EEE
ATMECE, Mysuru

Syllabus

Electrical Drives:

Electrical Drives, Advantages of Electrical Drives. Parts of Electrical Drives, Choice of Electrical Drives, Status of DC and ac Drives.

Dynamics of Electrical Drives:

Fundamental Torque Equations, Speed Torque Conventions and Multi-quadrant Operation. Equivalent Values of Drive Parameters, Components of Load Torques, Nature and Classification of Load Torques, Calculation of Time and Energy Loss in Transient Operations, Steady State Stability, Load Equalization.

Control Electrical Drives:

Modes of Operation, Speed Control and Drive Classifications, Closed loop Control of Drives.

Introduction to Drives

What is Drive

Systems employed for motion control are called drives.

It employs any of the prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors for supplying mechanical energy for motion control.

What is an Electric Drive?

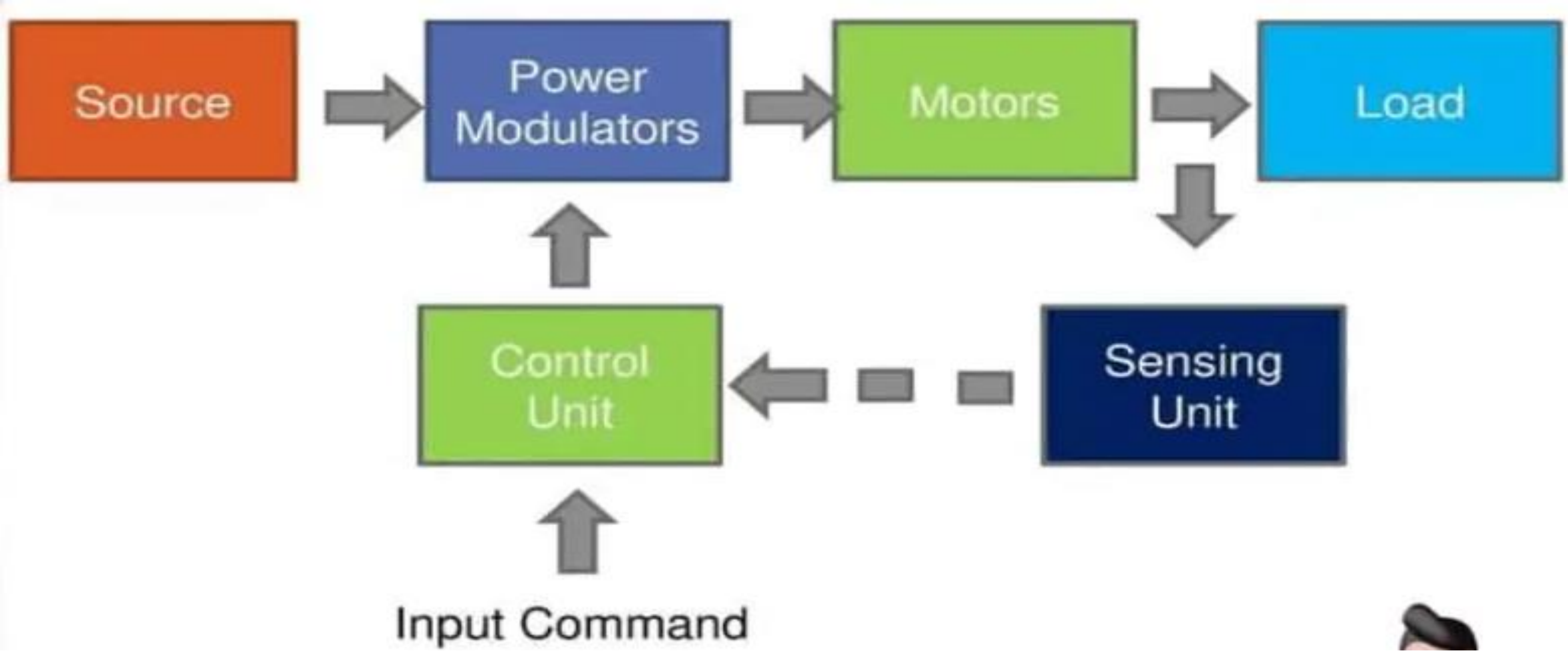
Drives employing electric motors are known as electrical drives.

Electrical Drives

➢ Motion control is required in large number of industrial and domestic applications

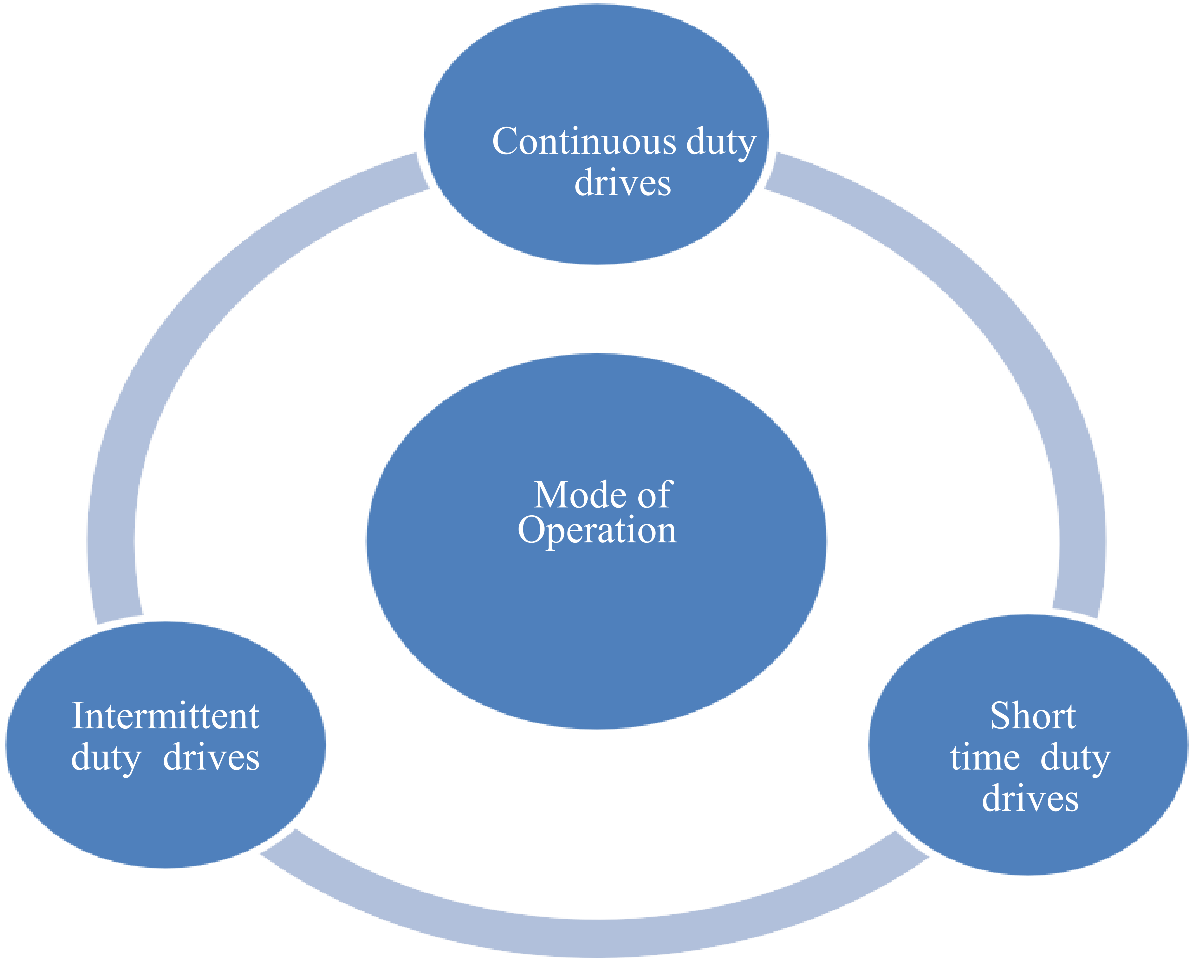
- Systems employed for motion control are called DRIVES, and may employ any of prime movers such as diesel or petrol engines, gas or steam turbines, steam engines, hydraulic motors and electric motors, for supplying mechanical energy for motion control

Block diagram of electric drive

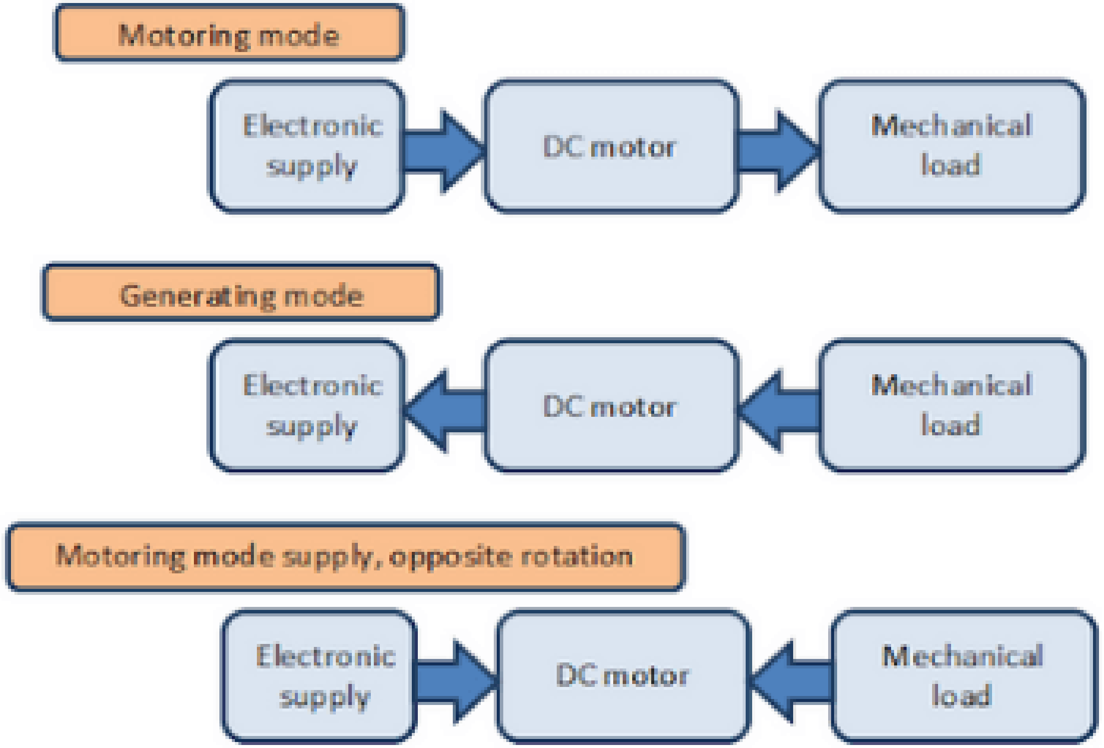


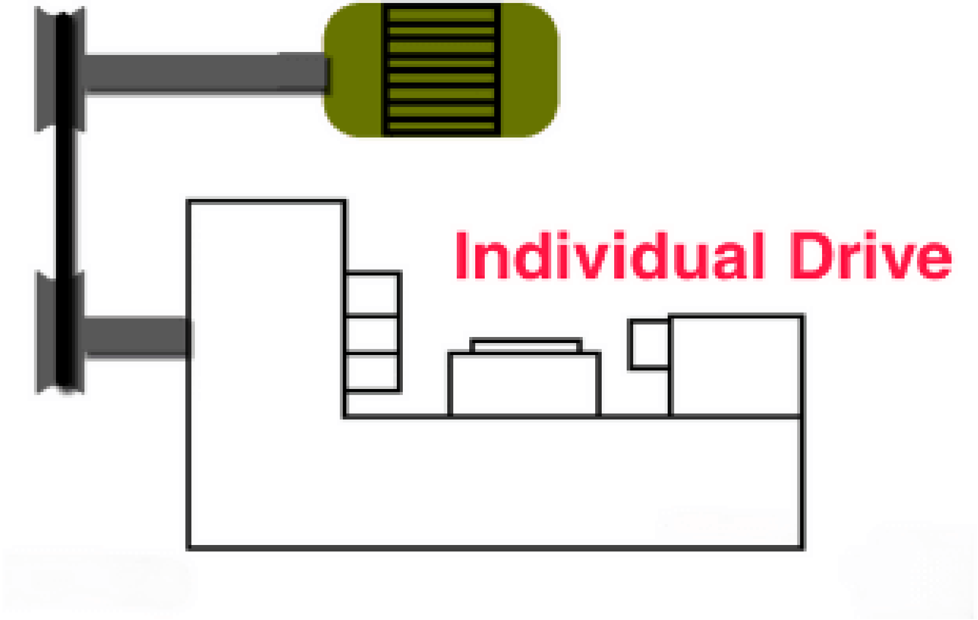
Classification of Electric Drives

- According to Mode of Operation
- According to Means of Control
- According to Number of machines
- According to Dynamics and Transients
- According to Methods of Speed Control



Types of Electrical Drives





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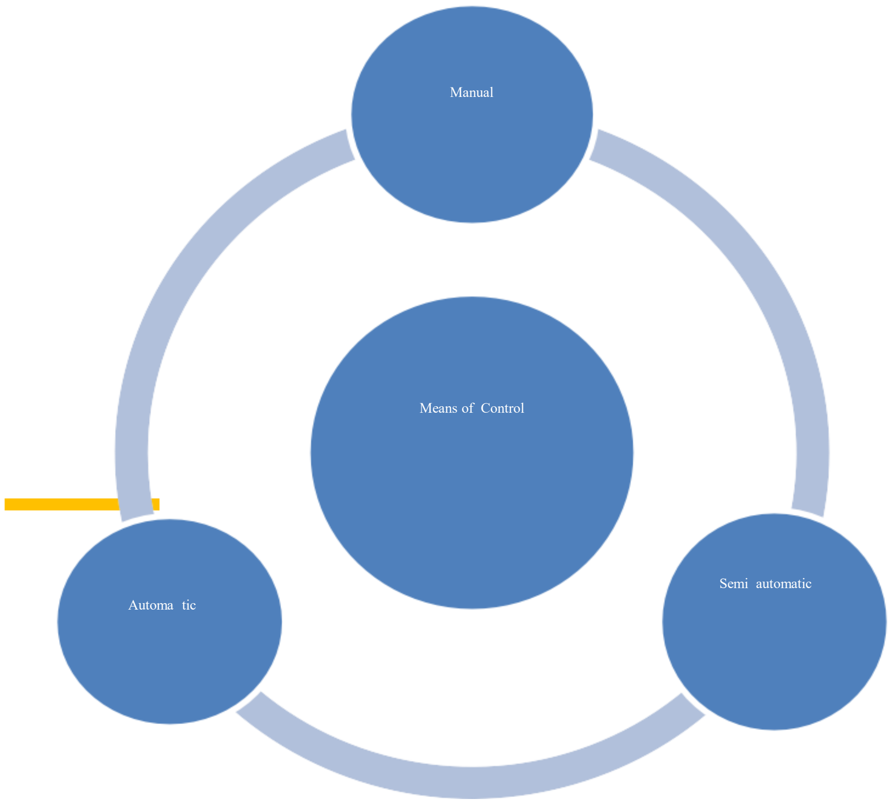
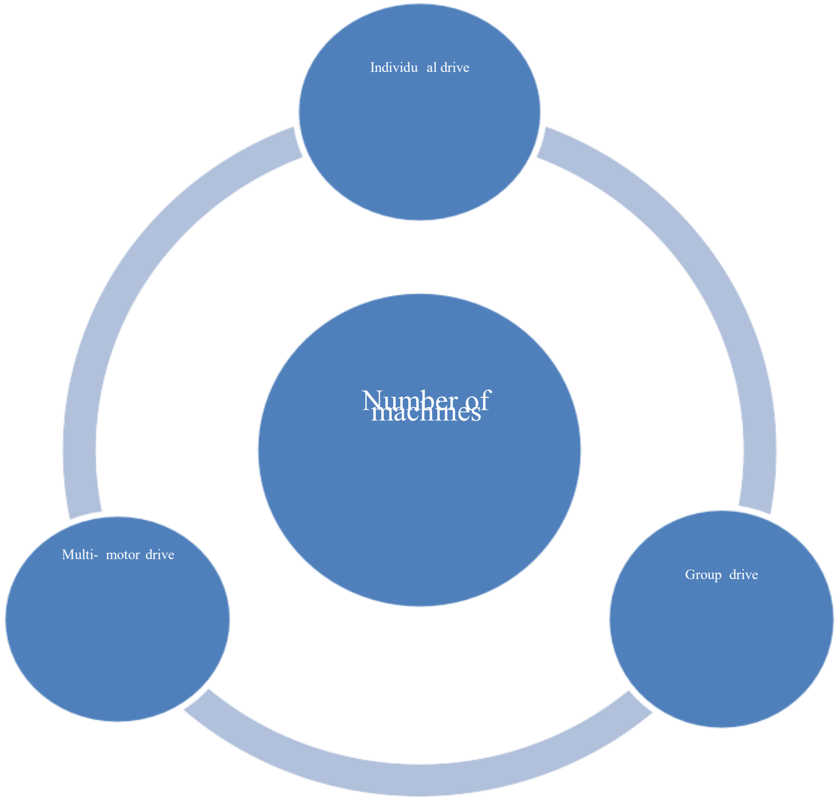
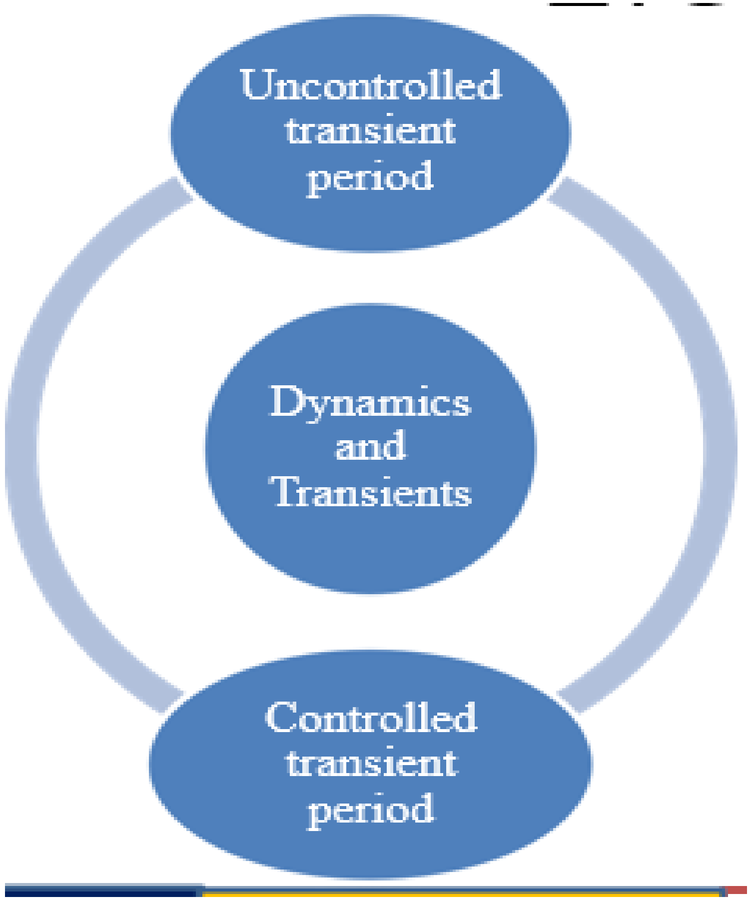
Classification of Electric Drives





Classification of Electric Drives

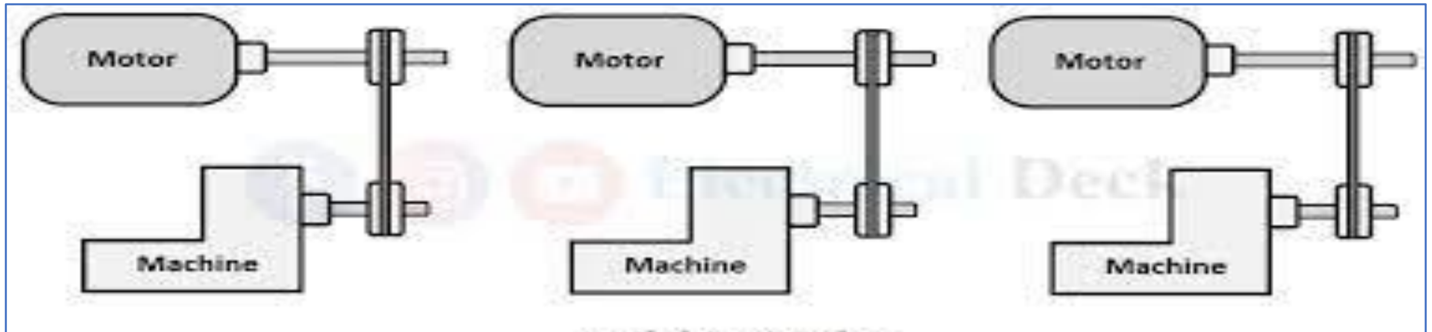


Methods of Speed Control

- Reversible and non-reversible uncontrolled constant speed.
- Reversible and non-reversible step speed control.
- Variable position control.
- Reversible and non-reversible smooth speed control.

Individual Electric Drive

In this drive each individual machine is driven by a separate motor. This motor also imparts motion to various parts of the machine.

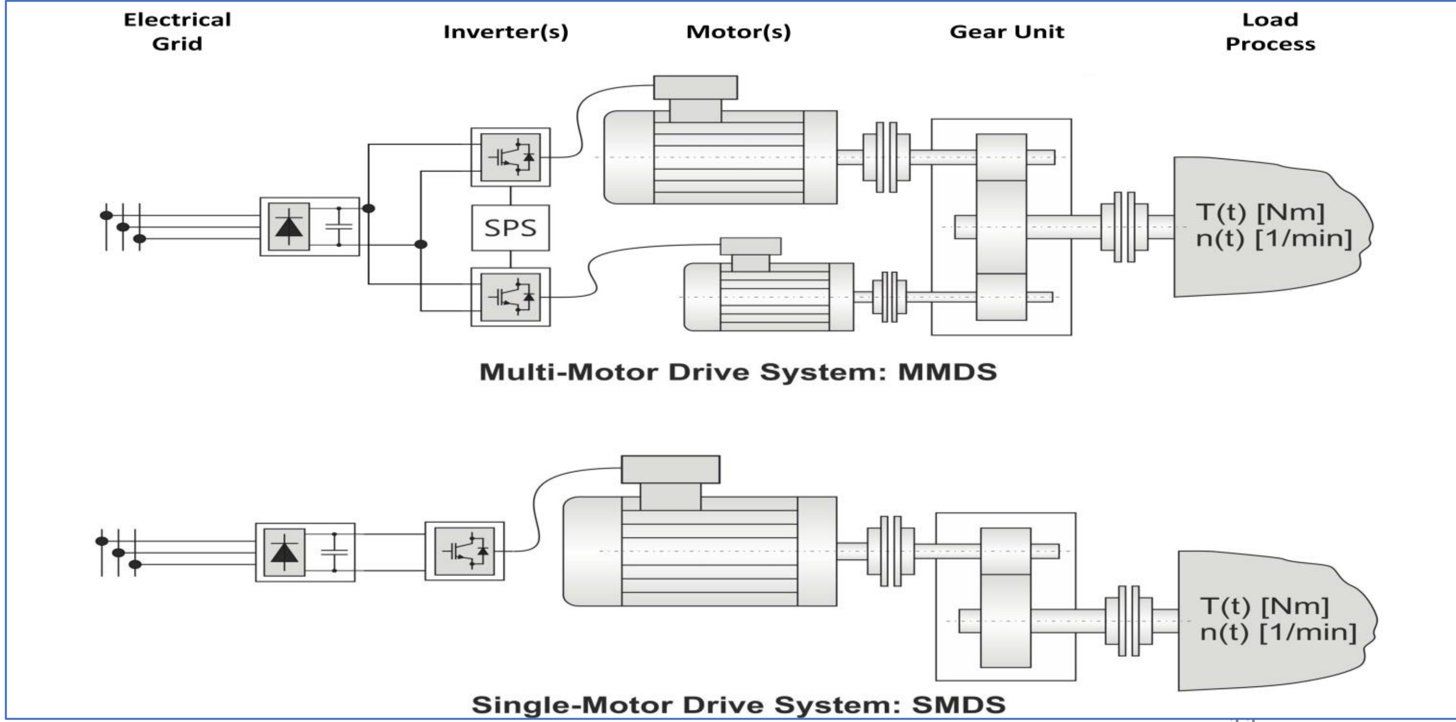


Individual Drive

Multi Motor Electric Drive

In this drive system, there are several drives, each of which serves to actuate one of the working parts of the drive mechanisms.

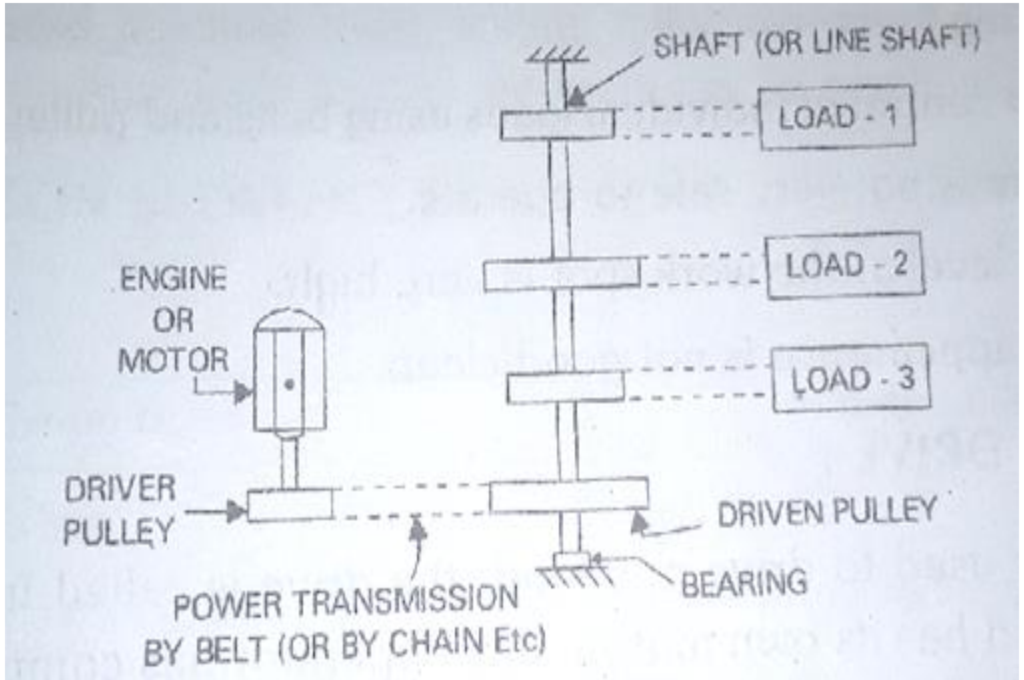
E.g.: Complicated metal cutting machine tools, Paper making industries, Rolling machines etc.



Electrical Drives

Group Electric Drive

This drive consists of a single motor, which drives one or more line shafts supported on bearings. The line shaft may be fitted with either pulleys and belts or gears, by means of which a group of machines or mechanisms may be operated. It is also some times called as SHAFT DRIVES.

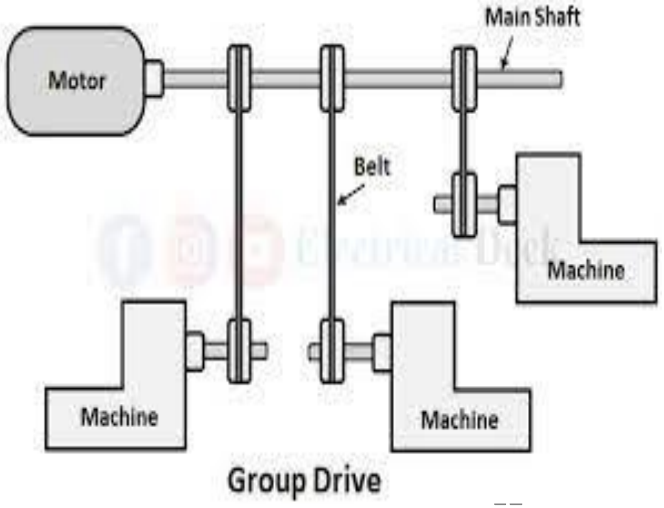


Advantages

A single large motor can be used instead of number of small motors

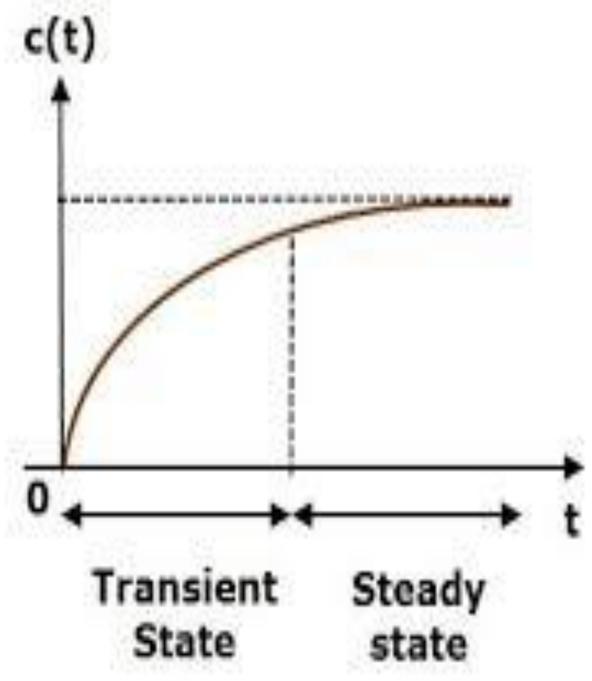
Disadvantages

There is no flexibility. If the single motor used develops fault, the whole process will be Stopped



Choice (or) Selection of Electrical Drives

- Steady State Operating conditions requirements.
- Transient operation requirements.
- Requirements related to the source.
- Capital and running cost, maintenance needs life.
- Space and weight restriction if any.
- Environment and location.
- Reliability.



Advantages of Electrical Drive

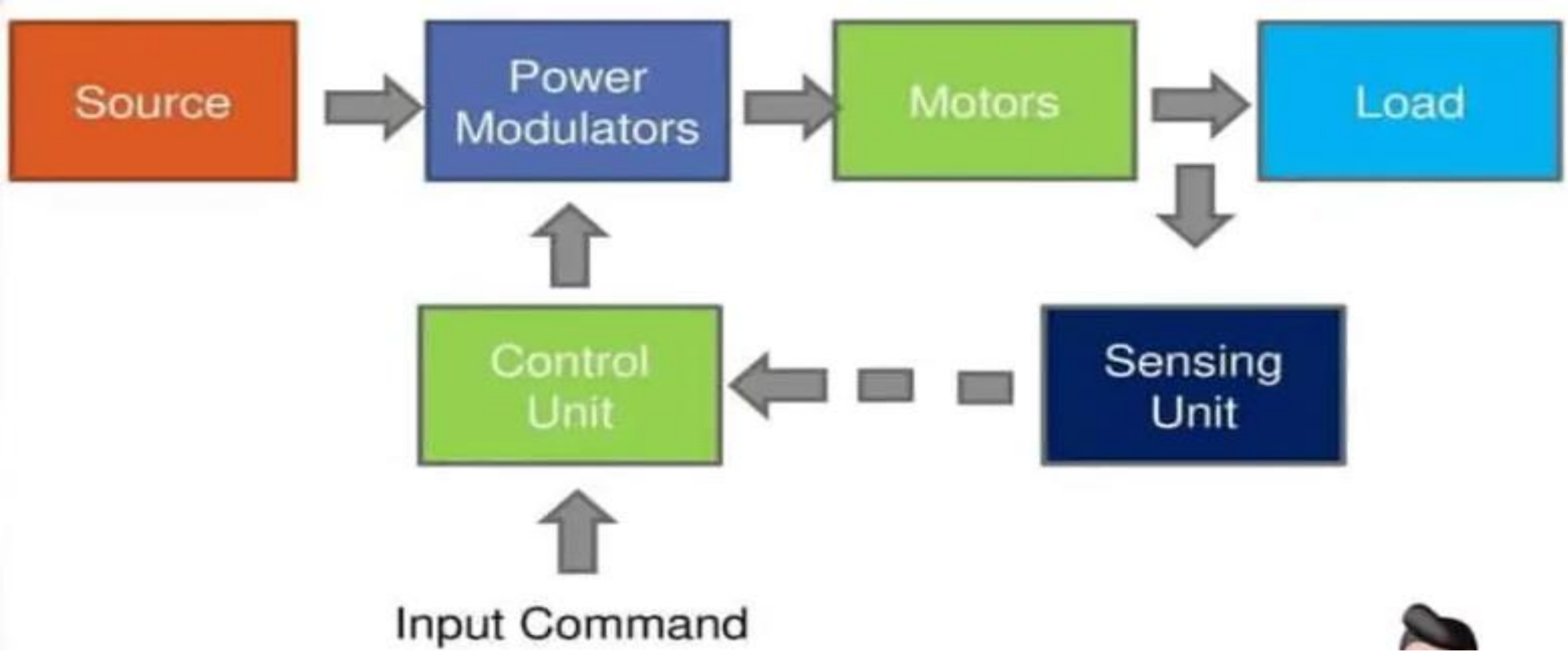
- Flexible Control Characteristics & Steady state & dynamic of drives can be shaped to Load requirements .
- Automatic fault detection systems & automatically control the drive operations in a desired sequence.
- Wide range of torque, speed and power.
- Adaptable to almost any operating conditions.
- Four quadrants of speed-torque plane.
- Started instantly and can immediately be fully loaded.
- Control operations, Braking is simple and easy to operate.

Advantages of Electrical Drives

Electrical drives are readily used these days for controlling purpose but this is not the only the **advantage of Electrical drives**. There are several other advantages which are listed below:

1. These drives are available in wide range torque, speed and power.
2. The control characteristics of these drives are flexible. According to load requirements these can be shaped to steady state and dynamic characteristics. As well as speed control, electric braking, gearing, starting many things can be accomplished.
3. The are adaptable to any type of operating conditions, no matter how much vigorous or rough it is.
4. They can operate in all the four quadrants of speed torque plane, which is not applicable for other prime movers.
5. They do not pollute the environment.
6. They do not need refueling or preheating, they can be started instantly and can be loaded immediately.
7. They are powered by electrical energy which is atmosphere friendly and cheap source of power.

Block diagram of an electric drive



Parts of Electric Drive

1. Electrical Sources

- Very low power drives are generally fed from single phase sources.
- Rest of the drives is powered from a 3 phase source.
- Low and medium power motors are fed from a 400V supply.
- For higher ratings, motors may be rated at 3.3KV, 6.6KV and 11 KV.
- Some drives are powered from battery.

2. Power modulator

It is most commonly used as a converter

Power Modulators Functions:

- Modulates flow of power from the source to the motor 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 with in permissible limits.
- It converts electrical energy of the source in the form of suitable to the motor.
- Selects the mode of operation of the motor (i.e.) Motoring and Braking.

Types of Power Modulators

In the electric drive system, the power modulators can be any one of the following

- Controlled rectifiers (ac to dc converters)
- Inverters (dc to ac converters)
- AC voltage controllers (AC to AC converters)
- DC choppers (DC to DC converters)
- Cyclo converters (Frequency conversion)

Power Modulators - are the devices which alter the nature or frequency as well as changes the intensity of power to control electrical drives. Roughly, power modulators can be classified into three types,

1. Converters,
2. Variable impedance circuits,
3. Switching circuits.

As the name suggests, converters are used to convert currents from one type to other type. Depending on the type of function, converters can be divided into 5 types -

i. *AC to DC converters*

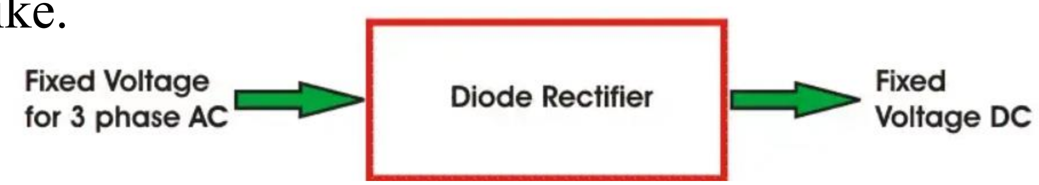
ii. *AC regulators*

iii. *Choppers or DC - DC converters*

iv. *Inverters*

v. *Cycloconverters*

AC to DC converters are used to obtain fixed DC supply from the AC supply of fixed voltage. The very basic diagram of AC to DC converters is like.



Power Modulators cntd.

ii.AC Regulators are used to obtain the regulated AC voltage, mainly auto transformers or tap changer transformers are used in this regulators.

iii. Choppers or DC-DC converters are used to get a variable DC voltage. Power transistors, IGBT's, GPO's, power MOSFET's are mainly used for this purpose.

Power Modulators cntd.

iv. Inverters are used to get AC from DC, the operation is just opposite to that of AC to DC converters. PWM semiconductors are used to invert the current.

v. Cycloconverters are used to convert the fixed frequency and fixed voltage AC into variable frequency and variable voltage AC. Thyristors are used in these converters to control the firing signals.

Power Modulators cntd.

2. Variable Impedance circuits:

- These are used to control speed by varying the resistance or impedance of the circuit. But these controlling methods are used in low cost DC and AC drives.
- There can be two or more steps which can be controlled manually or automatically with the help of contactors.
- To limit the starting current inductors are used in AC motors.

3. Switching circuits:

- These are used in motors and electrical drives for running the motor smoothly and they also protects the machine during faults.
- These circuits are used for changing the quadrant of operations during the running condition of a motor.
- These circuits are implemented to operate the motor and drives according to predetermined sequence, to provide interlocking, to disconnect the motor from the main circuit during any abnormal condition or faults.

General Electric Drive System

Electrical Machines

DC Machines

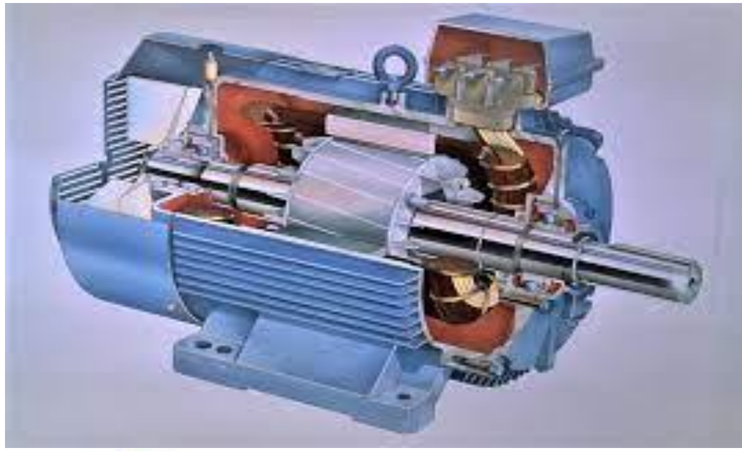
Shunt, series, compound, separately excited DC motors and switched reluctance machines.

AC Machines

Induction, wound rotor, synchronous, PM (Permanent Magnet) synchronous and synchronous reluctance machines

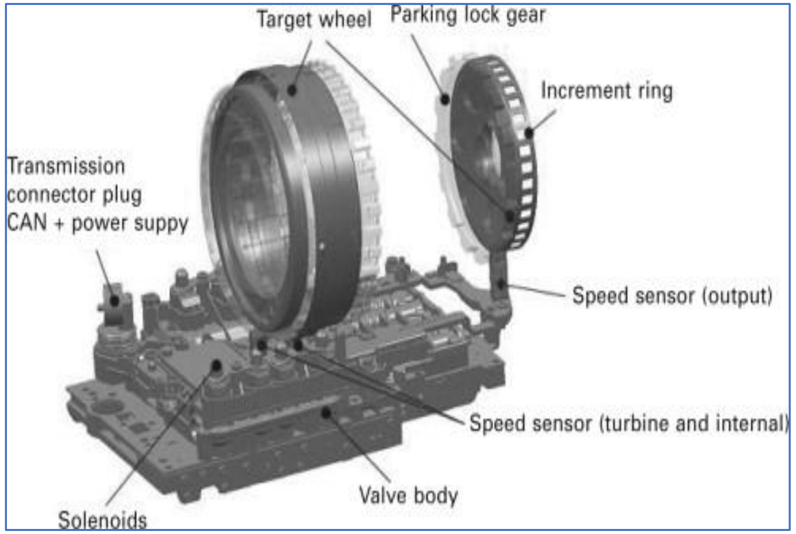
Special Machines

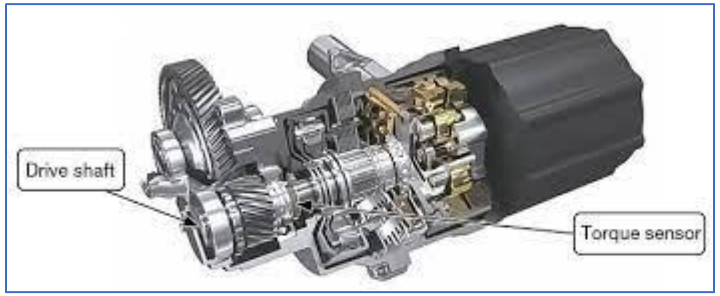
Brush less DC motors, stepper motors, switched reluctance motors are used.



Sensing Unit

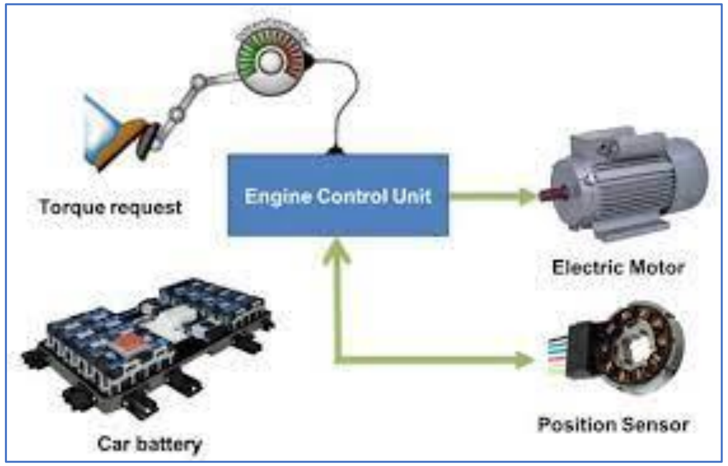
- Speed Sensing (From Motor)
- Torque Sensing
- Position Sensing
- Current sensing and Voltage Sensing from Lines or from motor terminals





From Load

- ➢ Torque sensing
- ➢ Temperature Sensing



Control unit: Choice of control unit depends upon the type of power modulator that is used. These are of many types, like when semiconductor converters are used, then the control unit consists of firing circuits, which employ linear devices and which employ linear and digital integrated circuits and transistors, and a microprocessor when sophisticated control is required.

Classification of Electrical Drives

Comparison between DC and AC drives

DC Drive	AC Drive
The power circuit and control circuit is simple and inexpensive	The power circuit and control circuit are complex
It requires frequent maintenance	Less Maintenance
The commutator makes the motor bulky, costly and heavy	These problems are not there in these motors and are inexpensive, particularly squirrel cage induction motors

DC Drive	AC Drive
Fast response and wide speed range of control, can be achieved smoothly by conventional and solid state control	In solid state control the speed range is wide and conventional method is stepped and limited
Speed and design ratings are limited due to commutations	Speed and design ratings have upper limits

Note:

- A power circuit supplies the main power (e.g. 3 phase AC) whereas the control circuit is lower in current & voltage which may consist of PLCs & small relays,low voltage DC power supply,etc.
- Solid state power controllers (SSPC) are semiconductor devices that control power (voltage and/or current) supplied to a load. They identify overload conditions and prevent short circuits.

Applications

- Paper mills
- Cement Mills
- Textile mills
- Sugar Mills
- Steel Mills
- Electric Traction
- Petrochemical Industries
- Electrical Vehicles

Paper mills

Cement Mills

Textile mills

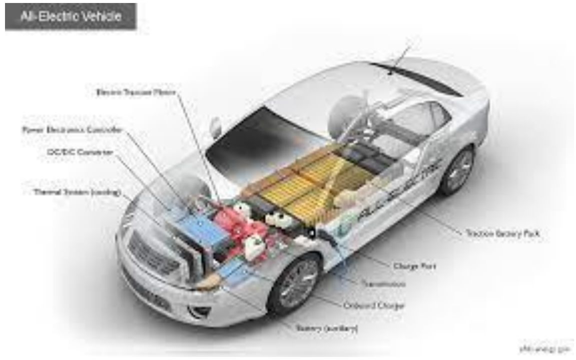
Sugar Mills

Steel Mills

Electric Traction

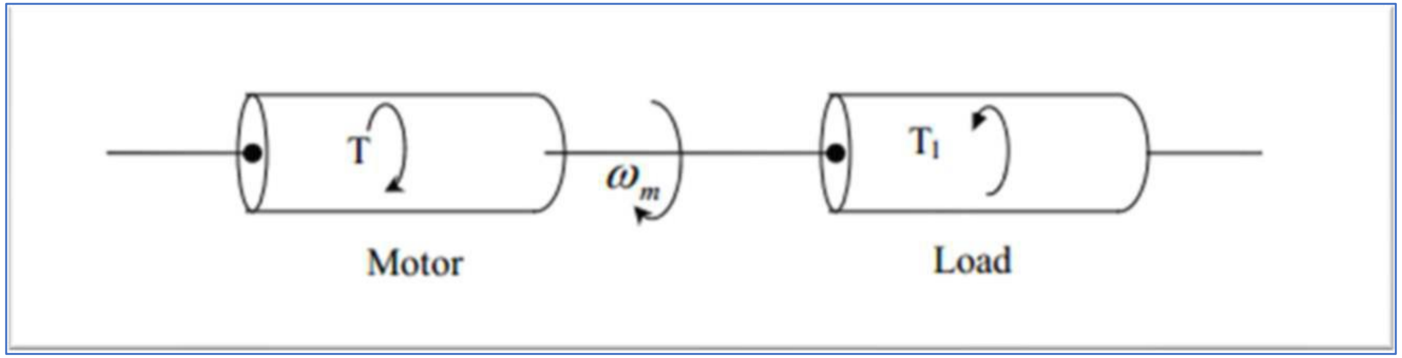
Petrochemical Industries

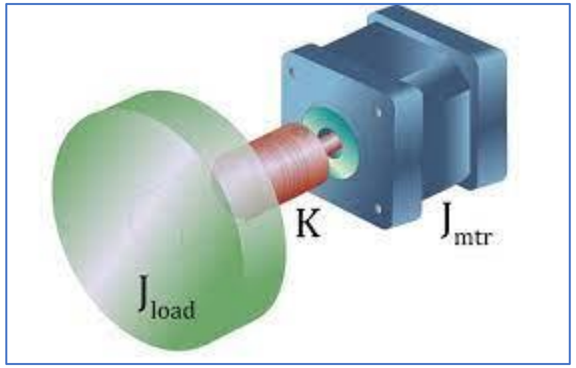
Electrical Vehicles



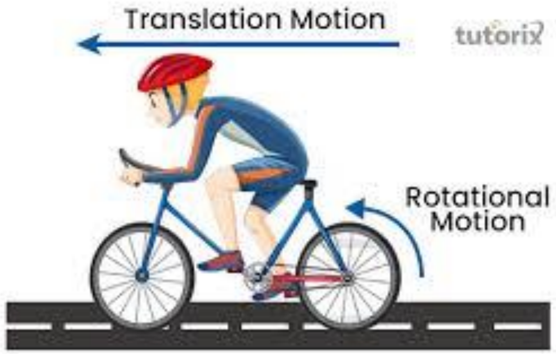
Fundamentals of Torque Equations

- A motor generally drives a load (Machines) through some transmission system.
- While motor always rotates, the load may rotate or undergo a translational motion.
- Load speed may be different from that of motor, and if the load has many parts, their speed may be different and while some parts rotate others may go through a translational motion.
- Equivalent rotational system of motor and load is shown in the figure.

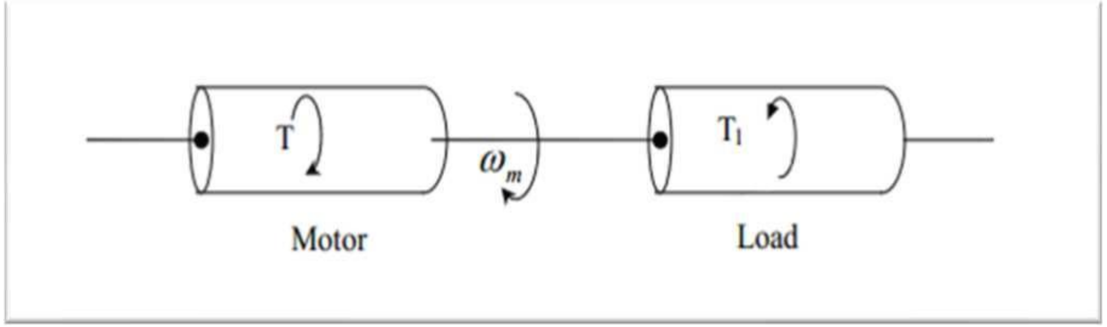




J = Moment of inertia of motor load system referred to the motor shaft kg−m^2
ω_m= Instantaneous angular velocity of motor shaft, rad/sec.
T = Instantaneous value of developed motor torque, N-m
T_l=Instantaneous value of load torque, referred to the motor shaft N-m



Fundamentals of Torque Equations



Load torque includes friction and windage torque of motor. Motor-load system shown in figure can be described by the following fundamental torque equation

$$T - T_l = \frac{d}{dt}(J\omega_m) = J\frac{d\omega_m}{dt} + \omega_m\frac{dJ}{dt} \text{------------} (1)$$

Equation (1) is applicable to variable inertia drives such as mine winders, reel drives, Industrial robots.

For drives with constant inertia $\frac{dJ}{dt} = 0$

For drives with constant inertia $\frac{dJ}{dt} = 0$

$$T = T_l + J\frac{d\omega_m}{dt} \qquad (1)$$

Equation (2) shows that torque developed by motor is counter balanced by load torque T_l and a dynamic torque $\left(J\frac{d\omega_m}{dt}\right)$. Torque component $\left(J\frac{d\omega_m}{dt}\right)$ is called dynamic torque because it is present only during the transient operations.

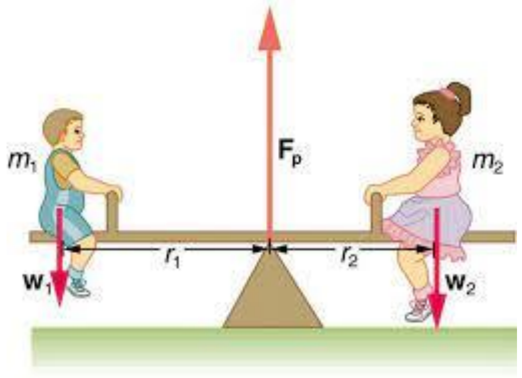
Classification of Load Torques

1. Active load torques
2. Passive load torques

1. Load torques which has the potential to drive the motor under equilibrium conditions are called active load torques. Such load torques usually retain their sign when the drive rotation is changed (reversed)

Examples

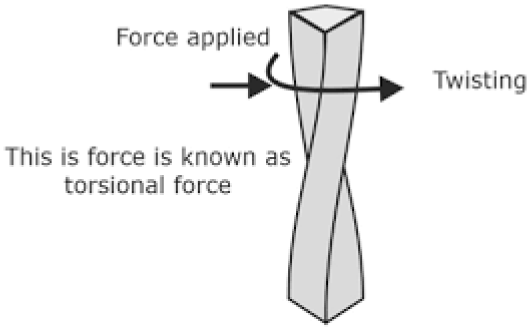
- Torque due to force of gravity
- Torque due to tension
- Torque due to compression and torsion etc



2. Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques

Examples

- Torque due to friction, cutting etc.



Components of Load Torques

The load torque T_l can be further divided in to following components

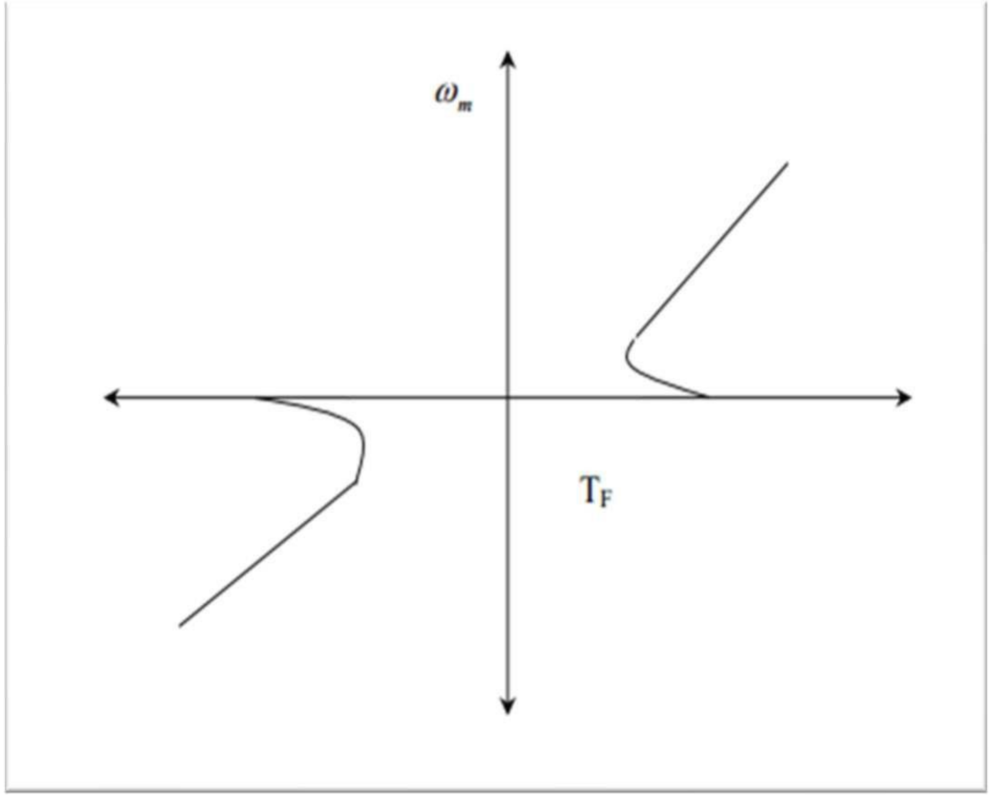
1. **Friction Torque (T_F)**
2. **Windage Torque (T_W)**
3. **Torque required to do useful mechanical work.**

1. Friction will be present at the motor shaft and also in various parts of the load. T_F is the equivalent value of various friction torques referred to the motor shaft.
2. When motor runs, wind generates a torque opposing the motion. This is known as windage torque.
3. Nature of this torque(Torque required to do useful mechanical work) depends upon particular application. It may be constant and independent of speed. It may be some function of speed, it may be time invariant or time variant, its nature may also change with the load's mode of operation.

Friction Torque

- Value of friction torque with speed is shown in figure below

➢ Its value at stand still is much higher than its value slightly above zero speed. Friction at zero speed is called stiction or static friction.



➢ In order to start the drive the motor should at least exceed stiction.

Characteristics of Different types of Loads

- One of the essential requirements in the selection of a particular type of motor for driving a machine is the matching of speed-torque characteristics of the given drive unit and that of the motor.
- Therefore the knowledge of how the load torque varies with speed of the driven machine is necessary.
- Different types of loads exhibit different speed torque characteristics.
- However, most of the industrial loads can be classified into the following four categories:

i. *Constant torque type load*

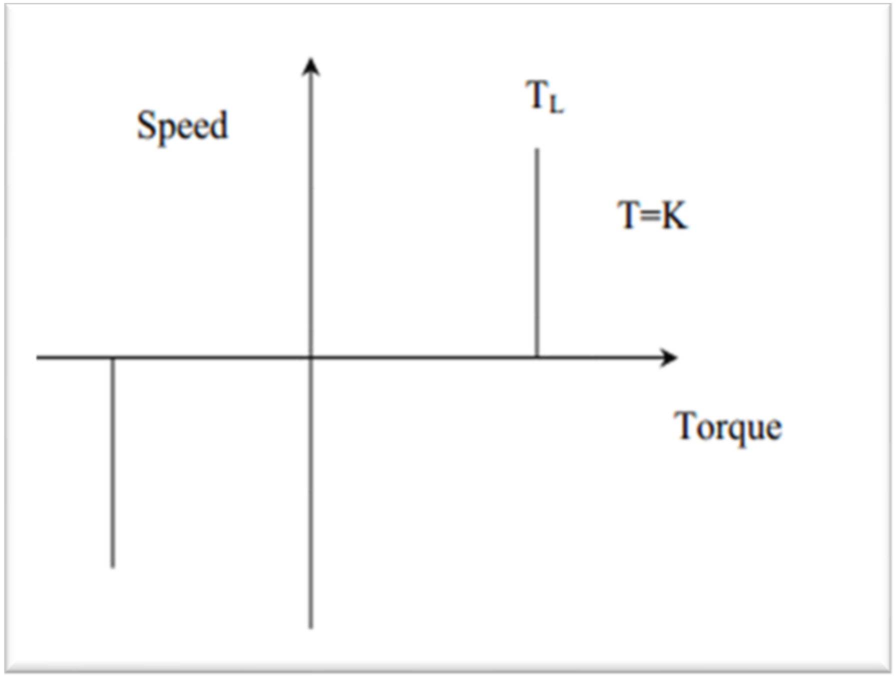
ii. *Torque proportional to speed (Generator Type load)*

iii. *Torque proportional to square of the speed (Fan type load)*

iv. *Torque inversely proportional to speed (Constant power type load)*

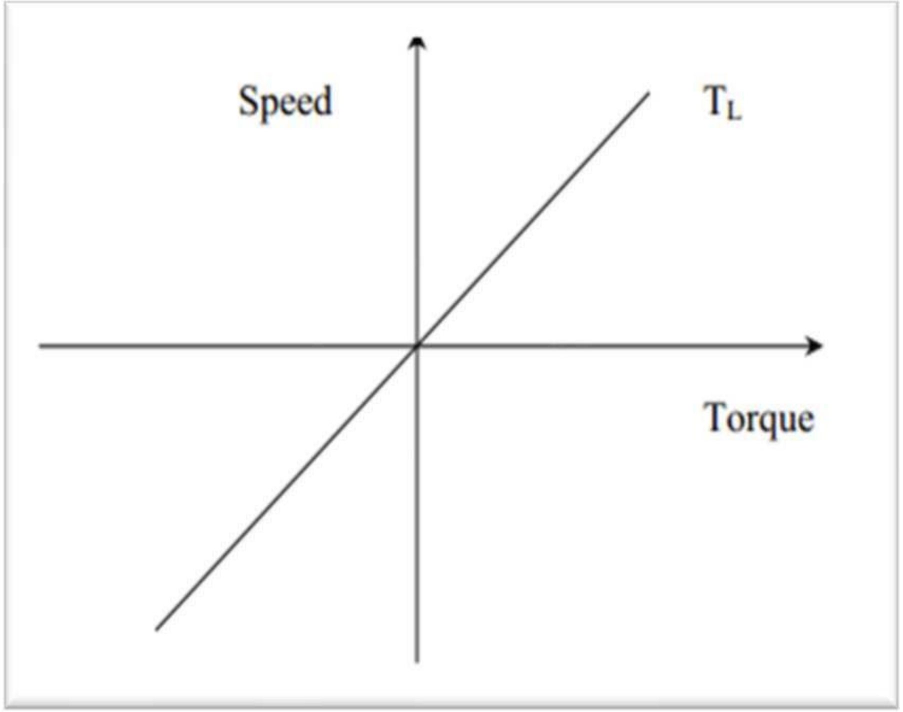
i. Constant Torque characteristics

- Most of the working machines that have mechanical nature of work like shaping, cutting, grinding or shearing, require constant torque irrespective of speed.
- Similarly cranes during the hoisting and conveyors handling constant weight of material per unit time also exhibit this type of characteristics.



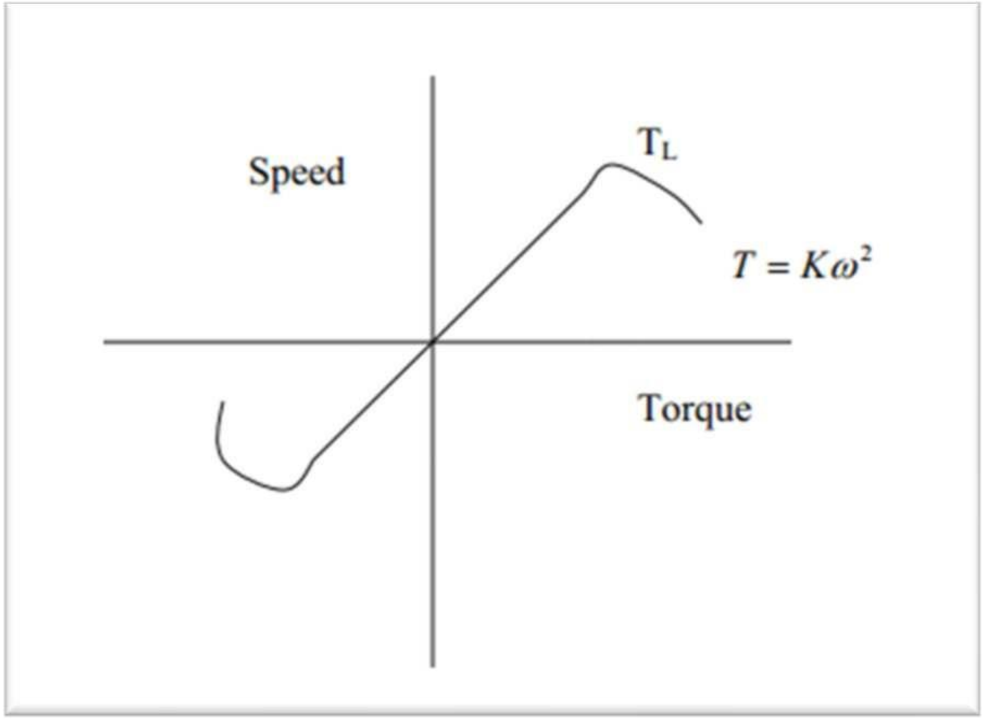
ii. Torque Proportional to speed

Separately excited dc generators connected to a constant resistance load, eddy current brakes have speed torque characteristics given by $T=k\omega$



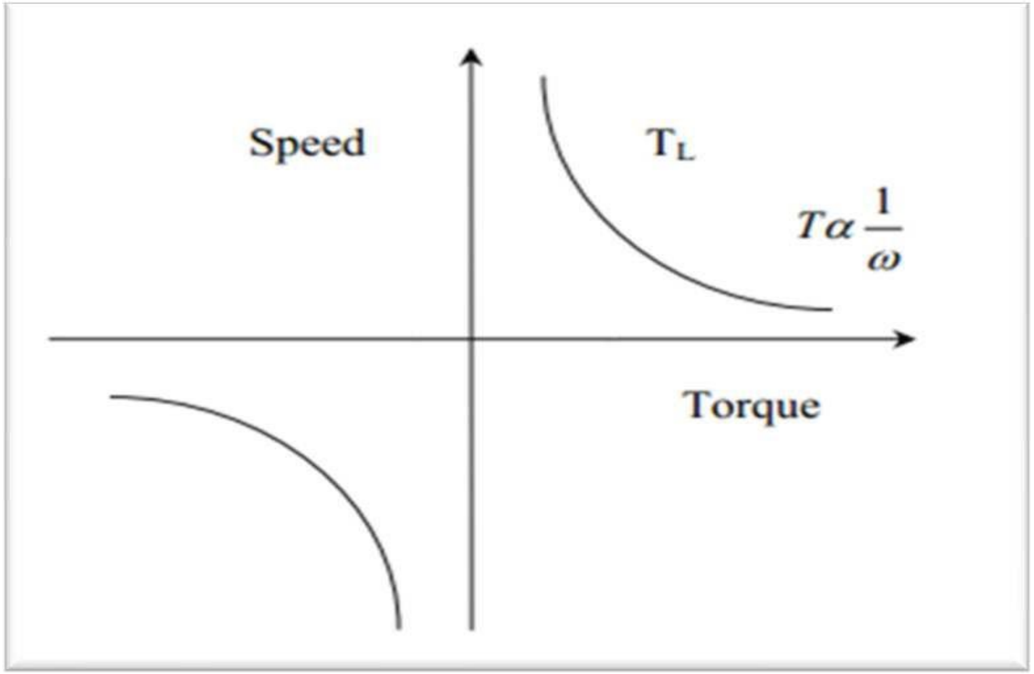
iii. Torque proportional to square of the speed

- Another type of load met in practice is the one in which load torque is proportional to the square of the speed.
- Ex: Fans rotary pumps, compressors and ship propellers.



iv. Torque Inversely proportional to speed

- Certain types of lathes, boring machines, milling machines, steel mill coiler and electric traction load exhibit hyperbolic speed-torque characteristics



Speed Torque Conventions and Multi-quadrant Operation

- For consideration of multi-quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed.
- Motor 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.
- According to Eq. (1) positive load torque is opposite in direction to the positive motor torque. Motor torque is considered negative if it produces deceleration.

$$T = T_l + J\frac{d\omega_m}{dt} \qquad (1)$$

Speed Torque Conventions and Multi-quadrant Operation cntd.

- 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 for both forward and reverse directions.
- Figure 2.2 shows the torque and speed coordinates for both forward (positive) and reverse (negative) motions.
- Power developed by a motor is given by the product of speed and 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.

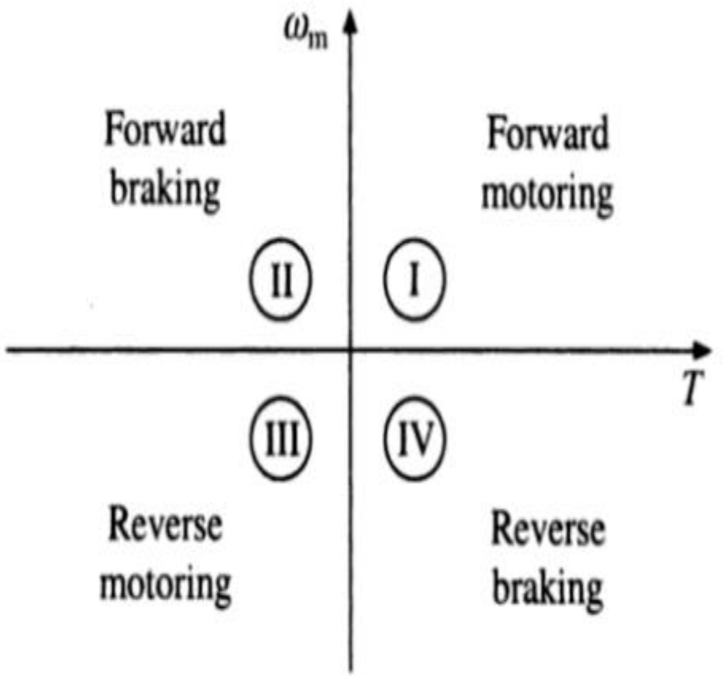


Fig. 2.2 Multiquadrant-operation of drives

- In quadrant II, power is negative. Hence, machine works under braking opposing the motion. Therefore, operation in Quadrant II is known as forward braking.
- Similarly, in quadrant Ill and IV can identified as reverse motoring and braking respectively.

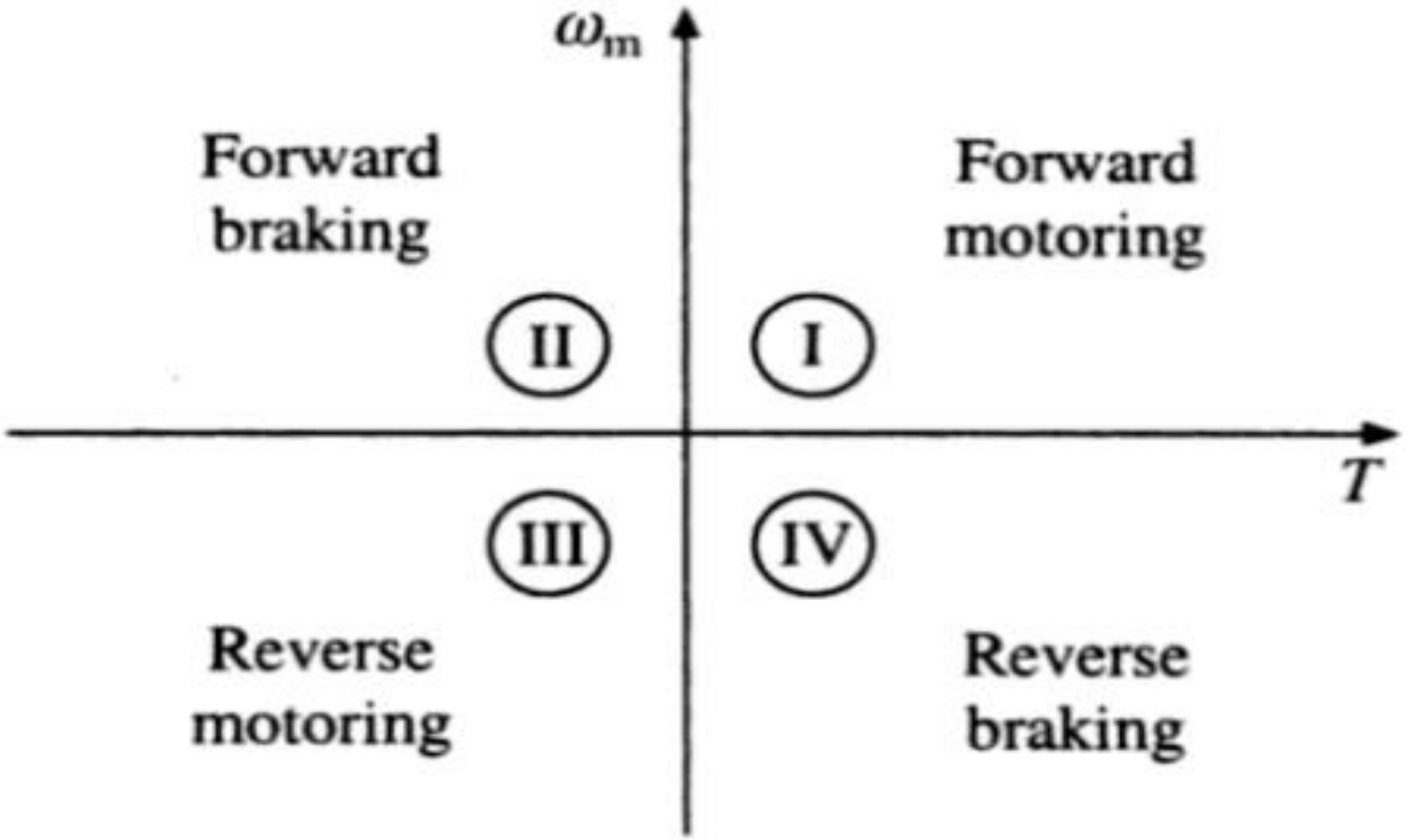


Fig. 2.2 Multiquadrant-operation of drives

🚗 **Example: Electric Car Going Uphill and Downhill**

1. Forward Motion with Braking (Negative Torque)

•Imagine an electric car driving **uphill** (forward direction).

•When the driver **presses the brake**, the motor applies **negative torque** to **slow down** the car.

•This braking torque **opposes** the forward motion → **negative torque**.

2. Reverse Motion with Acceleration (Still Negative Torque)

•Now imagine the same car is moving **backward** down a hill.

•If the motor **helps** the car accelerate in reverse (e.g., driver presses accelerator while in reverse), the motor torque is in the **reverse direction**.

•Since it's still opposite to the defined **forward** direction, it's considered **negative torque**.

Orientation of a hoist in four quadrants

- For better understanding of the above notations, **let us consider orientation of a hoist in four quadrants** as shown in Fig. 2.3. Directions of motor and load torques, and direction of speed are marked by arrows.
- A hoist consists of a rope wound on a drum coupled to the motor shaft.
- One end of the rope is tied to a cage which is used to transport man or material form one level to another level.
- Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of an empty cage but lower than of a fully loaded cage.

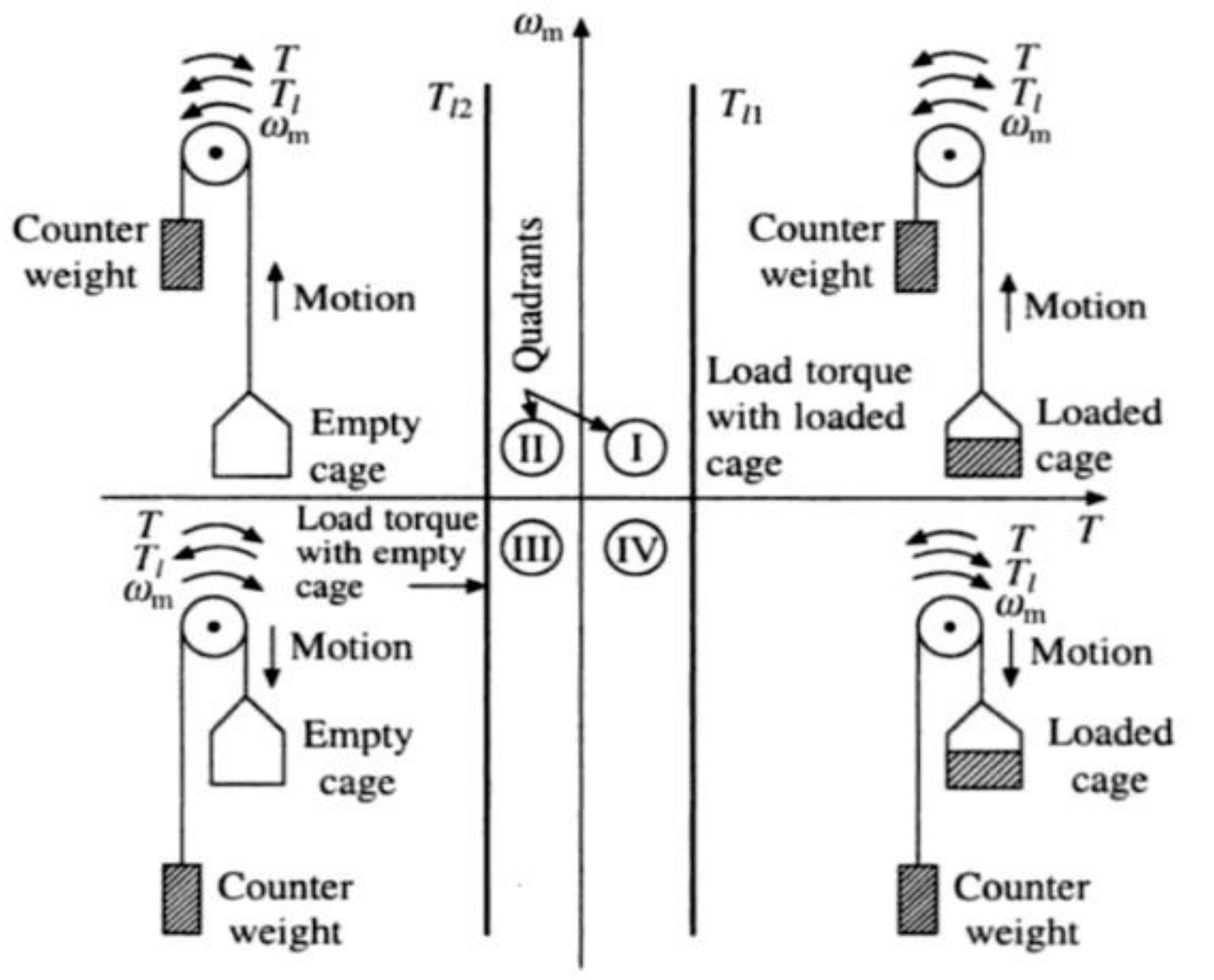


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

Orientation of a hoist in four quadrants cntd.

- Forward direction of motor speed will be one which gives upward motion of the cage. Speed- torque characteristics of the hoist load are also shown in Fig. 2.3.
- Though the positive load torque is opposite in sign to the positive motor torque, according to Eq. (2.2), it is convenient to plot it on the same axes.
- Load-torque curve drawn in this manner is, in fact, negative of the actual.

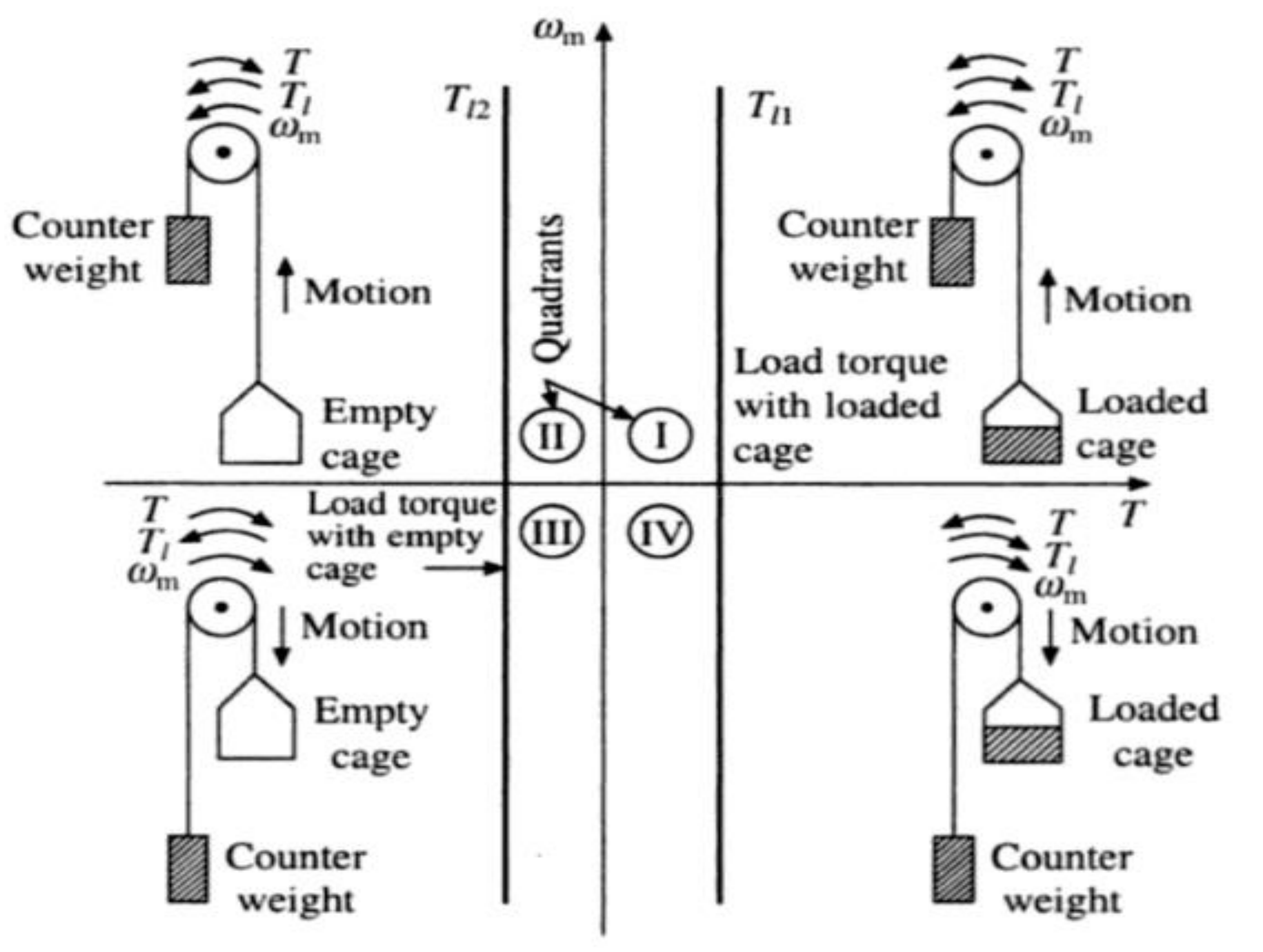


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

- Load torque line T_{L1} 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 T_{L2} 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.

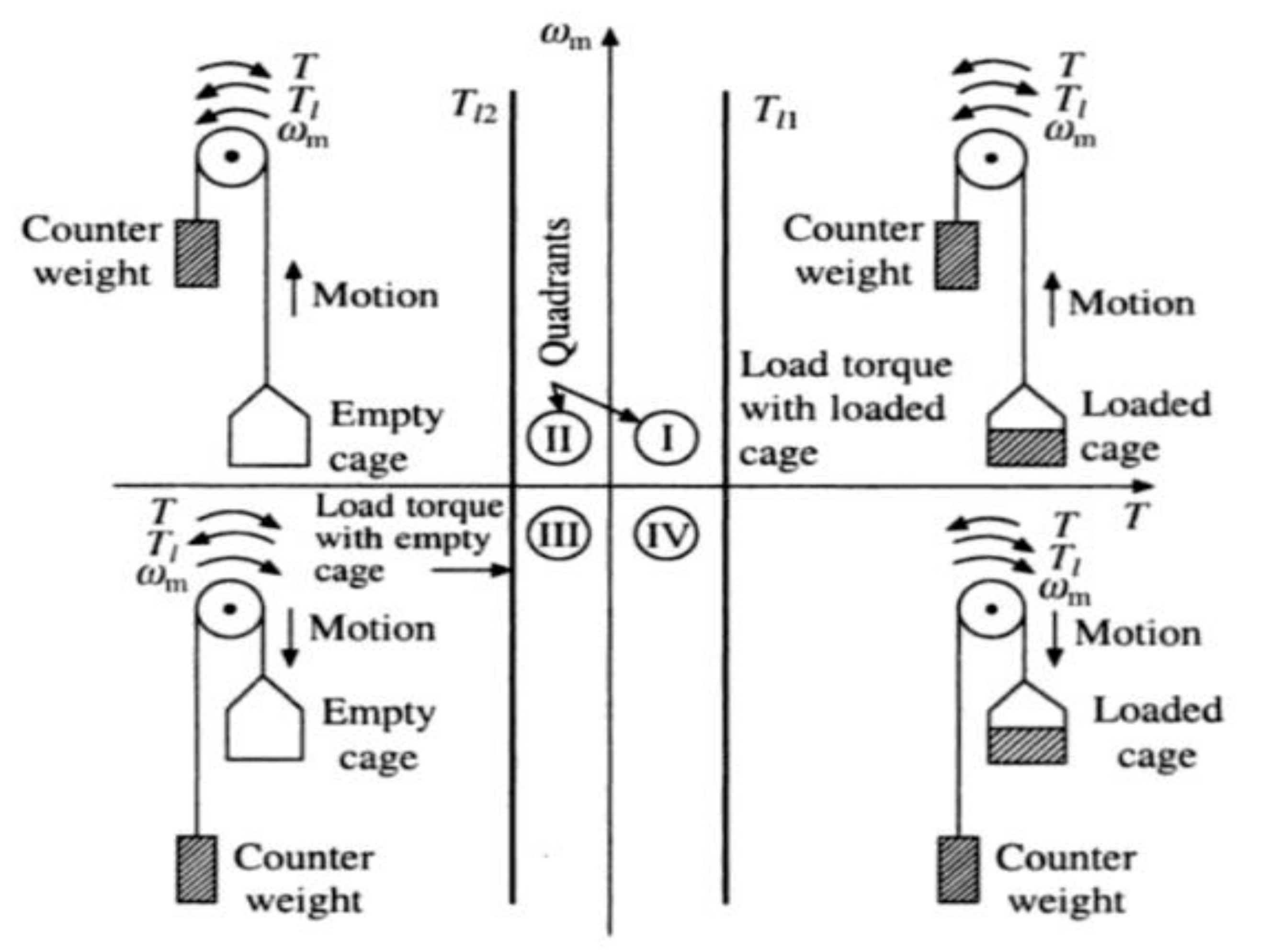


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

The quadrant I operation of a hoist requires the movement of the cage upward, which corresponds to the positive motor speed which is in anticlockwise direction here. This motion will be obtained if the motor produces positive torque in anticlockwise direction equal to the magnitude of load torque T_{L1}. Since developed motor power is positive, this is forward motoring operation.

Quadrant IV operation is obtained when a loaded cage is lowered. Since the weight of a loaded cage is higher than that of a counter weight, it is able to come down due to the gravity itself. In order to limit the speed of cage within a safe value, motor must produce a positive torque T equal to T_{L2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking.

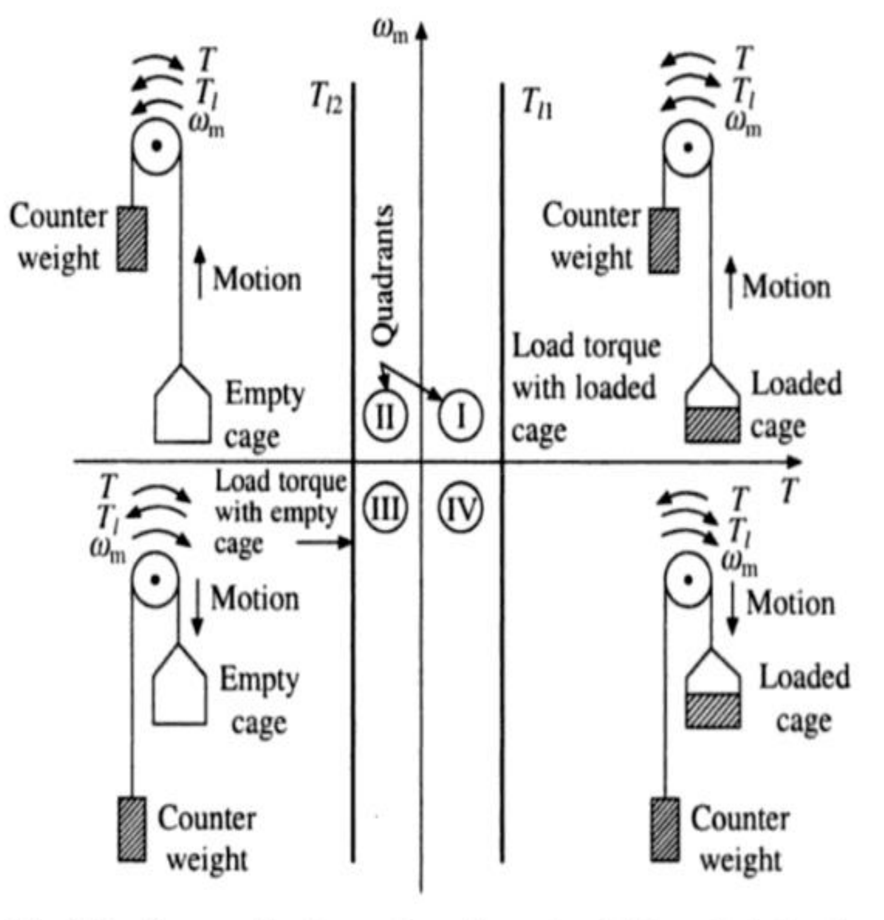


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weight is heavier than an empty cage, it is able to pull it up. In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{L2} in clockwise (negative) direction. Since speed is positive and power negative, it is forward braking.

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

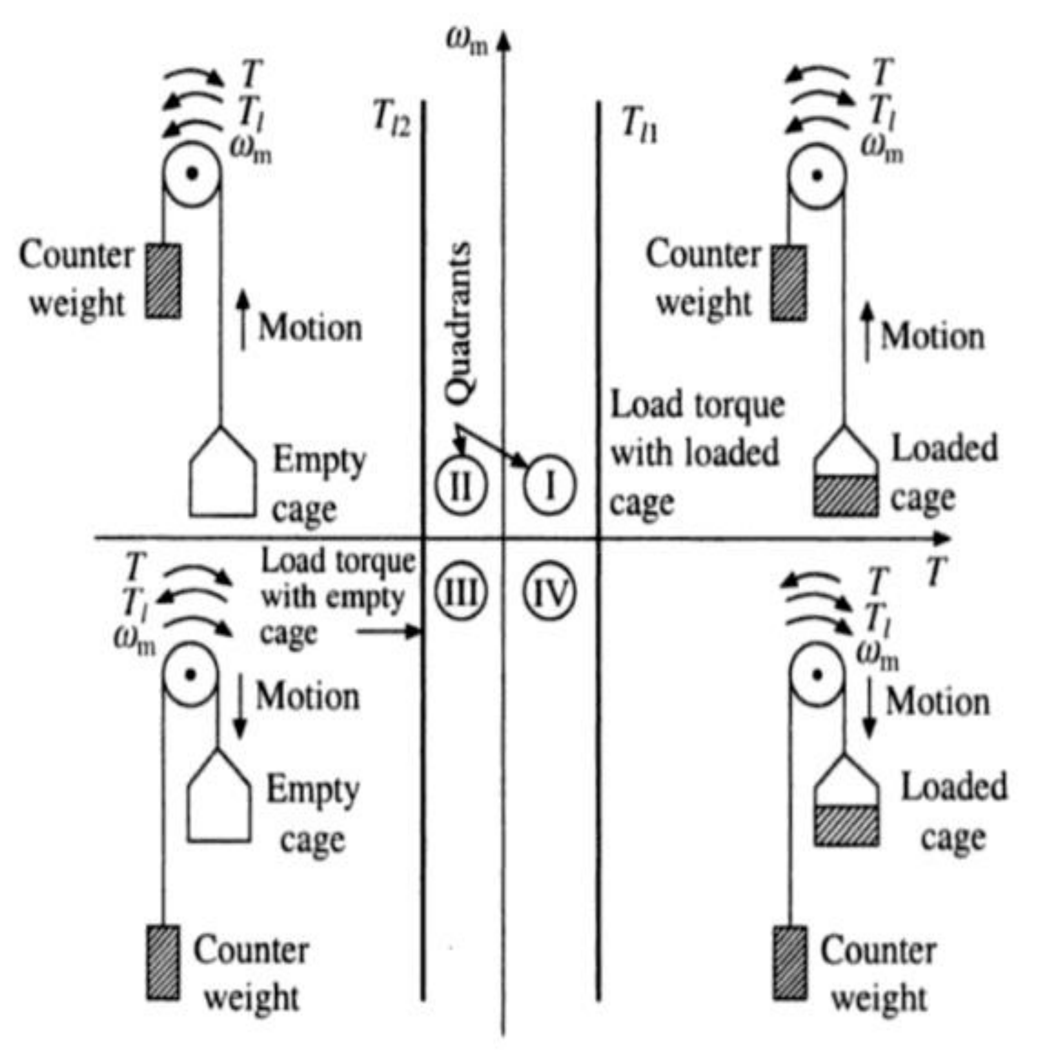
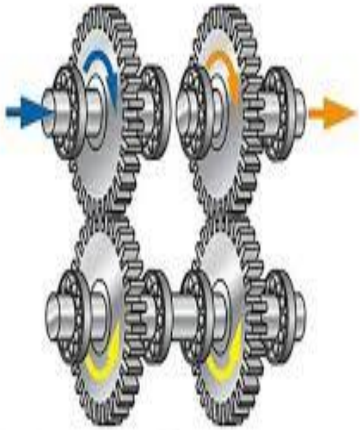


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

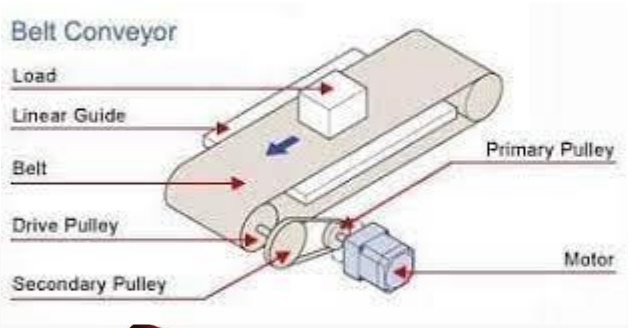
Equivalent Values of Drive Parameters

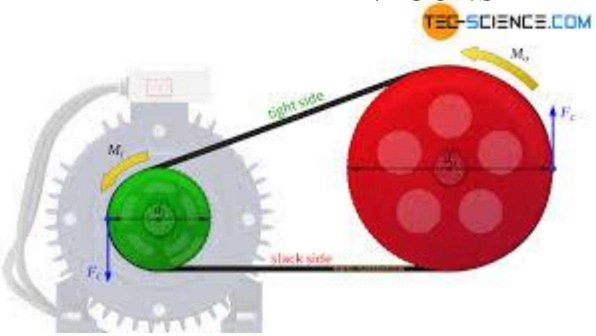
- Different parts of a load may be coupled through different mechanisms, such as gears, V-belts and crankshaft. These parts may have different speeds and different types of motions such as rotational and translational.
- The following presents the methods of finding the equivalent moment of inertia (J)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

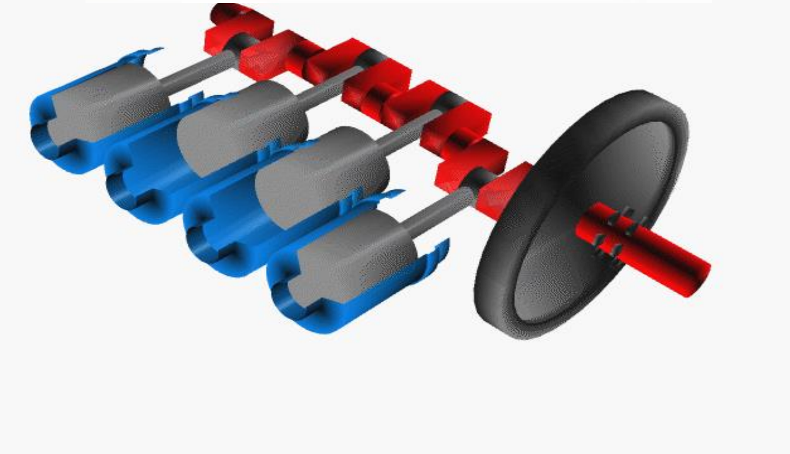


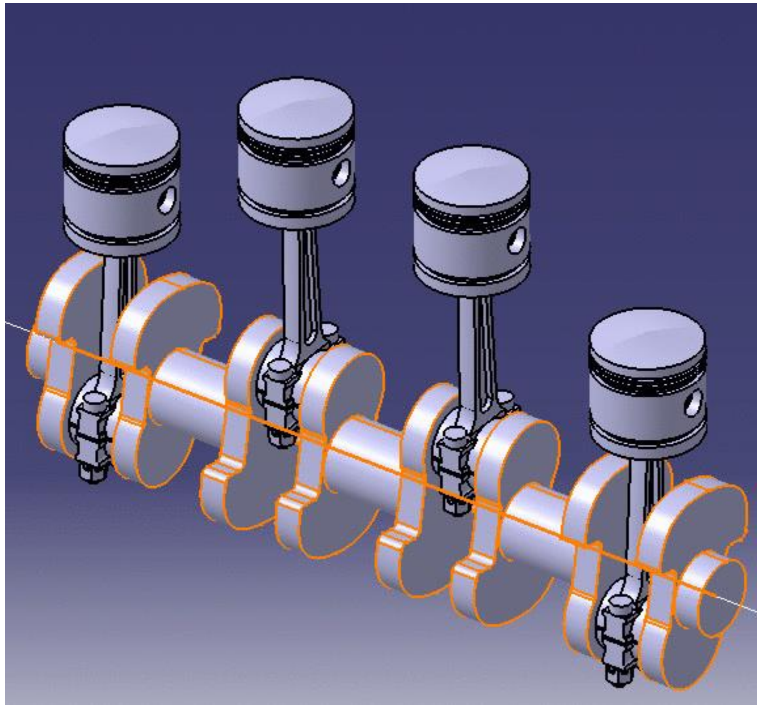
gears

V-belts





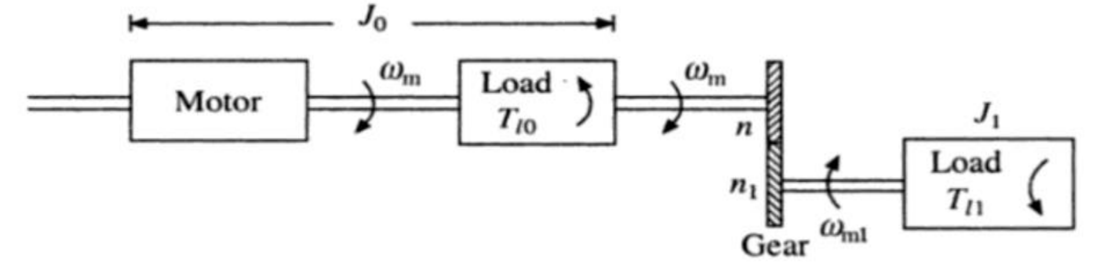




crankshaft

1. Loads with Rotational Motion

- Let us consider a motor driving two loads, one coupled directly to its shaft and other through a gear with n and n_1 and teeth as shown in Fig. (a).
- Let the moment of inertia of motor and load directly coupled to its shaft be Jo, motor speed and torque of the directly coupled load be ω_m and T_{LO} respectively.
- Let the moment of inertia, and torque of the load coupled through a gear be J_l, ω_{m1} and T_{L1} respectively. Now,



(a) Loads with rotational motion

$$\frac{\omega_{m1}}{\omega_m} = \frac{n}{n_1} = a_1 \quad (1)$$

where a_1 is the gear tooth ratio.

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

$$\frac{1}{2} J\omega_m^2 = \frac{1}{2} J_0\omega_m^2 + \frac{1}{2} J_1\omega_{m1}^2 \quad (2)$$

$$\omega_{m1} = a_1 . \omega_m$$

From equations 1 and 2

$$J = J_0 + a_1^2 J_1$$

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

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

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

From Eqs. (2.3) and (2.6)

$\omega_{m1} = a_1 . \omega_m$

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

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

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

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

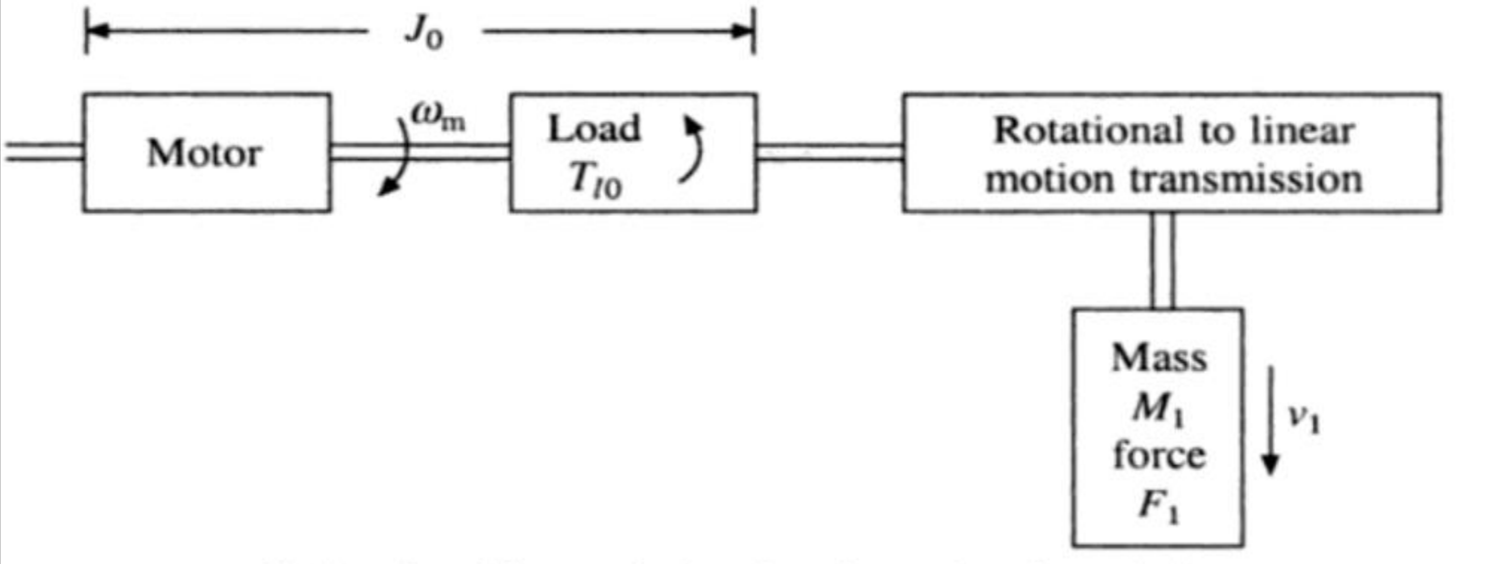
$$T_l = T_{l0} + \frac{a_1 T_{l1}}{\eta_1} + \frac{a_2 T_{l2}}{\eta_2} + \ldots + \frac{a_m T_{lm}}{\eta_m} \tag{2.9}$$

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

2. 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 Fig (b).

- Let moment of inertia of the motor and load directly coupled to it be Jo, load torque directly coupled to motor be T_{LO}), and the mass, velocity and force of load with translational motion be M_1 (kg), V_1 (m/sec) and F_1 (Newtons), respectively.



(b) Loads with translational and rotational motion

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

$$\frac{1}{2} J\omega_m^2 = \frac{1}{2} J_0\omega_m^2 + \frac{1}{2} M_1 v_1^2$$

or

$$J = J_0 + M_1\left(\frac{v_1}{\omega_m}\right)^2 \tag{2.10}$$

Similarly, power at the motor and load should be the same, thus if efficiency of transmission be η_1

$$T_l \omega_m = T_{l0} \cdot \omega_m + \frac{F_1 v_1}{\eta_1}$$

or

$$T_l = T_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right) \tag{2.11}$$

If, in addition to one load directly coupled to the motor shaft, there are m other loads with translational motion with velocities $v_1, v_2, \ldots v_m$ and masses $M_1, M_2, \ldots, M_m$, respectively, then

$$J = J_0 + M_1\left(\frac{v_1}{\omega_m}\right)^2 + M_2\left(\frac{v_2}{\omega_m}\right)^2 + \ldots + M_m\left(\frac{v_m}{\omega_m}\right)^2 \tag{2.12}$$

and

$$T_l = T_{l0} + \frac{F_1}{\eta_1}\left(\frac{v_1}{\omega_m}\right) + \frac{F_2}{\eta_2}\left(\frac{v_2}{\omega_m}\right) + \ldots + \frac{F_m}{\eta_m}\left(\frac{v_m}{\omega_m}\right) \tag{2.13}$$

EXAMPLE 2.1

A motor drives two loads. One has rotational motion. It is coupled to the motor through a reduction gear with $a = 0.1$ and efficiency of 90%. The load has a moment of inertia of 10 kg-m^2 and a torque of 10 N-m. Other load has translational motion and consists of 1000 kg weight to be lifted up at an uniform speed of 1.5 m/s. Coupling between this load and the motor has an efficiency of 85%. Motor has an inertia of 0.2 kg-m^2 and runs at a constant speed of 1420 rpm. Determine equivalent inertia referred to the motor shaft and power developed by the motor.

Solution

From Eqs. (2.8) and (2.12), the total moment of inertia referred to the motor shaft

$$J = J_0 + a_1^2 J_1 + M_1\left(\frac{v_1}{\omega_m}\right)^2 \quad (1)$$

Here $J_0 = 0.2$ kg-m^2, $a_1 = 0.1$, $J_1 = 10$ kg-m^2, $v = 1.5$ m/s and $\omega_m = (1420 \times \pi)/30 = 148.7$ rad/sec.

Substituting in Eq. (1) gives

$$J = 0.2 + (0.1)^2 \times 10 + 1000\left(\frac{1.5}{148.7}\right)^2 = 0.4 \text{ kg-m}^2$$

From Eqs. (2.9) and (2.13)

$$T_l = \frac{a_1 T_{l1}}{\eta_1} + \frac{F_1}{\eta_1'}\left(\frac{v_1}{\omega_m}\right) \quad (2)$$

Here $\eta_1 = 0.9$, $a_1 = 0.1$, $T_{l1} = 10$ N-m, $\eta_1' = 0.85$, $F_1 = 1000 \times 9.81$ N, $v_1 = 1.5$ m/s and $\omega_m = 148.7$ rad/sec.

Substituting in Eq. (2) gives

$$T_l = \frac{0.1 \times 10}{0.9} + \frac{1000 \times 9.81}{0.85}\left(\frac{1.5}{148.7}\right) = 117.53 \text{ N-m}$$

Measurement of Moment of Inertia

- Moment of inertia can be calculated if dimensions and weights of various parts of the load and motor are known. It can also be measured experimentally by **retardation test**.
- In **retardation test**, the drive is run at a speed slightly higher than rated speed and then the supply to it is cut off. Drive continues to run due to kinetic energy stored in it and decelerates due to rotational mechanical losses. Variation of speed with time is recorded.
- At any speed ω_m, power P consumed in supplying rotational losses is given by

P = Rate of change of kinetic energy

$$\mathbf{P} = \frac{d}{dt}\left(\frac{1}{2}J\omega_m^2\right) = J\omega_m\frac{d\omega_m}{dt} \qquad \text{Eq. (1).}$$

- From retardation test, $d\omega_m/dt$ at rated speed is obtained.
- Now drive is reconnected to the supply and run at rated speed and rotational mechanical power input to the drive is measured. This is approximately equal to P. Now J can be calculated from Eq. (1).
- Main problem in this method is that rotational mechanical losses cannot be measured accurately because core losses and rotational mechanical losses cannot be separated.
- In view of this, retardation test on a dc separately excited motor or a synchronous motor is carried out with field on. Now core loss is included in the rotational loss, which is now obtained as a difference of armature power input armature copper loss.
- In case of a wound rotor induction motor, retardation test can be carried out by keeping the stator supply and opening the rotor winding connection.

Not asked

- J can be determined more accurately by obtaining speed time curve from the retardation test as above and also rotational losses vs speed plot as shown in Fig.
- Using these two plots, rotational losses vs time plot can be obtained
- Ex:
  - For time t_1, $\omega_{m\,1}$ is found from the retardation plot.
  - Then for this speed rotational loss P_1 is obtained from the plot of rotational loss vs speed and plotted against t_1.
  - Area A enclosed between the rotational loss vs t plot and the time axis (shaded area), is the kinetic energy dissipated during retardation test.
  - If initial speed of the drive during retardation test was $\omega_{m\,0}$ then

$$\frac{1}{2} J\omega_{m0}^2 = A$$

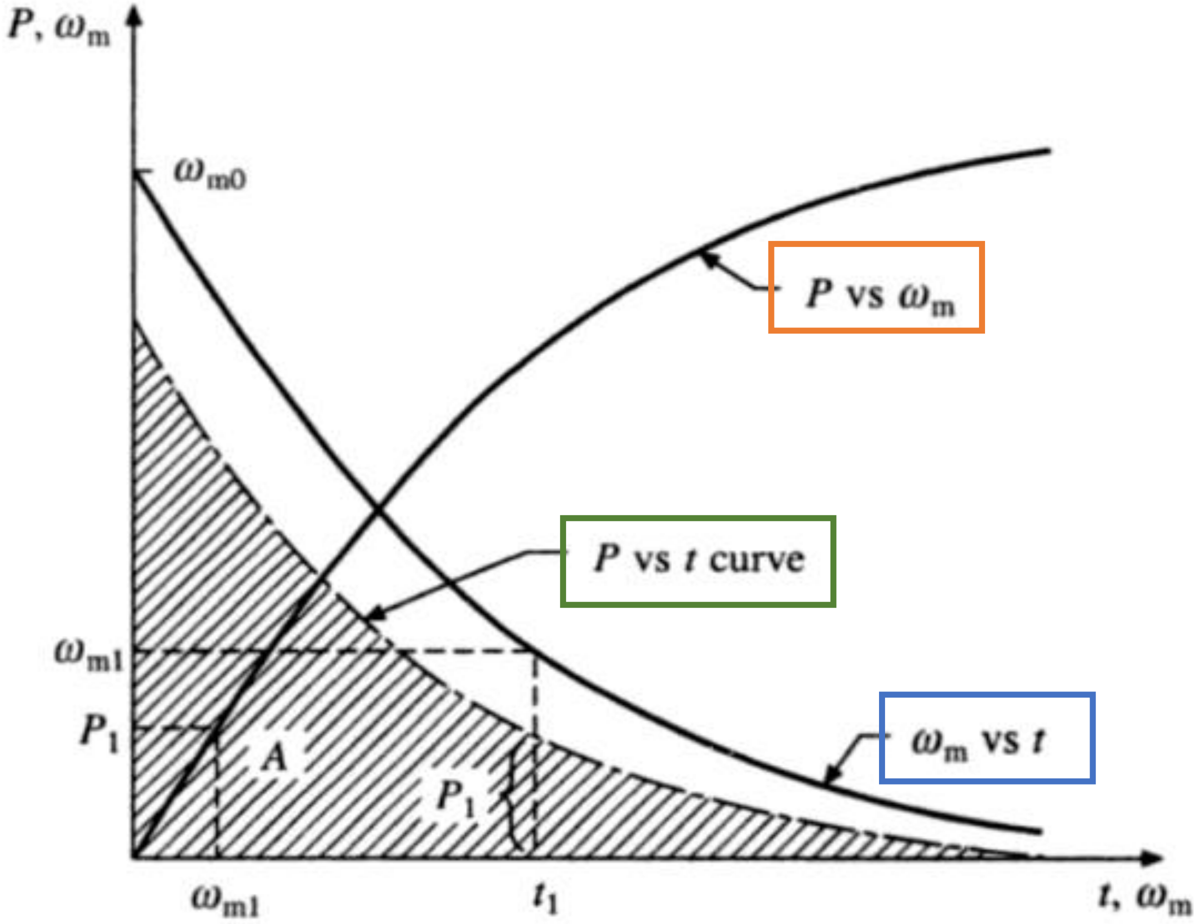


Fig. 2.5 Graphical method of determination of equivalent moment of inertia

Calculation of time and energy-loss in transient operations

- Starting, braking, speed change and speed reversal are transient operations.
- Time and Energy Loss in Transient Operations can be evaluated by solving Eq. along with motor circuit equations.

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

Where B is viscous friction coefficient

When T and T_L are constants or proportional to speed, Eq. 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, it will be a non-linear differential equation. It could then be solved numerically by **Runga-Kutta method**.

- For any of the above mentioned transients, final speed is an equilibrium speed.
- Theoretically, transients are over in infinite time, which is not so in practice.
- In order to resolve this anomaly, Time and Energy Loss in Transient Operations is considered to be over when 95% change in speed has taken place.
- For example, when speed changes from ω_{m1} to equilibrium speed ω_{me}, time taken for the speed to change from ω_{m1} to $[\omega_{m1} + 0.95(\omega_{me} - \omega_{m1})]$ is considered to be equal to the transient time.

Not asked

- Transient time and energy loss can also be computed with satisfactory accuracy using steady-state speed-torque and speed-current curves of motor and speed-torque curve of load.
- This is because mechanical time constant of a drive is usually very large compared to electrical time constant of motor.
- Consequently, electrical transients die down very fast and motor operation can be considered to take place along the steady-state speed-torque and speed-current curves.

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

- where $T(\omega_m)$ and $T_l(\omega_m)$ indicate that the motor and load torques are functions of drive speed ω_m. Time taken for drive speed to change from ω_{m1} to ω_{m2} is obtained by integrating Eq

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

- Equation can be integrated only if functions $T(\omega_m)$ and $T_l(\omega_m)$ are known and are of integral form.
- Otherwise the integral is evaluated graphically.
- Expression on the right of Eq. is the area between the reciprocal of the acceleration { $J/[T(\omega_m) - T_l(\omega_m)]$} VS ω_m curve and ω_m axis in the fig

- The transient time can be evaluated by measuring this area.
- When ω_{m2} is an equilibrium speed ω_{me}, then the reciprocal of acceleration will become infinite at ω_{me}. Consequently, time evaluated this way will be infinite. Therefore, in this case transient time is computed by measuring the area between speeds ω_{m1} and $\omega_{m1} + 0.95(\omega_{m2} - \omega_{m1})$.

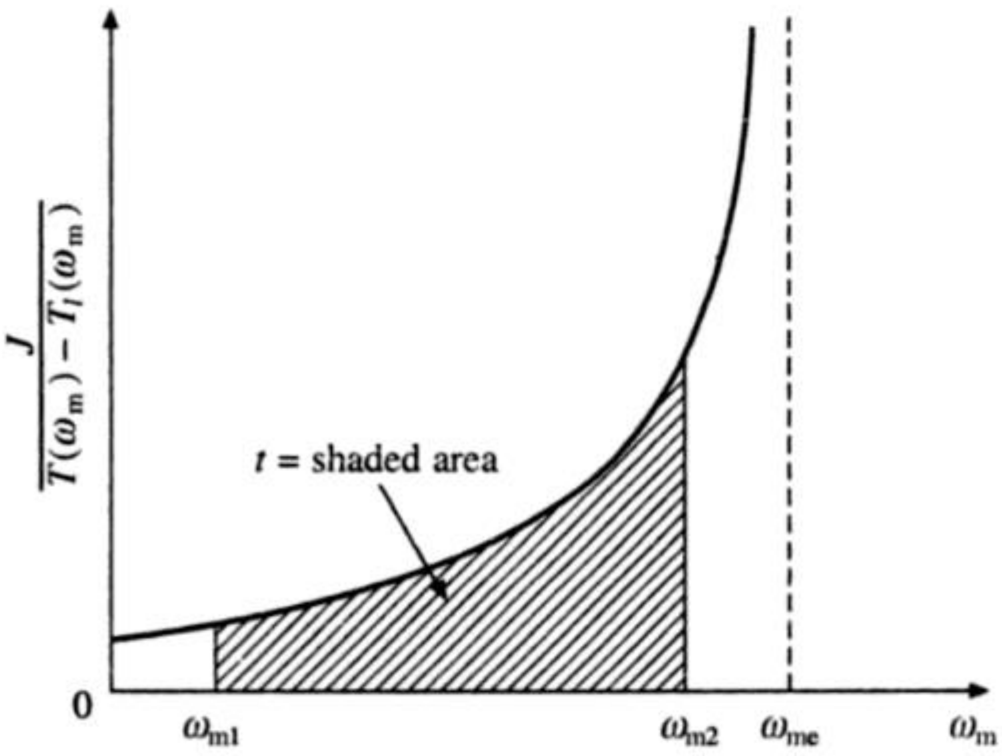


Fig. 2.8 Calculation of time during a transient operation

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

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

- where **R** is the motor winding resistance and **i** is the current flowing through it.
- In many applications, by making use, of speed-torque expressions for motor and load, it is possible to arrange Eq. in integrable form. However, this is not possible in applications where nonlinear impedance is present in the motor circuit.
- By graphical solution of Eq., ω_m vs t curve is obtained. From this curve and steady-state speed-current curve, i^2 vs t curve is obtained. Area enclosed between this curve and time axis multiplied by R gives the energy dissipated in motor winding

EXAMPLE 2.2

A drive has following parameters:

$J = 10$ kg-m^2, $T = 100 - 0.1N$, N-m, Passive load torque $T_l = 0.05N$, N-m, where N is the speed in rpm.

Initially the drive is operating in steady-state. Now it is to be reversed. For this motor characteristic is changed to $T = -100 - 0.1N$, N-m. Calculate the time of reversal.

Solution

For steady-state speed

$$T - T_l = 0$$

or
$$100 - 0.1N - 0.05N = 0$$

or
$$0.15N = 100 \quad \text{or} \quad N = 666.7 \text{ rpm}$$

After reversal, for steady-state speed, noting that the load is passive

$$-100 - 0.1N - 0.05N = 0$$

or
$$N = -666.7 \text{ rpm}$$

When reversing, from Eq. (2.2)

$$J\frac{d\omega_m}{dt} = -100 - 0.1N - 0.05N$$

$$\frac{dN}{dt} = \frac{30}{J\pi}(-100 - 0.15N) = -95.49 - 0.143N$$

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

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

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

Steady State Stability

- Equilibrium speed of a motor- load system is obtained when motor torque equals the load torque .
- A drive will operate in steady state at this speed, provided it is the speed of stable equilibrium.
- In most drives the electrical time constant of the motor is negligible compared to its mechanical time constant.
- Therefore, during transient operations, motor can be assumed to be in electrical equilibrium implying that steady-state speed-torque curves are also applicable to the transient operations.

Let us see the following example.

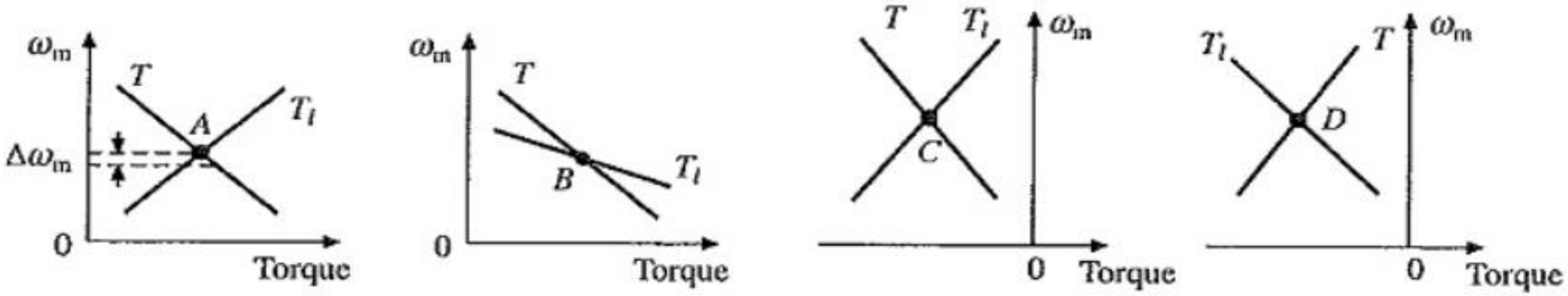
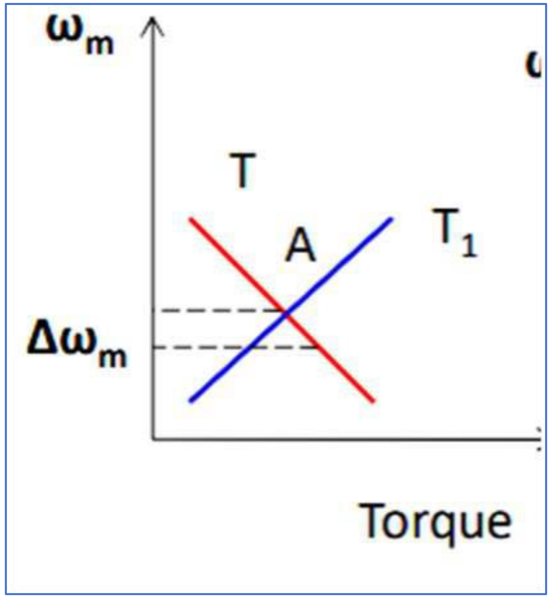


Fig. 2.9 Points A and C are stable and B and D are unstable

- Concept of steady state stability is used to evaluate the stability of an equilibrium point from the steady-state speed-torque curves of the motor and load.

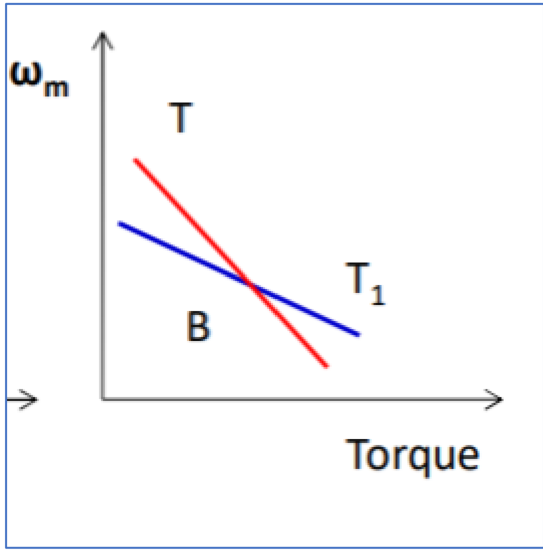
i. Equilibrium point A

- The equilibrium point A will be termed as stable when the operation will be restored to its initial position after a small departure from it due to a disturbance in the motor or load.
- Let the disturbance causes a reduction of $\Delta\omega_m$ in speed. At new speed, motor torque is greater than the load torque, consequently, motor will accelerate and **operation will be restored to A.**
- Similarly, an increase of $\Delta\omega_m$ in speed caused by a disturbance will make load torque greater than the motor torque, resulting into deceleration and **restoration of operation to point A**. Hence, the drive is **steady state stable at point A**.



ii. Equilibrium point B

- This is obtained when the same motor drives another load.
- A decrease in speed causes the load torque to become greater than the motor torque, drive decelerates and **operating point moves away from B**
- Similarly, an increase in speed will make motor torque greater than the load torque which will move the operating point away from B. Thus, **B is an unstable point of equilibrium**



Similarly case iii and case iv could be analysed

Hence 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

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

Inequality in equation can be derived by an alternative approach. Let a small perturbation in speed,

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

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

$$\Delta T = \left(\frac{dT}{d\omega_m}\right)\Delta\omega_m \quad (2.27)$$

$$\Delta T_l = \left(\frac{dT_l}{d\omega_m}\right)\Delta\omega_m \quad (2.28)$$

By reducing,

$$\Delta\omega_m = (\Delta\omega_m)_0 \exp\left\{-\frac{1}{J}\left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)t\right\}$$

An operating point will be stable when $\Delta\omega_m$ approaches zero as t approaches infinity

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Load Equalisation

In some drive applications, load torque fluctuates widely within short intervals of time.

For example: In pressing machines a large torque of short duration is required during pressing operation, otherwise the torque is nearly zero. Other examples are electric hammer, steel rolling mills and reciprocating pumps.

In such drives, if motor is required to supply peak torque demanded by load:

1. Motor rating has to be high.
2. Motor will draw a pulsed current from the supply. When amplitude of pulsed current forms an appreciable proportion of supply line capacity, it gives rise to line voltage fluctuations, which adversely affect other loads connected to the line.

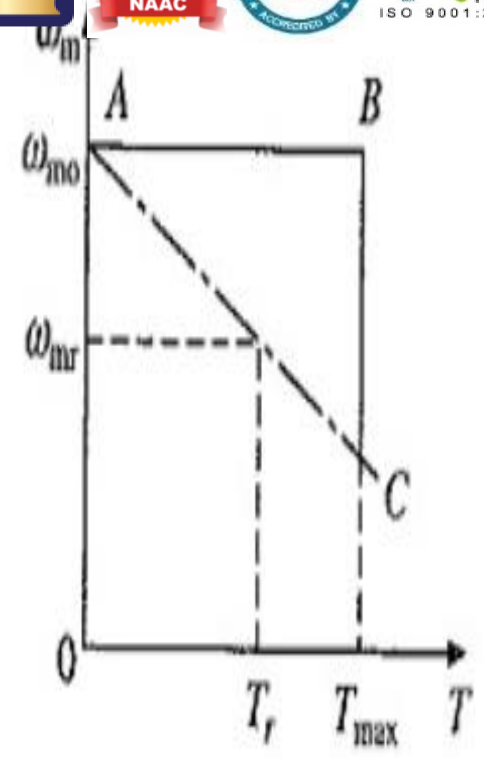


Fig. 2.10 Shapes of motor speed torque curves for fluctuating roads

3. In some applications, peak load demanded may form major proportion of the source capacity itself, as in blooming mills, then load fluctuations may also adversely affect the stability of source.

Above mentioned problems of fluctuating loads are overcome by <u>mounting a **flywheel** on the motor shaft in non-reversible drives</u>.

- Motor speed-torque characteristic is made drooping(characteristic AC in Fig. 2.10).
- Alternatively by closed loop current control, torque is prevented from exceeding a permissible value (characteristic ABC in Fig. 2.10).
- During high load period, load torque will be much larger compared to the motor torque. Deceleration occurs producing a large dynamic torque component (J $d\omega_m/dt$).
- Dynamic torque and motor torque together are able to produce torque required by the load. Because of deceleration, the motor speed falls.
- During light load period, the motor torque exceeds the load torque causing acceleration. Speed is brought back to original value before the next high load period.

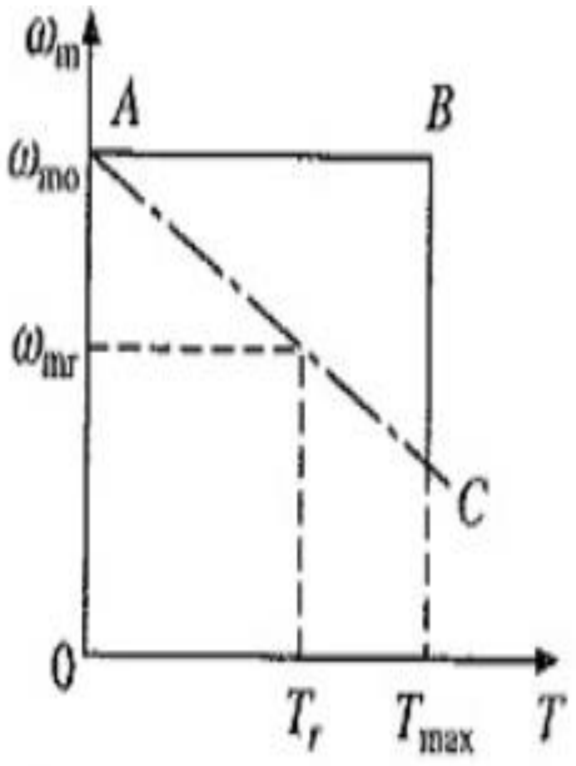


Fig. 2.10 Shapes of motor speed torque curves for fluctuating roads

- Variation of motor and load torques, and speed or a periodic load and for a drooping motor speed-torque curve (AC in Fig. 2.10) are shown in Fig. 2.11.
- It shows that peak torque required from the motor has much smaller value than the peak load torque. Hence, a motor with much smaller rating than peak load can be used and peak current drawn by motor from the source is reduced by a large amount.
- Fluctuations in motor torque and speed are also reduced. Since power drawn from the source fluctuates very little, **this is called load equalisation.**
- In variable speed and reversible drives, a flywheel cannot be mounted on the motor shaft, as it will increase transient time of the drive by a large amount.
- If motor is fed from a motor- generator set (Ward-Leonard Drive), then flywheel can be mounted on the shaft of the motor-generator set. This arrangement equalises load on the source, but not the load on motor.
- Consequently, motor capable of supplying peak-load-torque is required.

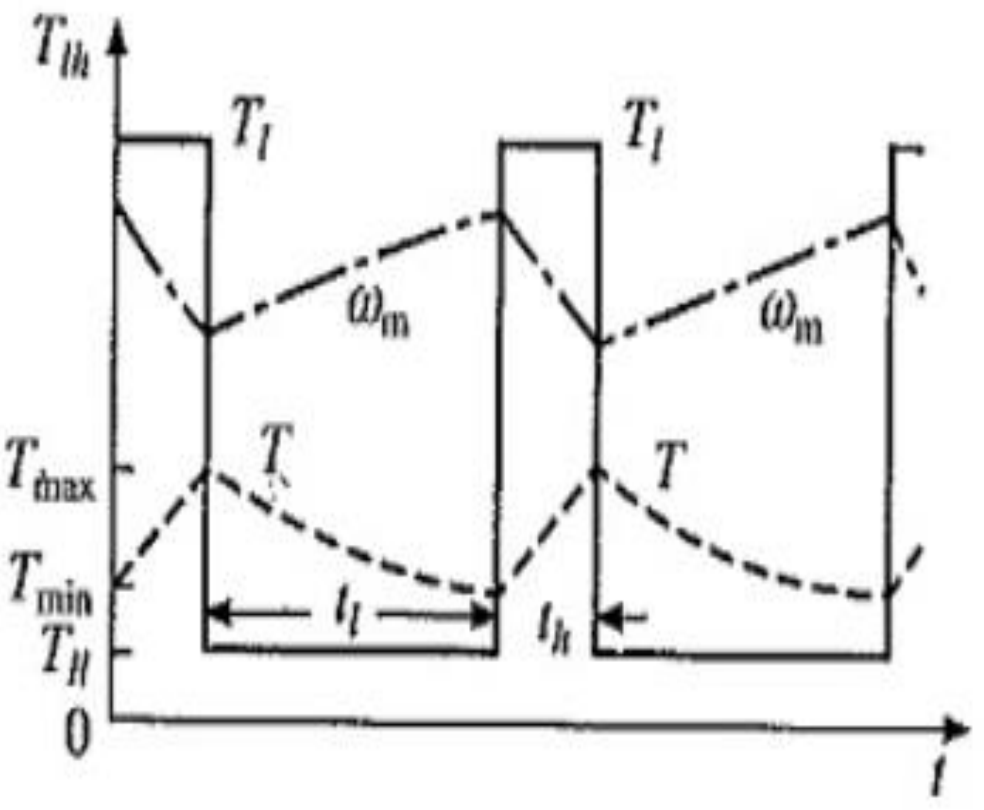


Fig. 2.11

T_{lh}- High load torque
T_{ll}- Light load torque
t_h-High load period duration
t_l- light load period duration

Moment of inertia of the flywheel required for load equalisation is calculated as follows:

Assuming a linear motor-speed-torque curve in the region of interest (drooping characteristic AC of Fig. 2.10)

$$\omega_m = \omega_{m0} - \frac{\omega_{m0} - \omega_{mr}}{T_r} \cdot T \qquad (2.31)$$

Where ω_{m0}, ω_{mr}, and T_r are no load speed, rated speed and rated torque respectively.

Because of slow response due to large inertia, motor can be assumed to be in electrical equilibrium during transient operation of the motor load system

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

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

Moment of inertia of the flywheel required can be calculated either from above 2 equations. Hence,

$$J = WR^2, \text{ kg-m}^2 \qquad (2.45)$$

where W is the weight of the flywheel (kg) and R is the radius (m).

Example 2.3

A motor equipped with a flywheel is to supply a load torque of 1000 N-m for 10 sec followed by a light load period of 200 N-m long enough for the flywheel to regain its steady-state speed. It is desired to limit the motor torque to 700 N-m. What should be the moment of inertia of flywheel? Motor has an inertia of 10 kg-m^2. Its no load speed is 500 rpm and the slip at a torque of 500 N-m is 5%. Assume speed-torque characteristic of motor to be a straight line in the region of interest.

Solution

From Eq. (2.42)

$$J = \frac{T_r}{(\omega_{m0} - \omega_{mr})}\left[\frac{t_h}{\log_e\left(\dfrac{T_{lh} - T_{min}}{T_{lh} - T_{max}}\right)}\right] \quad (1)$$

Here no load speed $= \dfrac{500 \times 2\pi}{60} = 52.36$ rad/sec

Speed at 500 N-m = (1 – 0.05) 52.36 = 49.74 rad/sec

$$\frac{T_r}{(\omega_{m0} - \omega_{mr})} = \frac{500}{52.36 - 49.74} = 190.84$$

$T_{lh} = 1000$ N-m, $T_{max} = 700$ N-m, $T_{min} = T_{ll} = 200$ N-m, $t_h = 10$ S.
Substituting in Eq. (1)

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

$$J = 190.84\left[\frac{10}{\log_e\left(\dfrac{1000 - 200}{1000 - 700}\right)}\right] = 1871.8 \text{ kg-m}^2$$

Moment of inertia of the flywheel = 1871.8 – 10 = 1861.8 kg-m^2.

Control of Drives

Control requirements to all electrical drives are presented for open & closed loop drives.

Modes of Operation:

An electrical drive operates in three modes:

- Steady state
- Acceleration including Starting
- Deceleration including Stopping

i. Steady state

We know that $T = T_l + J\frac{d\omega_m}{dt}$

- According to the above expression the steady state operation takes place when motor torque equals the load torque.
- Adjustment: Change in speed is achieved by varying the steady state motor speed torque curve so that motor torque equals the load torque at the new desired speed.
- In the figure shown, when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed ω_{m1} . Speed is changed to ω_{m2} when the motor parameters are adjusted to provide speed torque curve 2.
- When load torque opposes motion, the motor works as a motor operating in quadrant I or III depending on the direction of rotation.
- When the load is active it can reverse its sign and act to assist the motion.
- Steady state operation for such a case can be obtained by adding a mechanical brake which will produce a torque in a direction to oppose the motion.
- The steady state operation is obtained at a speed for which braking torque equal the load torque.
- Drive operates in quadrant II or IV depending upon the rotation.

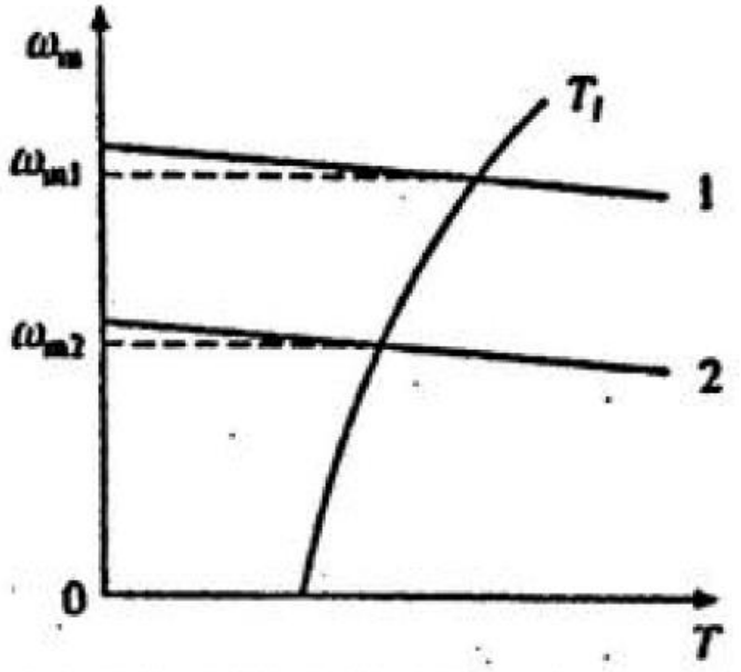
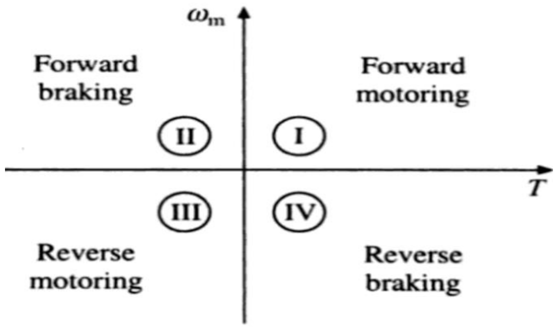


Fig. 3.1 Principle of speed control



ii. Acceleration State:

- Acceleration and Deceleration modes are transient modes.
- Drive operates in acceleration mode whenever an increase in its speed is required.
- For this, motor speed torque curve must be changed so that motor torque exceeds the load torque.
- Time taken for a given change in speed depends on inertia of motor load system and the amount by which motor torque exceeds the load torque.
- Increase in motor torque is accompanied by an increase in motor current.
- Motor current must be with in a value which is safe for both motor and power modulator.
- For long duration acceleration, current must not be allowed to exceed the rated value. For short duration acceleration a current should be higher than the rated value.
- In closed loop drives requiring fast response, motor current may be intentionally forced to the maximum value in order to achieve high acceleration.

- Figure shows the transition from operating point A at speed ω_{m1} to operating point B at a **higher speed ω_{m2}**-when the motor torque is held constant during acceleration. The Path consists of AD_1E_1B.
- In the fig,1 to 5 are motor speed torque curves. All points mentioned in relation to acceleration are applicable to starting.
- The maximum current allowed should not only be safe for motor and power modulator but drop in source voltage caused due to it should also be in acceptable limits.
- In some applications the motor should accelerate smoothly, without any jerk. This is achieved when the starting torque can be increased steplessly from its zero value. Such a start is known as soft start.

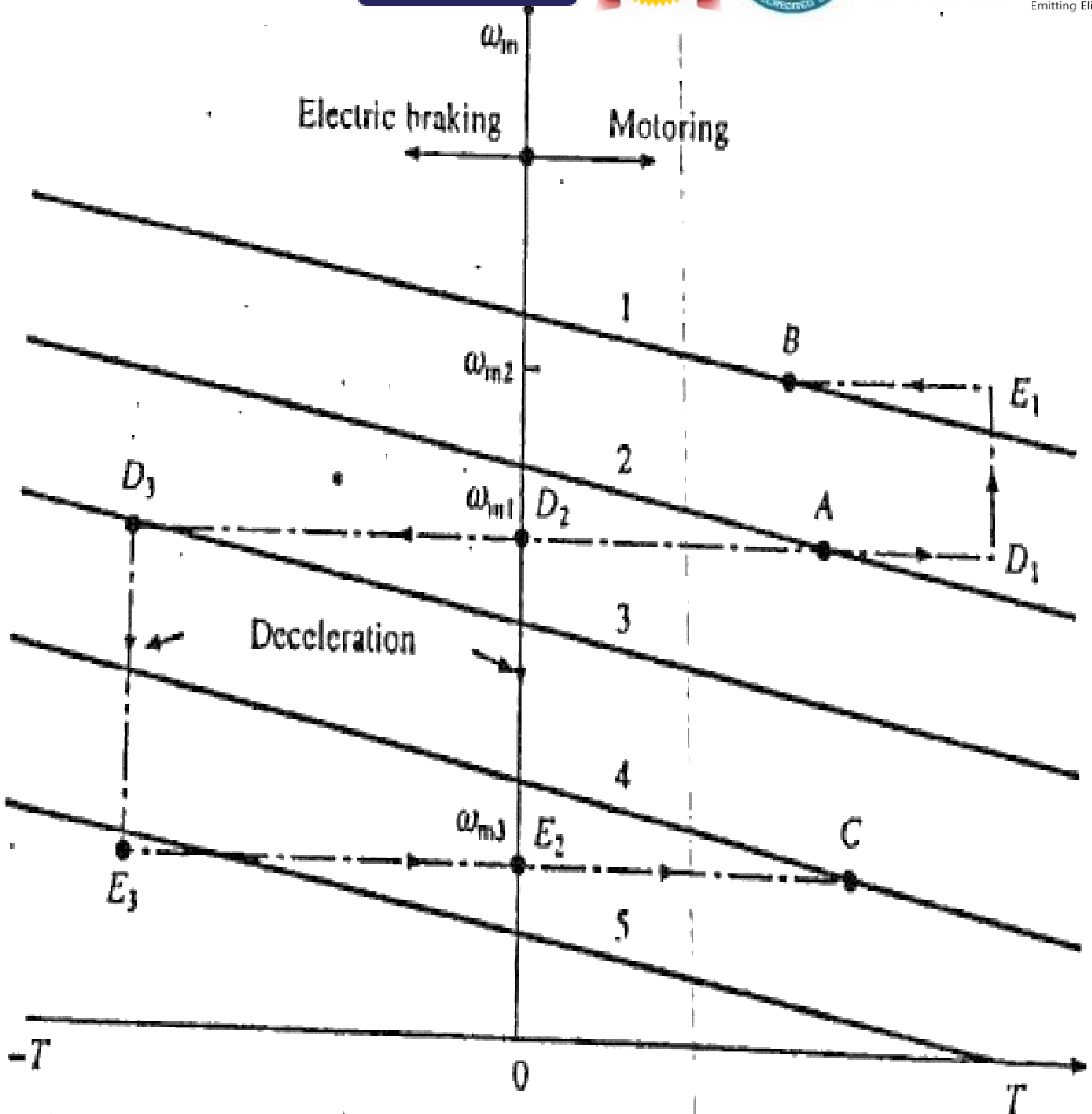


Fig. 3.2 Speed transition paths (1 to 5 are motor speed torque curves)

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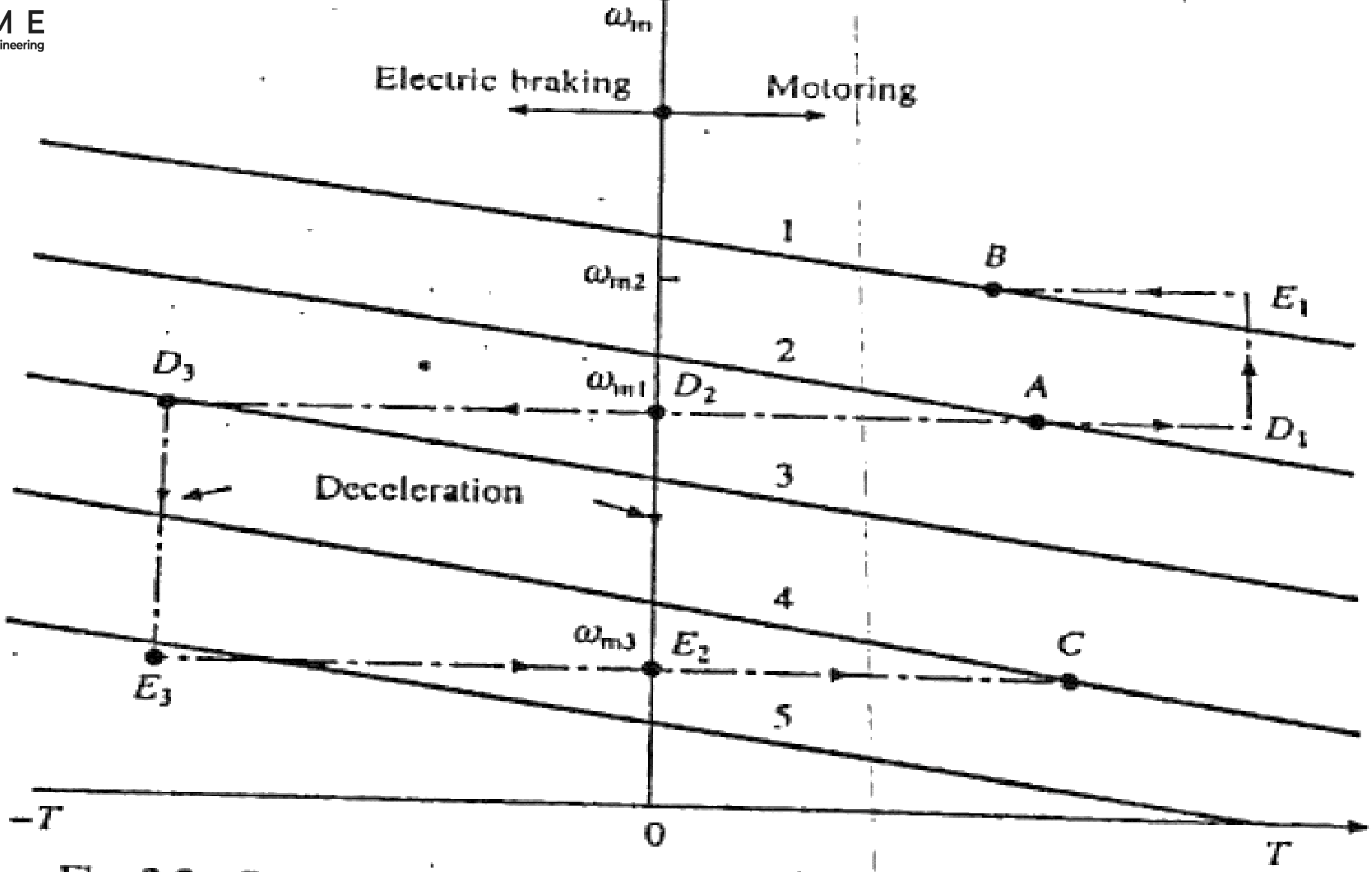


Fig. 3.2 Speed transition paths (1 to 5 are motor speed torque curves)

iii. Deceleration State:

- Motor operation in deceleration mode is required when a decrease in its speed is required. Deceleration occurs when load torque exceeds the motor torque.
- In few applications, load torque with substantial magnitude, enough deceleration can be achieved by simply reducing the motor torque to zero.
- In applications, load torque without substantial magnitude or where simply reducing the motor torque to zero does not provide enough deceleration, **mechanical brakes** may be used.
- Alternatively, **electric braking** may be employed. Now both motor and the load torque oppose the motion, thus producing larger deceleration.
- During electric braking motor current tends to exceed the safe limit. Current is restricted within the safe limit.
- Figure shows paths followed during transition from point A at speed ω_{m1} to point C at a **lower speed ω_{m3}**. When deceleration is carried out using electric braking at a constant braking torque, the operating point moves along the path AD_3E_3C

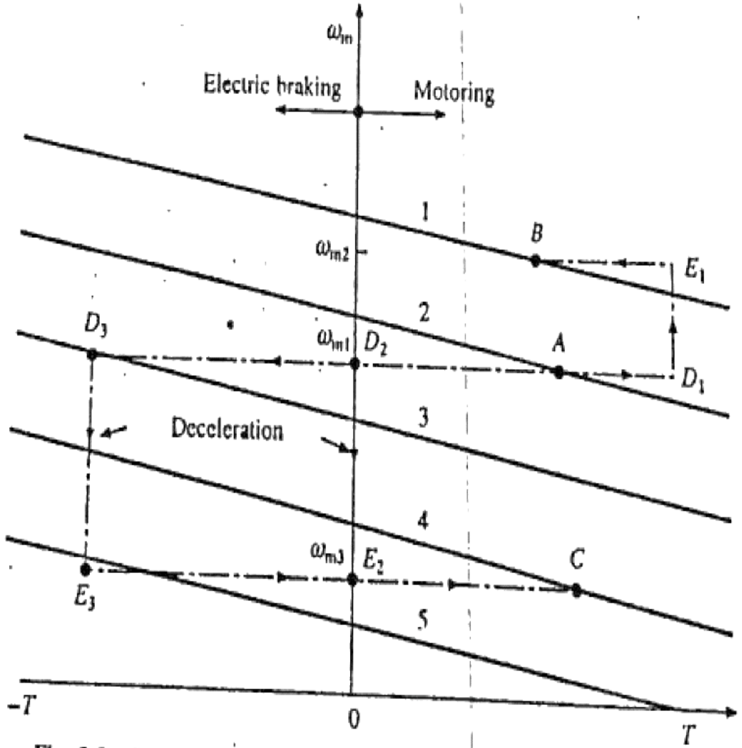


Fig. 3.2 Speed transition paths (1 to 5 are motor speed torque curves)

- When sufficient load torque is present or when mechanical braking is used the operation takes place along the path AD_2E_2C.
- Stopping is a special case of deceleration where the speed of a running motor is changed to zero.

Speed Control and Drive Classifications:

- **Constant Speed** or **Single Speed Drives**- Drives where the driving motor runs at a nearly fixed speed.
- **Multi-speed drives-** are those which operate at discrete speed settings.
- **Variable Speed Drives**- Drives needing stepless change in speed and multispeed drives
- **Multi-motor drive** -When a number of motors are fed from a common converter, or when a load is driven by more than one motor.
- **Constant Torque Mode -A variable speed drive-** also called as **constant torque drive,** if the drive's maximum torque capability does not change with a change in speed setting. It must be noted that the term **'Constant Torque'** refers to maximum torque capability of the drive and not to the actual output torque, which may vary from no load to full load torque.
- The **Constant Power Drive** and **Constant Power Mode** (or region) are defined in the same way.
- Ideally it is desired that for a given speed setting, the motor speed should remain constant as load torque is changed from no load to full load.
- In practice, speed drops with an increase in the load torque.
- Quality of a speed control system is measured in terms of speed-regulation which is defined as

$$\text{Speed regulation} = \frac{\text{No load speed} - \text{Full load speed}}{\text{Full load speed}} \times 100\%$$

Closed Loop control of drives

- In closed loop system, the output of the system is feedback to the input.
- The closed loop system controls the electrical drive, and the system is self-adjusted.
- Feedback loops in an electrical drive may be provided to satisfy the following requirements.
  - ✓ **Enhancement of speed of torque**
  - ✓ **To improve steady-state accuracy**
  - ✓ **Protection**

- The main parts of the closed-loop system are the controller, converter, current limiter, current sensor, etc.
- The converter converts the variable frequency into fixed frequency and vice-versa.
- The current limiter limits the current from rising above the maximum set value.
- The different types of closed loop configuration are explained below.
  - ❖Current Limit Control
  - ❖Closed-Loop Torque Control
  - ❖Closed-Loop Speed Control
  - ❖Closed-Loop Speed Control of Multi Motor Drives

1. Current Limit control

- This scheme is used to limit the converter and motor current below a safe limit during the transient operation.
- The system has a current feedback loop with a threshold logic circuit.
- The logic circuit protects the system from a maximum current.
- If the current is raised above maximum set value due to a transient operation, the feedback circuit becomes active and force the current to remains below the maximum value.
- When the current become normal, the feedback loop remains inactive.

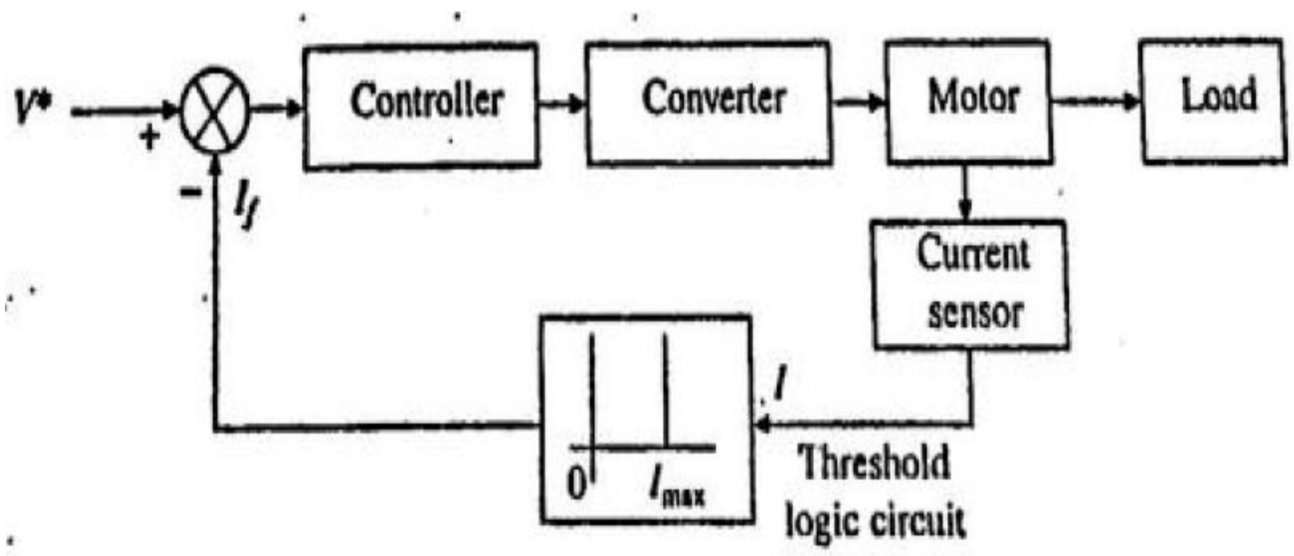


Fig. 3.3 Current limit control

ii. Closed-Loop Torque Control

- Such types of loop are used in battery powered vehicles, rails, and electric trains.
- The reference torque T* is set through the accelerator, and this T* follows by the loop controller and the motor.
- The speed of the drive is controlled by putting pressure on the accelerator.

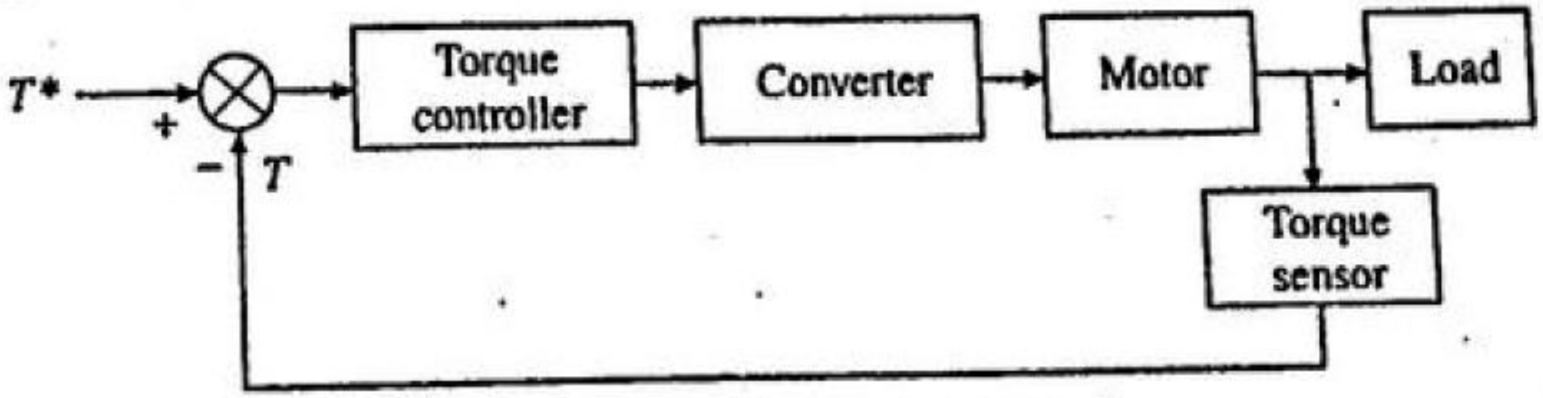


Fig. 3.4 Closed-loop torque control

iii. Closed-Loop Speed Control

- The block diagram of the closed loop speed control system is shown in the figure.
- This system uses an inner control loop within an outer speed loop.
- The inner control loop controls the motor current and motor torque below a safe limit.
- Consider a reference speed ω^*_m which produces a positive error $\Delta \omega^*_m$. The speed error is operated through a speed controller and applied to a current limiter which is overloaded even for a small speed error.
- The current limiter set current for the inner current control loop. Then, the drive accelerates, and when the speed of the drive is equal to the desired speed, then the motor torque is equal to the load torque. This, decrease the reference speed and produces a negative speed error.
- When the current limiter saturates, then the drive becomes de-accelerate in a braking mode.
- When the current limiter becomes desaturated, then the drive is transferred from braking to motoring.

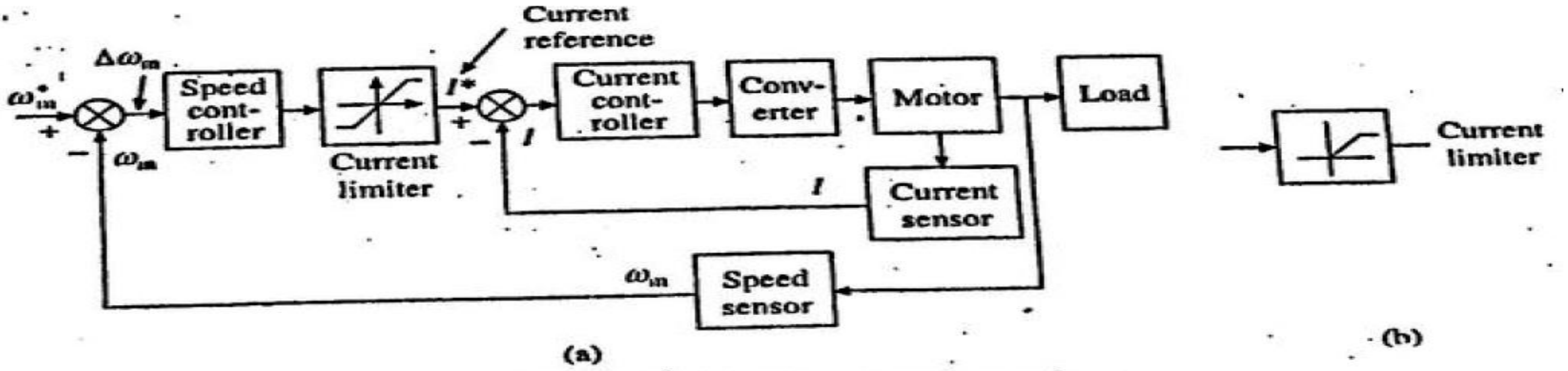
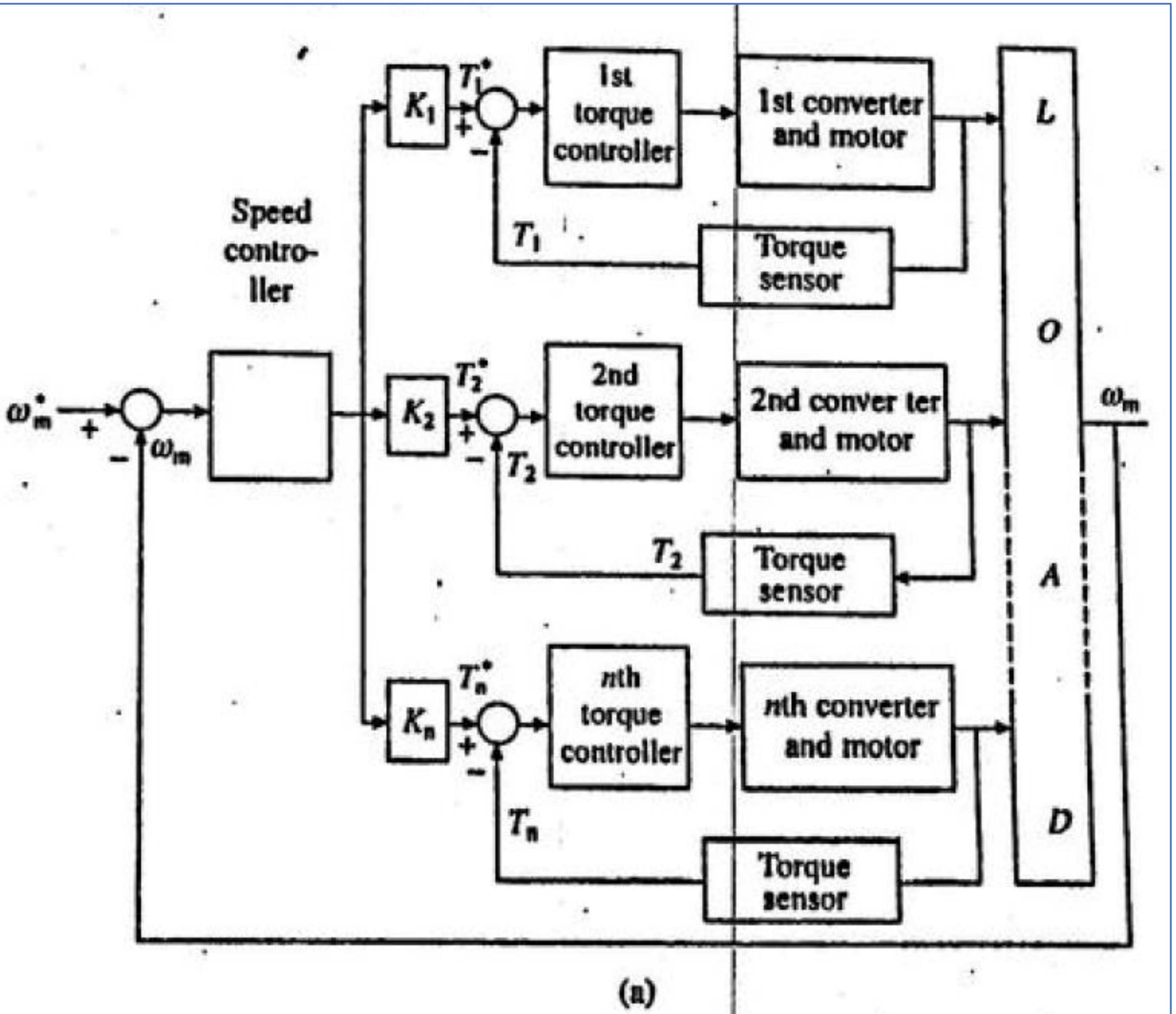


Fig. 3.5 Closed-loop speed control

iv. Closed-Loop Speed Control of Multi Motor Drives

- In such type of drive, the load is shared between the several motors.
- In this system, each section has its own motor which carries most of its load.
- The rating of the motor is different for the different type of load, but all the motor run at the same speed.
- If the torque requirement of each motor is fulfilled by its own driving motor, then the driving shaft has to carry only small synchronizing torque.
- In a locomotive, because of different amount of wear and tear the wheel of the locomotive revolve at the different speed. Thus, the driving speed of the vehicle also vary.
- Along with speed, it is also essential that the torques are shared equally between the various motor; otherwise, the one motor is fully loaded and another, is under loaded.
- Thus, the rated locomotive torque will be less than the sum of the individual motor torque rating.



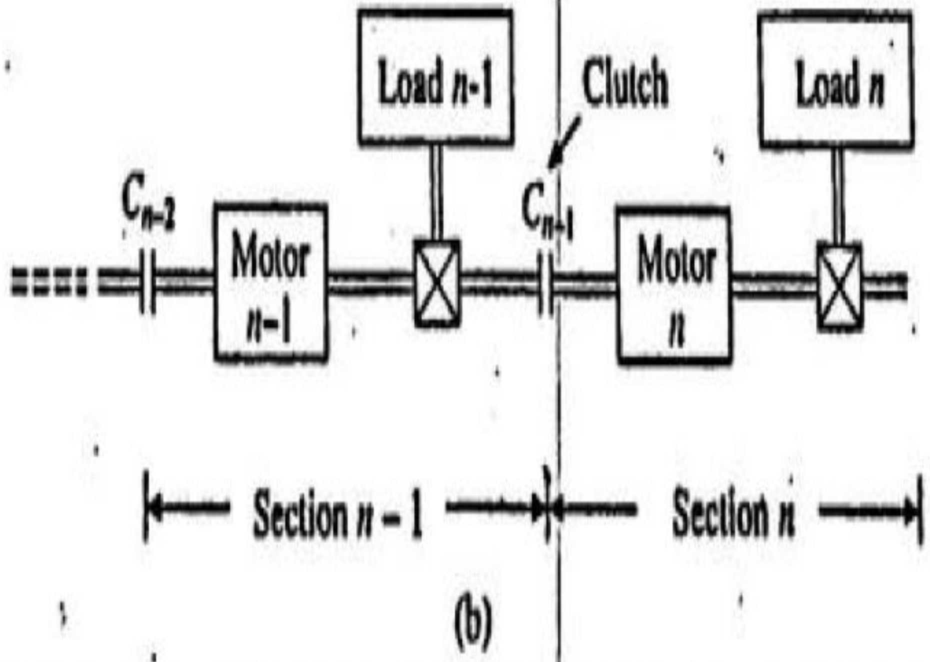


Fig. 3.6 Multi-motor drive with mechanically coupled loads or common drive shaft: (a) closed loop system, (b) mechanical coupling

End of Module-1

Components of Load Torques

Load torque T_l can be further divided into following components:
(i) Friction torque T_F: Friction will be present at the motor shaft and also in various parts of the load. T_F is equivalent value of various friction torques referred to the motor shaft.
(ii) Windage torque, T_w: When a motor runs, wind generates a torque opposing the motion. This is known as windage torque.
(iii) 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 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

Variation of friction torque with speed is shown in Fig. 2.6(a). 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 resolved into three components (see Fig. 2.6(b)). Component T_V which varies linearly with speed is called viscous friction and is given by:

$$T_v = B\omega_m$$

where B is the viscous friction coefficient.

Another component Tc, which is independent of speed is known as Coulomb friction. Third component Ts accounts for additional torque present at standstill. Since Ts is present only at standstill it is not taken into account in the dynamic analysis.

Windage torque Tw, which is proportional to speed squared, is given by

$$T_w = C\omega_m^2$$

where C is a constant.

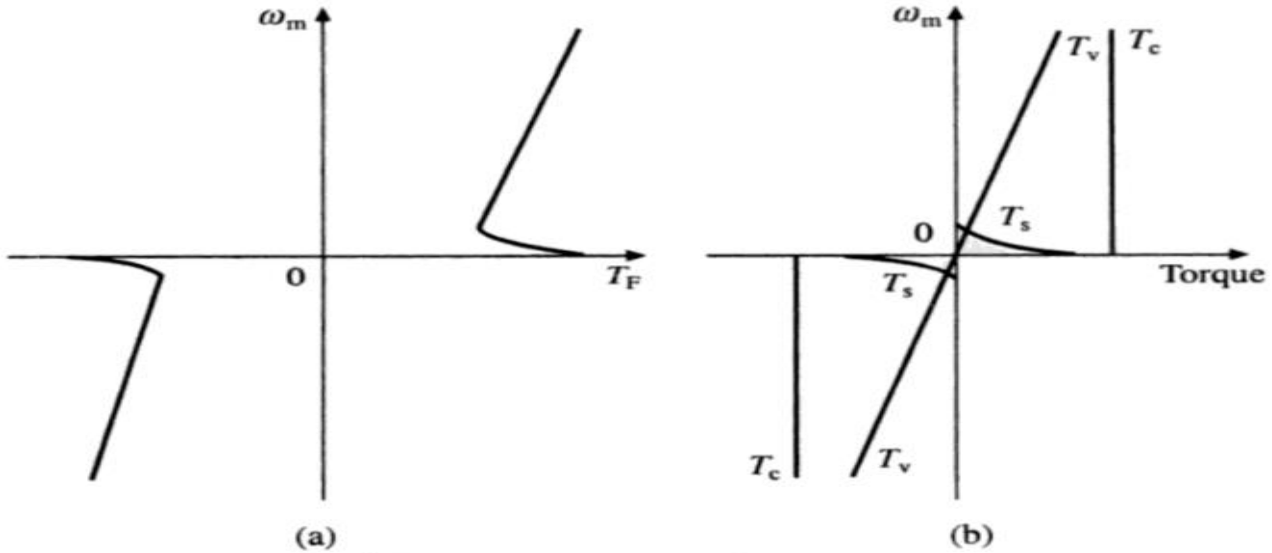


Fig. 2.6 Friction torque and its components

For finite speed $$T_l = T_L + B\omega_m + T_c + C\omega_m^2$$

In many applications $(T_c + C\omega_m^2)$ is very small compared to $B\omega_m$ and negligible compared to T_L. In order to simplify the analysis, term $(T_c + C\omega_m^2)$ is approximately accounted by updating the value of viscous friction coefficient, B. With this approximation, from Eq. (2.2)

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

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

$$T_e = K_e\theta_e \tag{2.20}$$

where θ_e is the torsion angle of coupling (radians) and K_e the rotational stiffness of the shaft (N-m/rad).

where $(dT/d\omega_m)$ and $(dT_l/d\omega_m)$ are respectively slopes of the steady-state speed-torque curves of motor and load at operating point under consideration. Substituting Eqs. (2.27) and (2.28) into (2.26) and rearranging the terms yields

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

(2.2[illegible])

(a) Converters

When a power modulator performs function (iii), it can classified as converter.

Usually, a converter also performs function (i) in addition to (ii). Depending on the circuit, it may also be able to perform function (iv) of the power modulator. Need for a converter arises

when nature of the available electrical IX)wer is different than what is required for the motor.

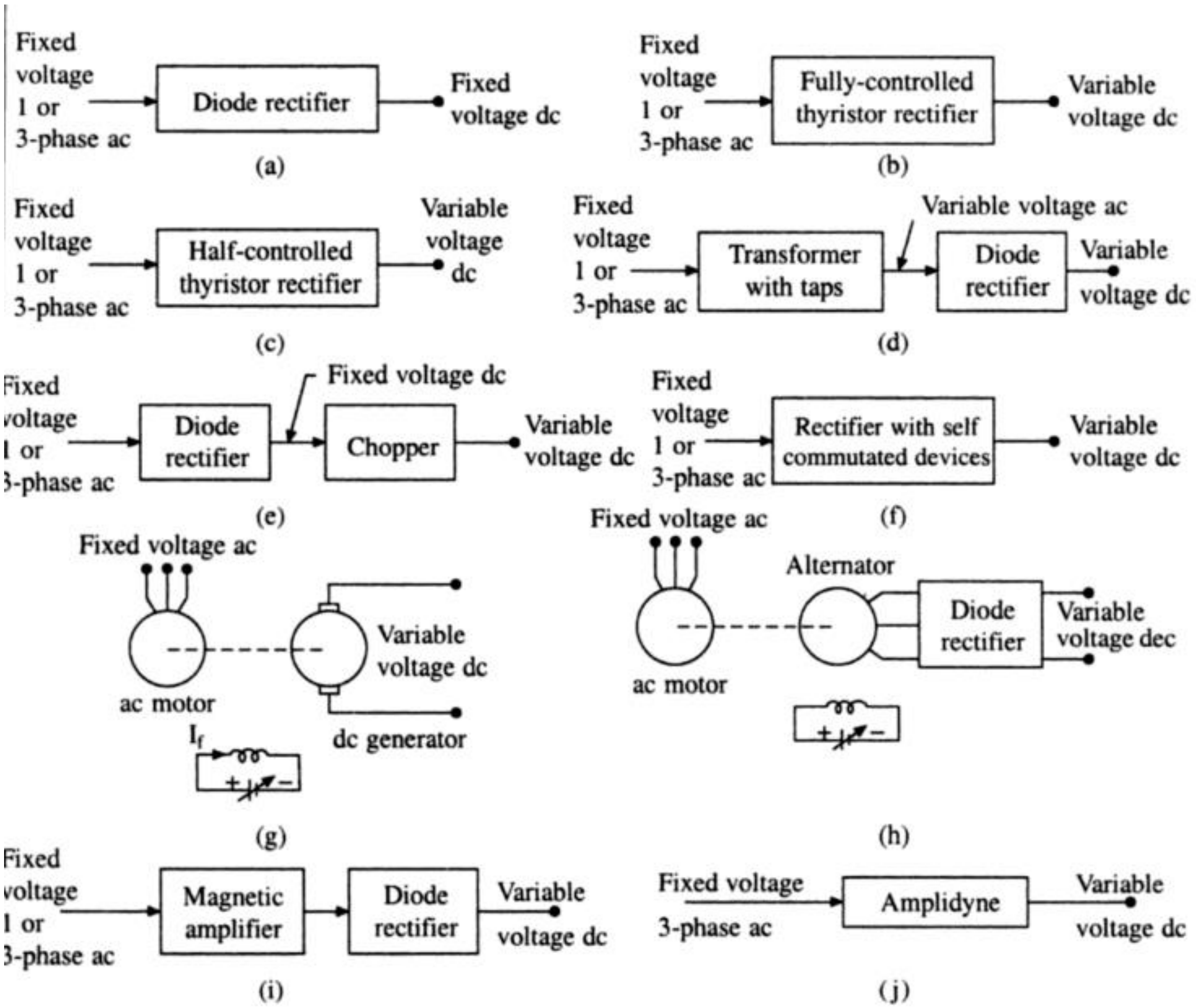
Power sources are usually of the following types:

(i) Fixed voltage and fixed frequency ac

(ii) Fixed voltage dc.

For the control of dc motors one requires variable dc voltage whereas for ac motors one requires either fixed frequency variable voltage ac or variable frequency variable voltage ac.

These motor requirements are met by the following converters and their combinations:


Fixed voltage 1 or 3-phase ac
Diode rectifier
Fixed voltage dc
(a)
Fixed voltage 1 or 3-phase ac
Fully-controlled thyristor rectifier
Variable voltage dc
(b)
Fixed voltage 1 or 3-phase ac
Half-controlled thyristor rectifier
Variable voltage dc
(c)
Fixed voltage 1 or 3-phase ac
Transformer with taps
Variable voltage ac
Diode rectifier
Variable voltage dc
(d)
Fixed voltage 1 or 3-phase ac
Diode rectifier
Fixed voltage dc
Chopper
Variable voltage dc
(e)
Fixed voltage 1 or 3-phase ac
Rectifier with self commutated devices
Variable voltage dc
(f)
Fixed voltage ac
ac motor
Variable voltage dc
dc generator
I_f
(g)
Fixed voltage ac
Alternator
ac motor
Diode rectifier
Variable voltage dec
(h)
Fixed voltage 1 or 3-phase ac
Magnetic amplifier
Diode rectifier
Variable voltage dc
(i)
Fixed voltage 3-phase ac
Amplidyne
Variable voltage dc
(j)

Load Equalisation

- Load equalisation is the process of smoothing the fluctuating load.
- The fluctuate load draws heavy current from the supply during the peak interval and also cause a large voltage drop in the system due to which the equipment may get damage.
- In load equalisation, the energy is stored at light load, and this energy is utilised when the peak load occurs.
- Thus, the electrical power from the supply remains constant.
- The load fluctuation mostly occurs in some of the drives.
- For example, in a pressing machine, a large torque is required for a short duration.
- Otherwise, the torque is zero. Some of the other examples are a rolling mill, reciprocating pump, planning machines, electrical hammer, etc.
- In electrical drives, the load fluctuation occurs in the wide range.
- For supplying the peak torque demand to electrical drives the motor should have high ratings, and also the motor will draw pulse current from the supply.
- The amplitude of pulse current gives rise to a line voltage fluctuation which affected the other load connected to the line.

l. ac to dc Converters:

ac-dc converters are shown in Fig. 1.2. The converter Of Fig. 1.2(a) is used to get dc 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 dc 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 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 dc voltage of either polarity with positive current. However, converter of Fig. I .2(c) is a single-quadrant converter (positive voltage and current). Converters of Fig. I .2(b) and (c) produce harmonics both on dc and ac side and have low power factor for low dc voltages. The converters of Fig. 1.2(d), (e) and (f) at unity fundamental power factor. The output voltage in converter 1.2(d) is changed by applying mechanical force. Few discrete steps of dc voltage can only be obtained. In converter of Fig. 1.2(e)

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.