ATME COLLEGE OF ENGINEERING

13th KM Stone, Bannur Road, Mysore - 570 028

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

NOTES

COURSE: Industrial Drives and Applications

COURSE CODE:BEE702

SEMESTER:VII

INSTITUTIONAL VISION AND MISSION

VISION:

- Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources.

MISSION:

- To keep pace with advancements in knowledge and make the students competitive and capable at the global level.
- To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torchbearers of tomorrow's society.
- To strive to attain ever-higher benchmarks of educational excellence.

Department Vision and Mission

Vision:

To produce Electrical & Electronics Engineers through greatest quality of technical education, technical skill training and intellectual capacity building of individuals.

Mission:

- To provide knowledge to students that builds a strong foundation in the basic principles of electrical engineering, problem solving abilities, analytical skills, soft skills and communication skills for their overall development.
- To offer outcome based technical education.
- To encourage faculty in training & development and to offer consultancy through research & industry interaction.

Program Educational Objectives (PEOs)

PEO1:

To produce competent and ethical Electrical and Electronics Engineers who will exhibit the necessary technical and managerial skills to perform their duties in society.

PEO2:

To make Graduates continuously acquire and enhance their technical and socio-economic skills.

PEO3:

To aspire Graduates on R&D activities leading to offering solutions and excel in various Career Paths

PEO4:

To produce quality engineers who have the capability to work in teams and contribute to real time projects.

Program Outcomes (POs)

Engineering Graduates will be able to:

PO1: Engineering Knowledge: Apply the knowledge of mathematics, science, engineering fundamentals and an engineering specialization to the solution of complex engineering problems.

PO2: Problem Analysis: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences.

PO3: Design / Development of solutions: Design solutions for complex engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and environmental considerations.

PO4: Conduct investigations of complex problems: Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

PO5: Modern tool usage: Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to complex engineering activities with an understanding of the limitations.

PO6: The engineer and society: Apply reasoning informed by the contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to the professional engineering practice.

PO7: Environment and sustainability: Understand the impact of the professional engineering solutions in societal and environmental contexts, and demonstrate the knowledge of, and need for sustainable development.

PO8: Ethics: Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9: Individual and team work: Function effectively as an individual and as a member or leader in diverse teams, and in multidisciplinary settings.

PO10: Communication: Communicate effectively on complex engineering activities with the engineering community and with society at large, such as, being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.

PO11: Project management and finance: Demonstrate knowledge and understanding of the engineering management principles and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO12: Life-long learning: Recognize the need for and have the preparation and ability to engage in independent and lifelong learning in the broadest context of technological change.

Program Specific Outcomes (PSO' s)

PSO1: Apply the concepts of Electrical & Electronics Engineering to evaluate the performance of power systems and also to control industrial drives using power electronics.

PSO2: Demonstrate the concepts of process control for Industrial Automation, design models for environmental and social concerns and also exhibit continuous self- learning.

Module-1: Electric Drives

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

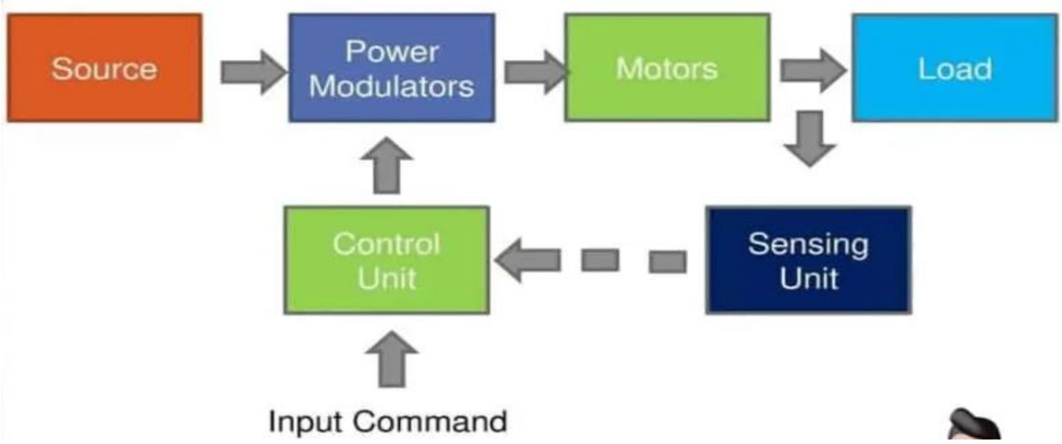
Drive: Systems employed for motion control are called drives.

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.

Electric Drive: Drives employing electric motors are known as 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



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. These are the devices which alter the nature or frequency as well as changes the intensity of power to control electrical drives.

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.

Power Modulators Classification

power modulators can be classified into three types,

a) Converters,
b) Variable impedance circuits,
c) Switching circuits.

a) Converters:

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:*

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.

ii. *AC regulators*

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*

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.

iv. ***Inverters***

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***

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.

b) <u>Variable Impedance circuits:</u>

- 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.

c) <u>Switching circuits:</u>

- 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.

3. <u>Sensing Unit</u>

- Speed Sensing (From Motor for closed loop operation)
- Torque Sensing
- Position Sensing
- Current sensing and Voltage Sensing from Lines or from motor terminals from Load

- Torque sensing
- Temperature Sensing

4. 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.

5. Motors:

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.

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

Advantage of Electrical drives.

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.

Choice (or) Selection of Electrical Drives

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

1**. *Steady State Operating conditions requirements***: Nature of speed torque characteristics, speed regulation, speed range, efficiency, duty cycle, quadrants of operation, speed fluctuations if any, ratings etc

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

3.***Requirements related to the source:*** Types of source and its capacity, magnitude of voltage, voltage fluctuations, power factor, harmonics and their effect on other loads, ability to accept regenerative power

4. ***Capital and running cost*:** maintenance needs life.

5. ***Space and weight restriction***

6. ***Environment and location.***

7. ***Reliability.***

Classification of Electric Drives

- According to Mode of Operation
  - Continuous duty drives
  - Short time duty drives
  - Intermittent duty drives

- According to Means of Control
    - Manual
    - Semi automatic
    - Automatic
- According to Number of machines
    - Individual drive
    - Group drive
    - Multi-motor drive
- According to Dynamics and Transients
    - Uncontrolled transient period
    - Controlled transient period
- According to 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 contro

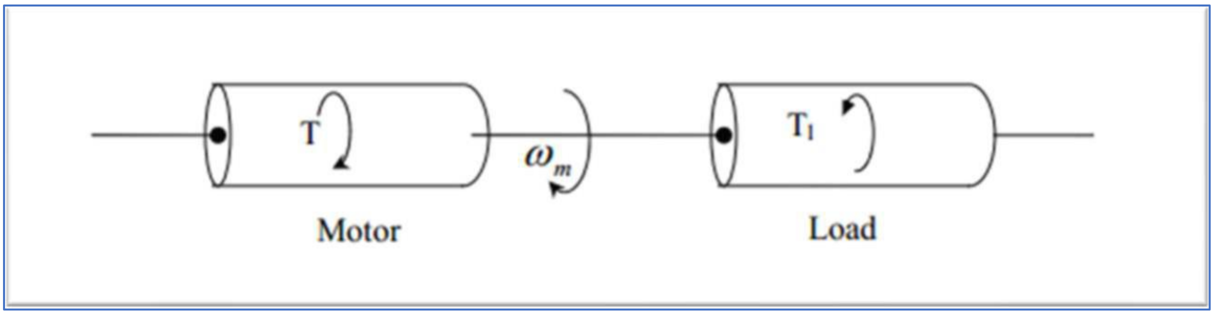
Applications

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

Module-1: Dynamics of Electrical Drives

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.



Where,

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

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

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

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

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

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

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

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.

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.

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

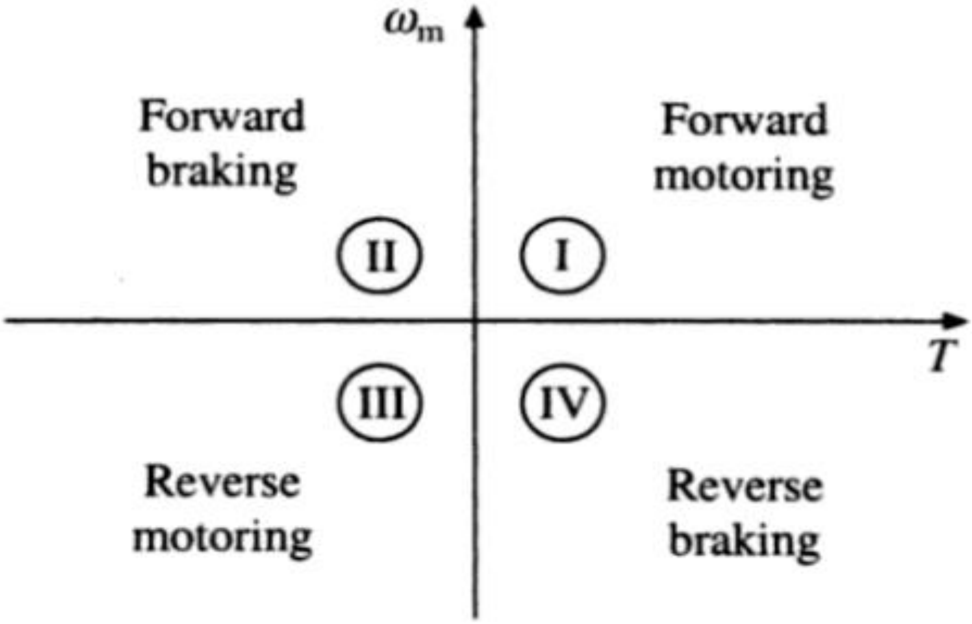


Fig. 2.2 Multiquadrant-operation of drives

- 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.
- 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.

Orientation of a hoist in four quadrants

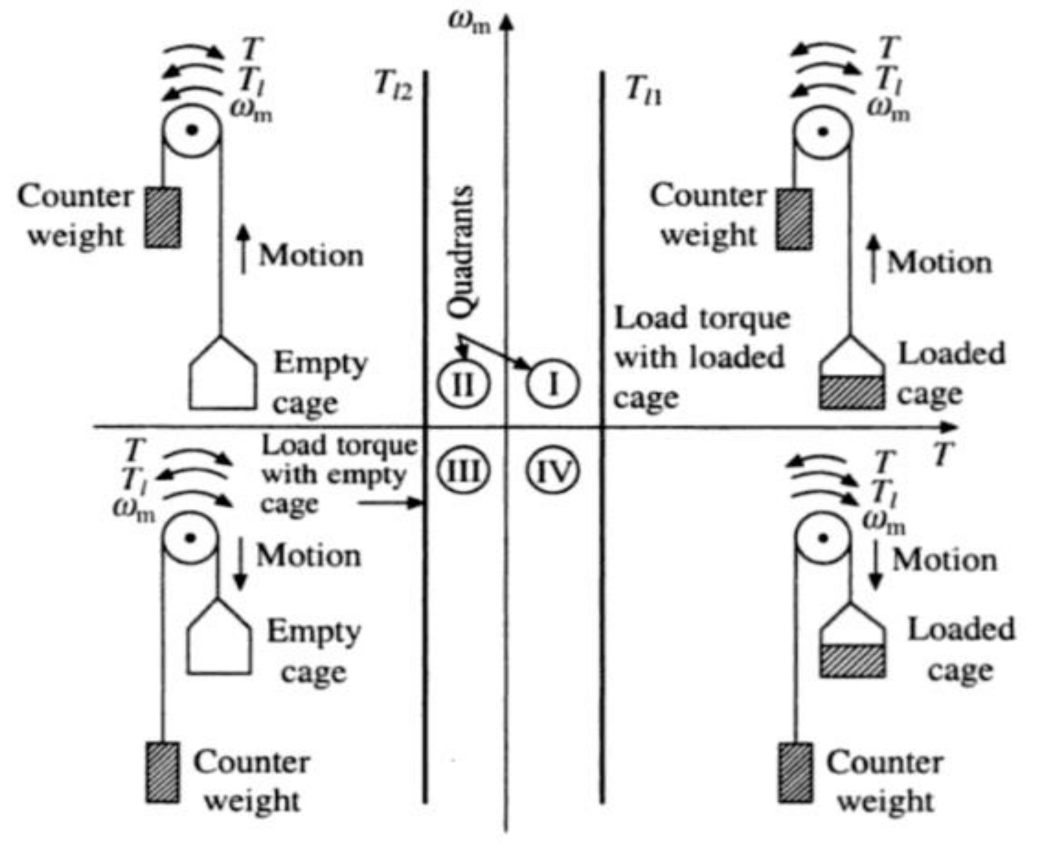


Fig. 2.3 Four quadrant operation of a motor driving a hoist load

- 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.
- 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.
- 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
- The **quadrant I** operation of a hoist requires the movement of the cage upward, which corresponds to the positive motor speed which is in anticlockwise direction here. This motion will be obtained if the motor produces positive torque in anticlockwise direction equal to the magnitude of load torque T_{L1}. Since developed motor power is positive, this is forward motoring operation.
- **Quadrant IV** operation is obtained when a loaded cage is lowered. Since the weight of a loaded cage is higher than that of a counter weight, it is able to come down due to the gravity itself. In order to limit the speed of cage within a safe value, motor must produce a positive torque T equal to T_{L2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking.
- Operation in **quadrant II** is obtained when an empty cage is moved up. Since a counter weight is heavier than an empty cage, it is able to pull it up. In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{L2} in clockwise (negative) direction. Since speed is positive and 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.

Equivalent Values of Drive Parameters

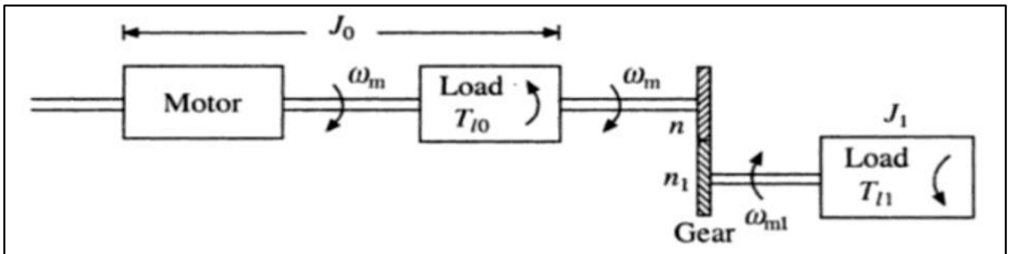
- Different parts of a load may be coupled through different mechanisms, such as gears, V-belts and crankshaft. These parts may have different speeds and different types of motions such as **rotational and translational.**
- The following presents the methods of finding the equivalent moment of inertia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

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

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

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

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)

$$T_l = T_{l0} + \frac{a_1 T_{l1}}{\eta_1} \quad (2.7)$$

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

$$J = J_0 + a_1^2 J_1 + a_2^2 J_2 + \ldots + a_m^2 J_m \quad (2.8)$$

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

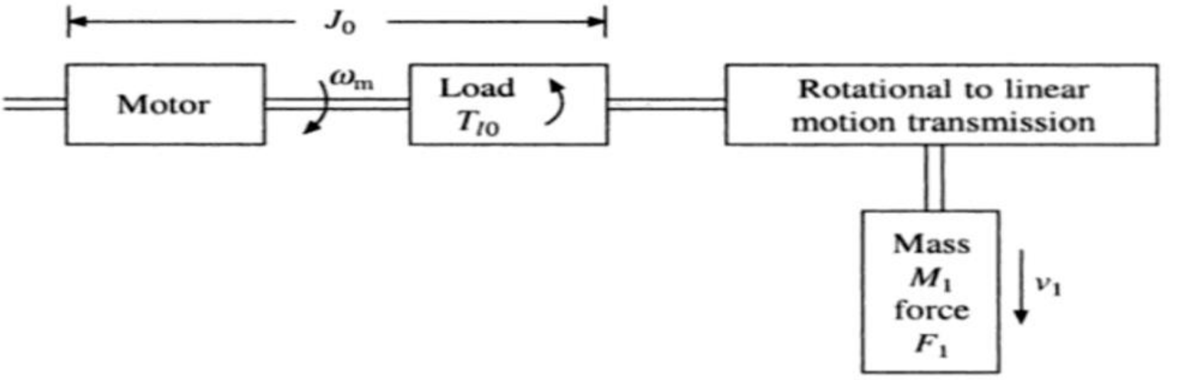
$$T_l = T_{l0} + \frac{a_1 T_{l1}}{\eta_1} + \frac{a_2 T_{l2}}{\eta_2} + \ldots + \frac{a_m T_{lm}}{\eta_m} \quad (2.9)$$

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_l (kg), V_l (m/sec) and F_l (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

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

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

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

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

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

and

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

Classification of Load Torques

1. Active load torques
2. Passive load torques

1. **Active load torques:** 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. **Passive load torques**: 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

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; also depends on the modes of operations of load.

Friction Torque with Speed:

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.
- Hence friction torque is resolved into 3 components.
  1. 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.
  2. Another component **T_C,** which is independent of is known as Coulomb friction.

iii. Third component **Ts** accounts for additional torque present at standstill.
iv. Windage torque **Tw**, which is proportional to speed squared, is given by

$$T_w = C\omega_m^2$$

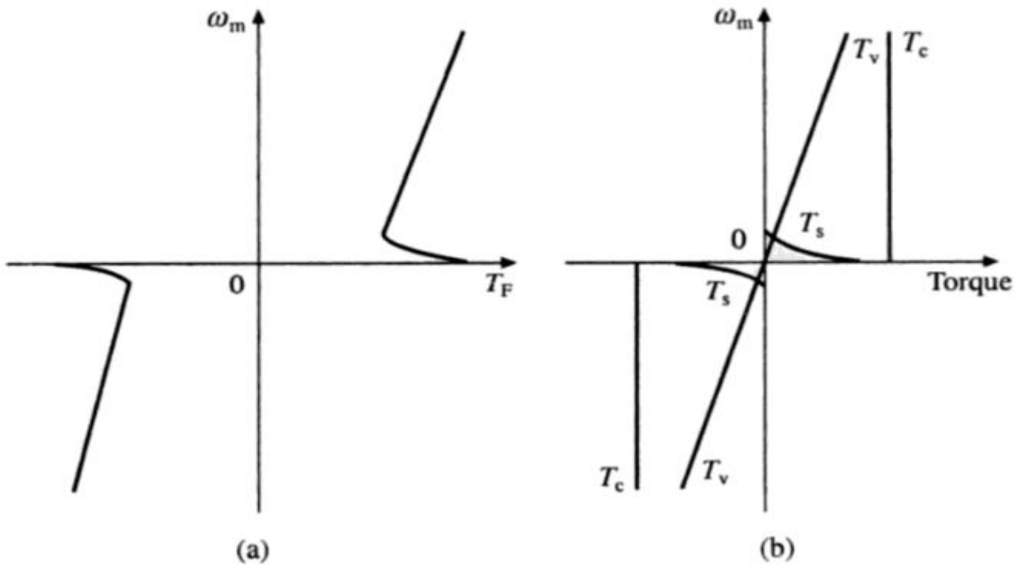


Fig. 2.6 Friction torque and its components

Therefore from above equations:

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

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

Nature and Classification of Load Torques

The nature of load torque depends on particular application.

Fig(a) Load torque is proportional to square of the speed: Fans, compressors, aeroplanes, centrifugal pumps, ship-propellors, coilers, high speed hoists, traction etc,

Fig (b) In a high speed hoist, viscous friction and windage also have appreciable magnitude, in addition to gravity, thus giving the speed-torque curve shown.

Fig (c) Nature of speed-torque characteristic of a traction load when moving on a levelled ground is shown.

Fig. 2.7(d). Hyperbolic in nature as shown. Because of its heavy mass, the stiction is large. Near zero speed, net torque is mainly due to stiction. Because of large stiction and need for accelerating a heavy mass, the motor torque required for starting a train is much larger than what is required to run it at full speed.

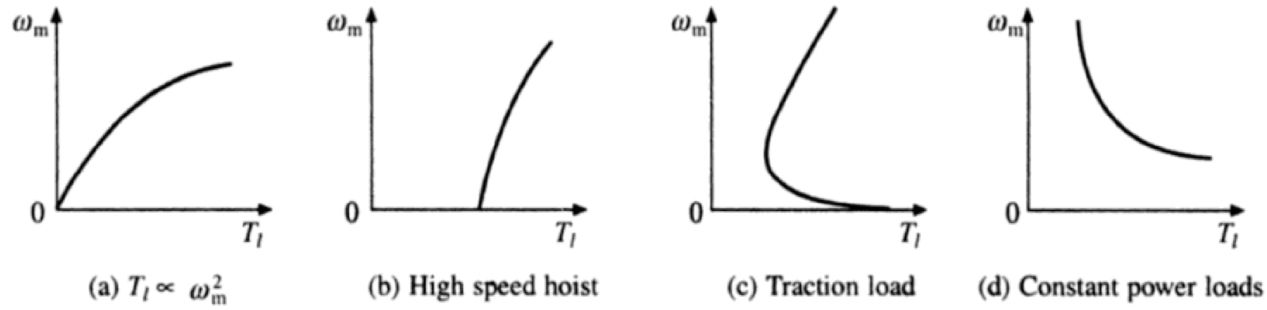


Fig. 2.7 Steady state load torque speed curves

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.

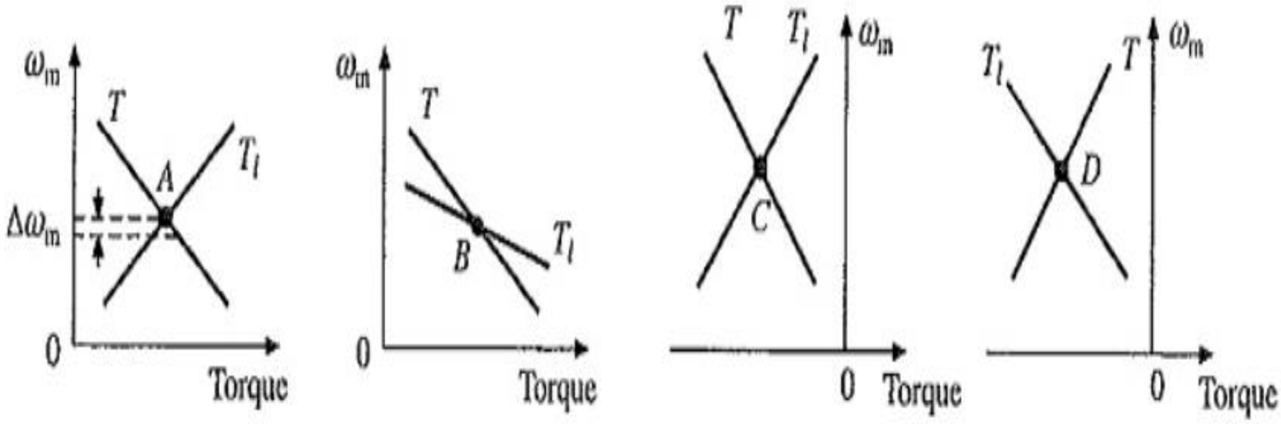
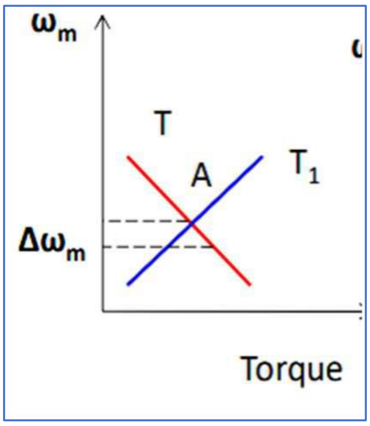


Fig. 2.9 Points A and C are stable and B and D are unstable

- 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

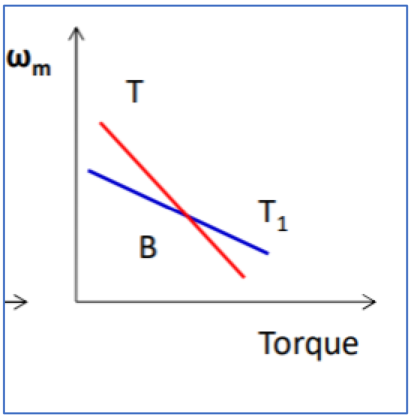
- The equilibrium point A will be termed as stable when the **operation will be restored** to its initial position after a small departure from it due to a disturbance in the motor or load.



- 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,

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

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

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

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

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

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:

i. Motor rating has to be high.
ii. 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.
iii. 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 mounting a **flywheel** on the motor shaft in non-reversible drives.

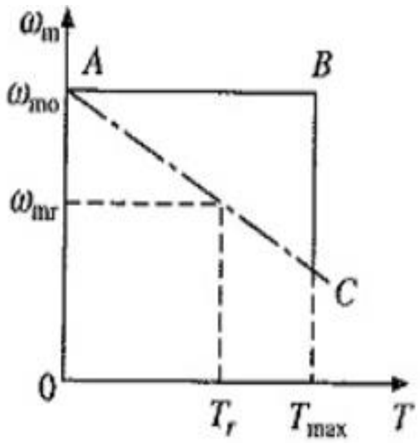


Fig. 2.10 Shapes of motor speed torque curves for fluctuating roads

- 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.

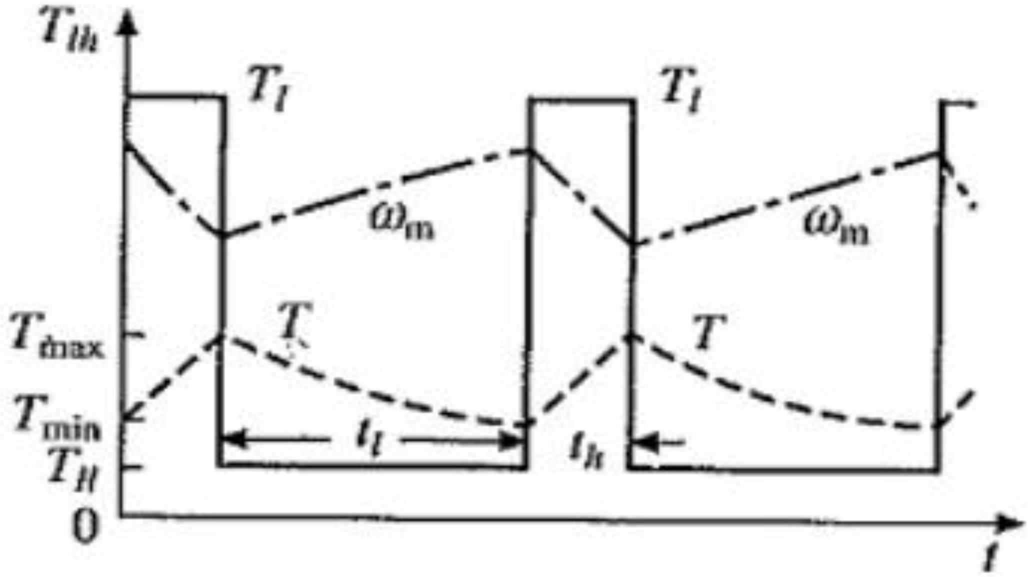


Fig. 2.11

T_{lh}*- *High load torque*,** ***T_{ll}*- *Light load torque

t_h*-*High load period duration*, *t_l*- *light load period duration

- 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.

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).

Control of Drives

Modes of Operation:

An electrical drive operates in three modes:

- **i.** Steady state
- **ii.** Acceleration including Starting
- **iii.** Deceleration including Stopping

i. Steady state

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

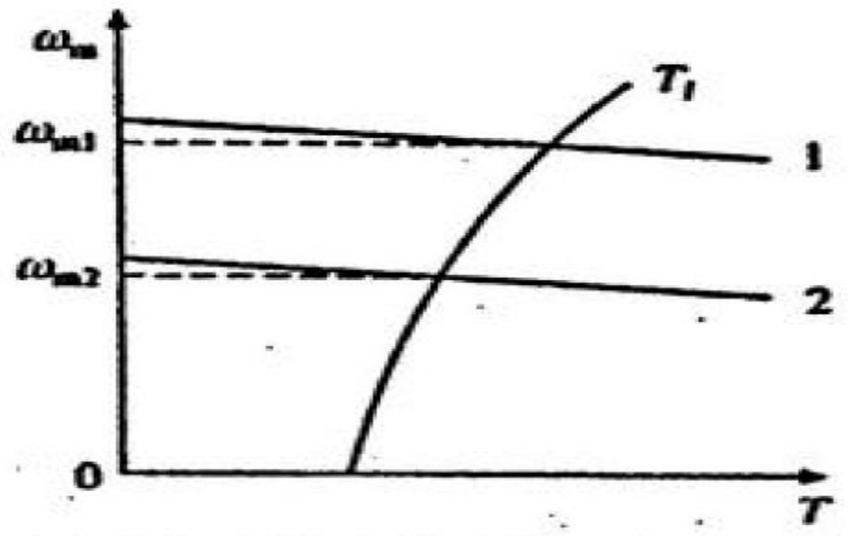


Fig. 3.1 Principle of speed control

- 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.

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.

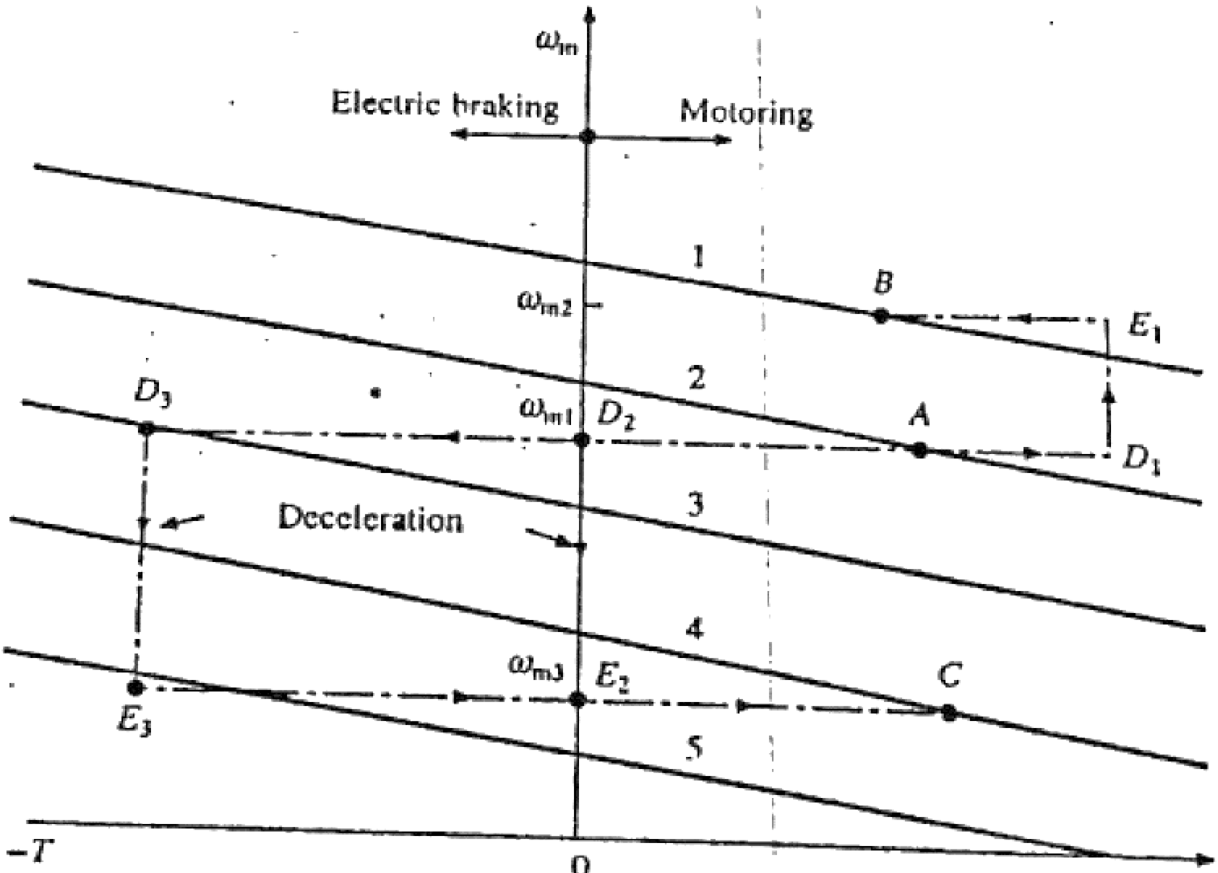


Fig. 3.2 Speed transition paths (1 to 5 are motor speed torque curves)

- 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.

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
- 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.
  - i. Current Limit Control
  - ii. Closed-Loop Torque Control
  - iii. Closed-Loop Speed Control
  - iv. Closed-Loop Speed Control of Multi Motor Drives

1. Current Limit control

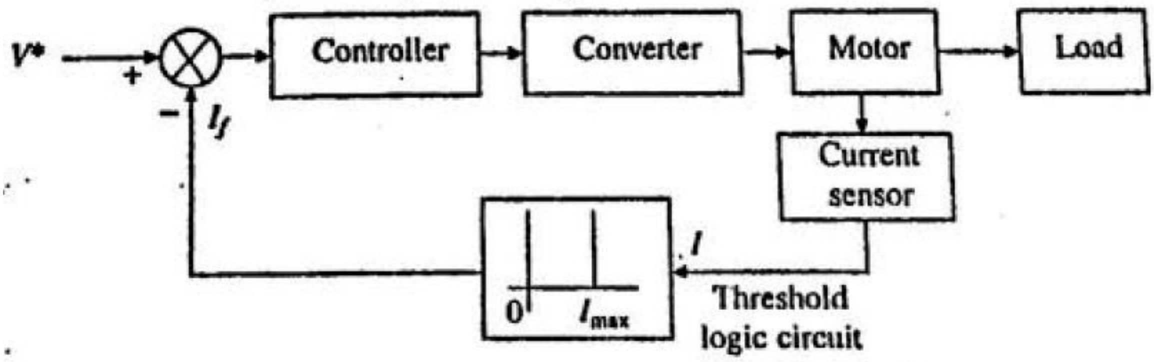


Fig. 3.3 Current limit control

- 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.

ii. Closed-Loop Torque Control

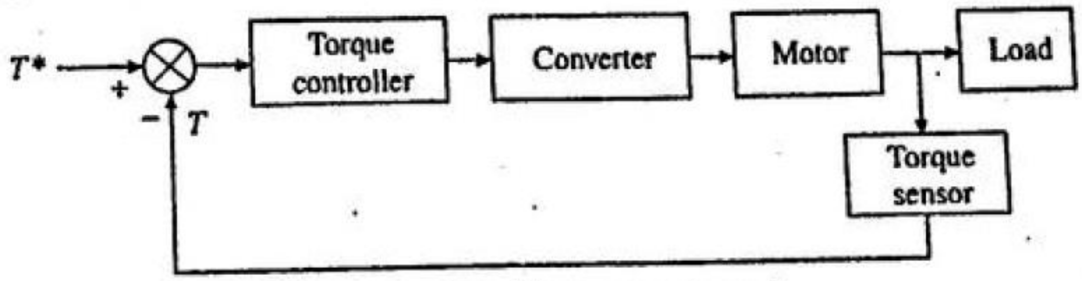


Fig. 3.4 Closed-loop torque control

- 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.

iii.Closed-Loop Speed Control

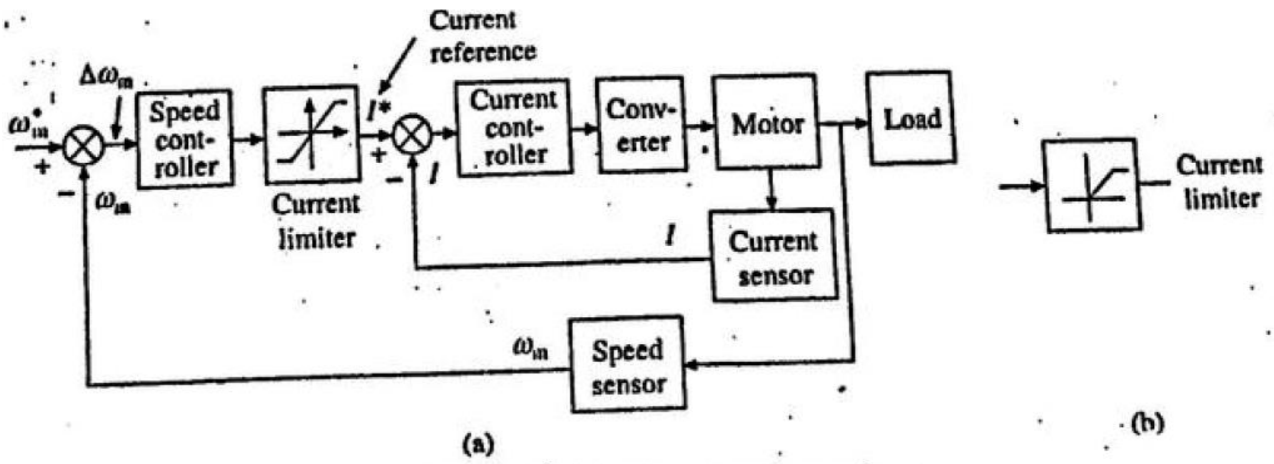


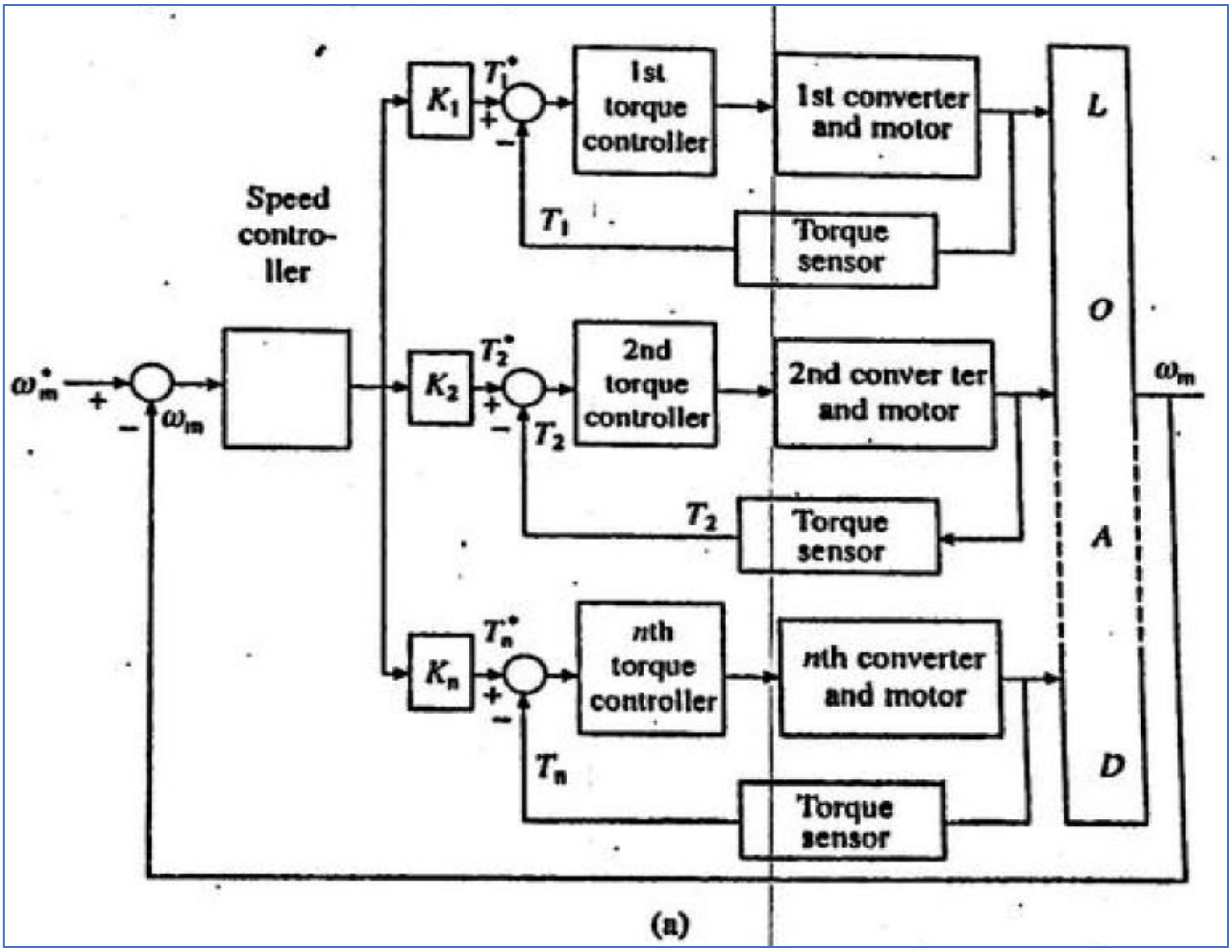
Fig. 3.5 Closed-loop speed control

- 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.

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.



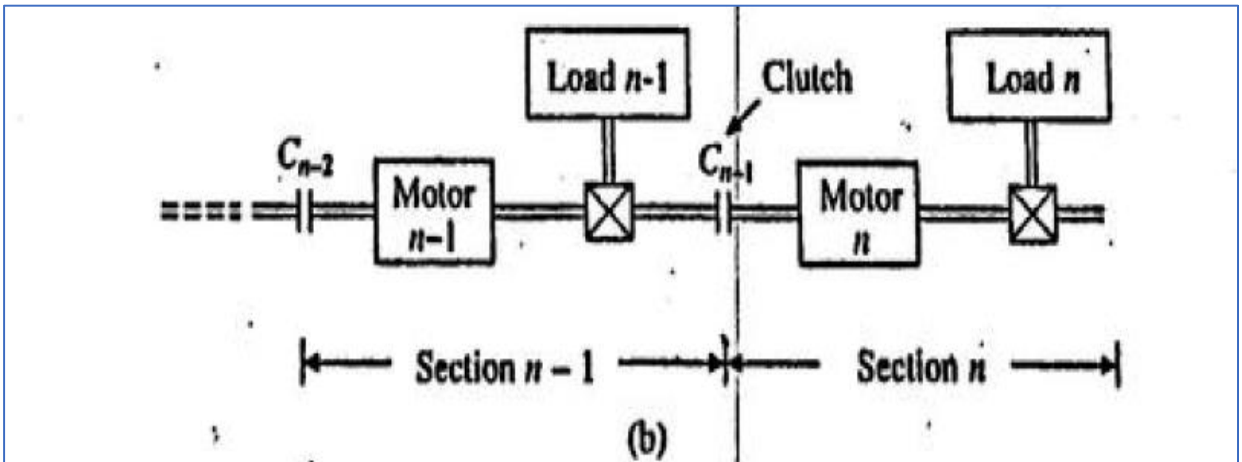


Fig. 3.6 Multi-motor drive with mechanically coupled loads or common drive shaft: (a) closed loop system, (b) mechanical coupling

Numericals:

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

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

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.

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)

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

Here no load speed $= \frac{500 \times 2\pi}{60} = 52.36$ 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)

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)

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

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