INDUSTRIAL DRIVES & APPLICATIONS

Subject Code	:	10EE74	IA Marks	:	25
No. of Lecture Hrs./ Week	:	04	Exam Hours	:	03
Total No. of Lecture Hrs.	:	52	Exam Marks	:	100

PART - A

UNIT - 1

AN INTRODUCTION TO ELECTRICAL DRIVES & ITS DYNAMICS: 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 equation, speed torque conventions and multiquadrant operation. Equivalent values of drive parameters, components of low torques, nature and classification of load torques, calculation of time and energy loss in transient operations, steady state stability, load equalization. **9 Hours**

UNIT - 2

SELECTION OF MOTOR POWER RATING: Thermal model of motor for heating and cooling, Classes of motor duty, determination of motor rating. **5 Hours**

UNIT - 3 & 4

D C MOTOR DRIVES:

(a) Starting braking, transient analysis, single phase fully controlled rectifier, control of dc separately excited motor, Single-phase half controlled rectifier control of dc separately excited motor.

(b) Three phase fully controlled rectifier control of dc separately excited motor, three phases half controlled rectifier control of dc separately excited motor, multiquadrant operation of dc separately excited motor fed form fully controlled rectifier. Rectifier control of dc series motor, chopper controlled dc drives, chopper chopper control of separately excited dc motor. Chopper control of series motor.

12 Hours

PART - B

UNIT - 5 & 6

INDUCTION MOTOR DRIVES:

(a) Operation with unbalanced source voltage and single phasing, operation with unbalanced rotor impedances, analysis of induction motor fed from non-sinusoidal voltage supply, starting braking, transient analysis.

(b) Stator voltage control variable voltage frequency control from voltage sources , voltage source inverter control, closed loop control, current source inverter control, current regulated voltage source inverter control, rotor resistance control, slip power recovery, speed control of single phase induction motors. **12 Hours**

UNIT - 7

SYNCHRONOUS MOTOR DRIVES: Operation form faced frequency supply, synchronous motor variable speed drives, and variable frequency control of multiple synchronous motors. Self-controlled synchronous motor drive employing load commutated thruster inverter. **10 Hours**

UNIT - 8

INDUSTRIAL DRIVES: Rolling mill drives, cement mill drives, paper mill dries and textile mill drives. **4 Hours**

TEXT BOOK:

1. **Fundamentals of Electrical Drives**"- G.K Dubey -2 Edition, 5th reprint Narosa publishing house

REFERENCE BOOKS:

1. **Electrical Drives**- N.K De and P.K. Sen- PHI, 2007
2. **A First Course On Electric Drives**- S.K Pillai-Wiley Eastern Ltd 1990.
3. **Power Electronics, Devices, Circuits and Industrial Applications**- V.R. Moorthi, "Oxford University Press, 2005.

CONTENTS

UNIT - 1

AN INTRODUCTION TO ELECTRICAL DRIVES & ITS DYNAMICS

- 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 equation
- Speed torque conventions and multiquadrant operation.
- Equivalent values of drive parameters, components of low torques
- Nature and classification of load torques
- Calculation of time and energy loss in transient operations
- Steady state stability, load equalization.

Electrical Drives:

Motion control is required in large number of industrial and domestic applications like transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, washing machines etc.

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. Drives employing electric motors are known as ELECTRICAL DRIVES.

An ELECTRIC DRIVE can be defined as an electromechanical device for converting electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control.

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 control.

Advantages of Electrical Drive

1. They have flexible control characteristics. The steady state and dynamic characteristics of electric

drives can be shaped to satisfy the load requirements.

2. Drives can be provided with automatic fault detection systems. Programmable logic controller and computers can be employed to automatically control the drive operations in a desired sequence.
3. They are available in wide range of torque, speed and power.
4. They are adaptable to almost any operating conditions such as explosive and radioactive environments
5. It can operate in all the four quadrants of speed-torque plane
6. They can be started instantly and can immediately be fully loaded
7. Control gear requirement for speed control, starting and braking is usually simple and easy to operate.

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 if any.
6. Environment and location.

7. Reliability.

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.

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.

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.

General Electric Drive System

Block diagram of an electric drive system is shown in the figure below.

A modern variable speed electrical drive system has the following components

Electrical machines and loads

Power Modulator

Sources

Control unit

Sensing unit

Electrical Machines

Most commonly used electrical machines for speed control applications are the following

DC Machines

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

AC Machines

Induction, wound rotor, synchronous, PM synchronous and synchronous reluctance machines.

Special Machines

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

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)

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.

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

Control unit for a power modulator are provided in the control unit. It matches the motor and power converter to meet the load requirements.

Classification of Electrical Drives

Another main classification of electric drive is

DC drive, AC drive

Comparison between DC and AC drives

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

Applications

Paper mills

Cement Mills

Textile mills

Sugar Mills

Steel Mills

Electric Traction

Petrochemical Industries

Electrical Vehicles

Dynamics of Electrical drives

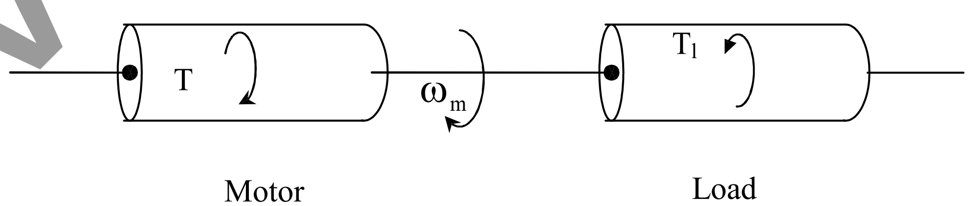
Fundamental torque equations

Dynamics of Motor Load System

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.



Notations Used:

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 wind age torque of motor. Motor-load system shown in figure can be described by the following fundamental torque equation.

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

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 =

Torque component $J \frac{d\omega_m}{dt}$ is called dynamic torque. Because it is present only during the transient conditions.

Speed torque conventions

Classification of Load Torques:

Various load torques can be classified into broad categories.

Active load torques

Passive 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)

Eg: Torque due to force of gravity

Torque due tension

Torque due to compression and torsion etc.

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

Eg: Torque due to friction, cutting etc.

Components of load torque

The load torque T_l can be further divided in to 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 the equivalent value of various friction torques referred to the motor shaft.

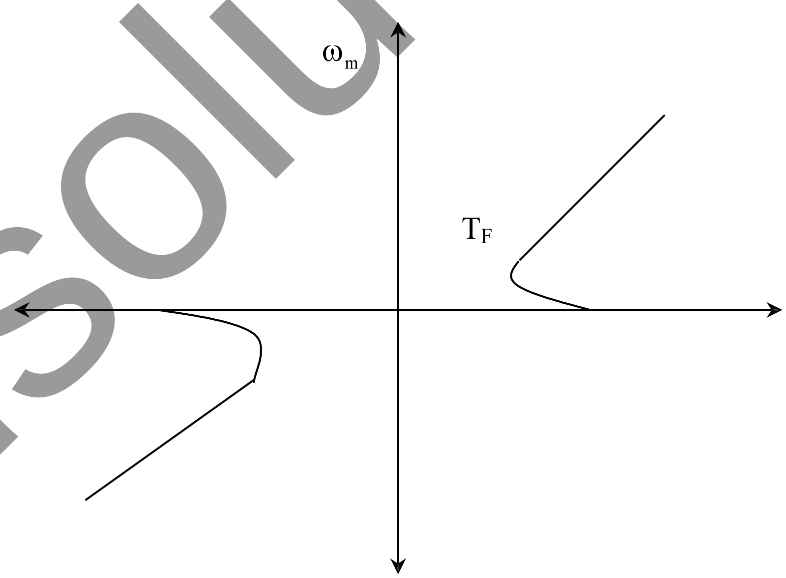
(ii) Windage Torque (T_W)

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

(iii) Torque required to do useful mechanical work.

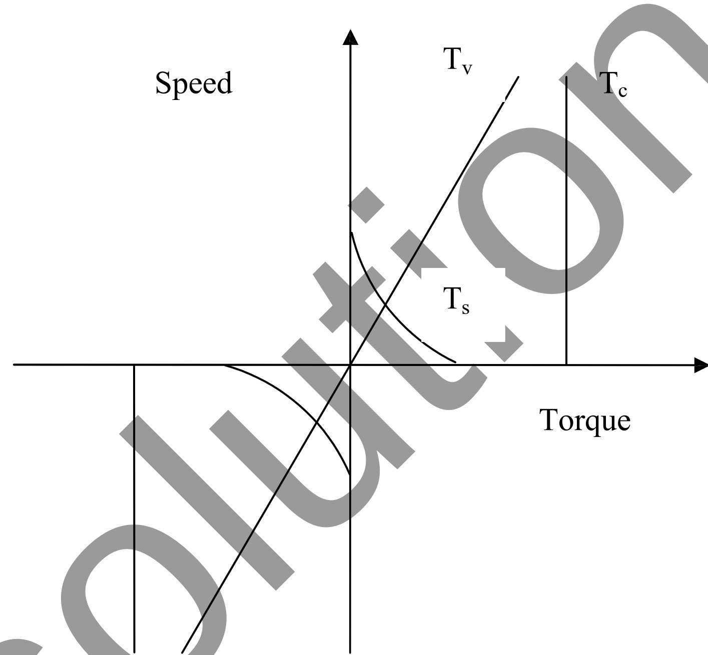
Nature of this torque depends upon particular application. It may be constant and independent of speed. It may be some function of speed, it may be time invariant or time variant, its nature may also change with the load‟s mode of operation.

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.

Friction torque can also be resolved into three components



Another component T_C, which is independent of speed, is known as COULOMB friction. Third component T_S accounts for additional torque present at stand still. Since Ts is present only at stand still it is not taken into account in the dynamic analysis. Windage torque, T_W which is proportional to speed squared is given by

From the above discussions, for finite speed

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

Characteristics of Different types of Loads

One of the essential requirements in the section 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.

Constant torque type load

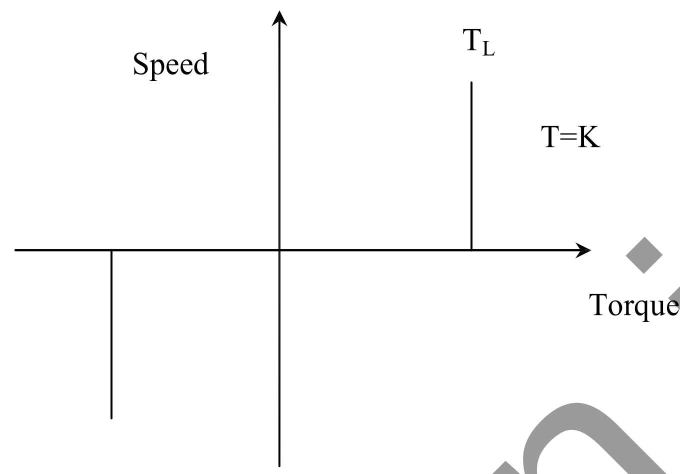
Torque proportional to speed (Generator Type load)

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

Torque inversely proportional to speed (Constant power type load)

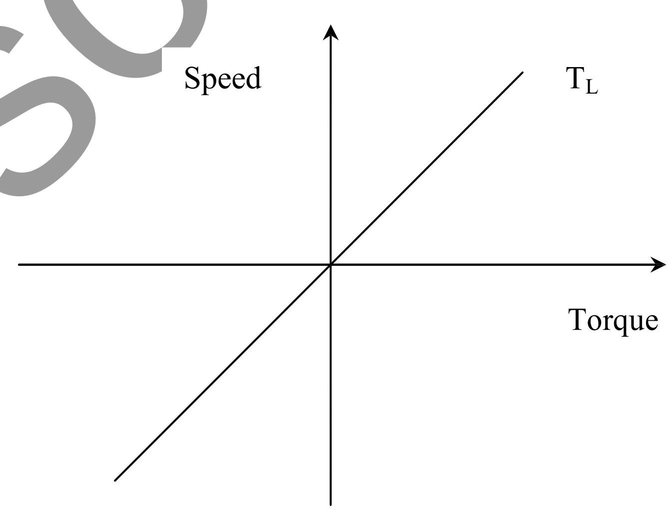
Constant Torque characteristics:

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.



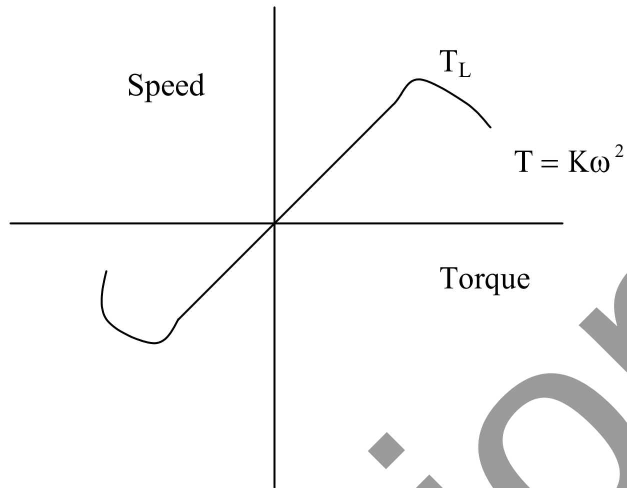
Torque Proportional to speed:

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



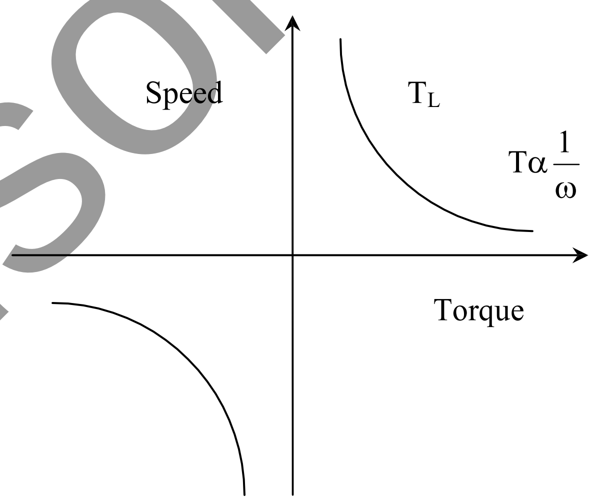
Torque proportional to square of the speed:

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



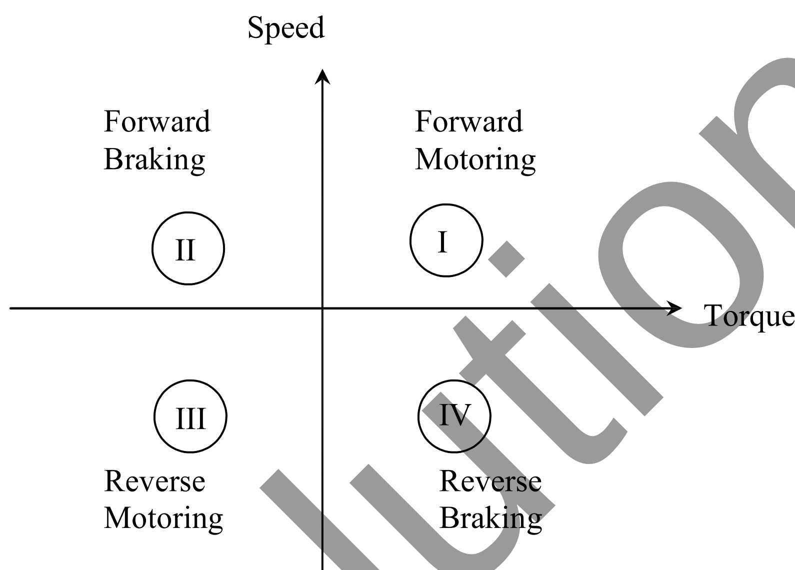
Torque Inversely proportional to speed:

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

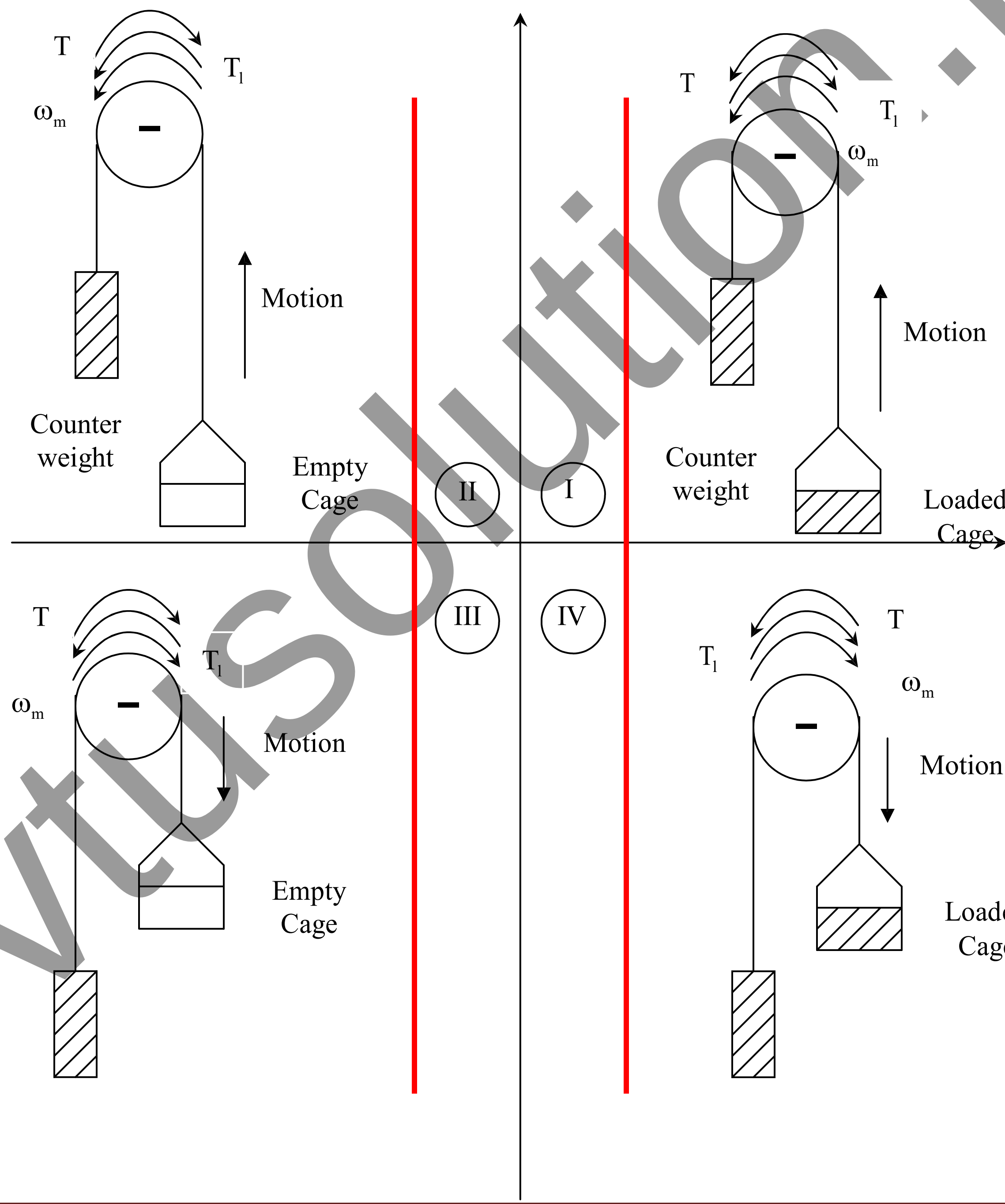


Multi quadrant Operation:

For consideration of multi quadrant operation of drives, it is useful to establish suitable conventions about the signs of torque and speed. A motor operates in two modes – Motoring and braking. In motoring, it converts electrical energy into mechanical energy, which supports its motion. In braking it works as a generator converting mechanical energy into electrical energy and thus opposes the motion. Motor can provide motoring and braking operations for both forward and reverse directions. Figure shows the torque and speed co-ordinates for both forward and reverse motions. Power developed by a motor is given by the product of speed and torque. For motoring operations power developed is positive and for braking operations power developed is negative.



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 developed is negative. Hence, machine works under braking opposing the motion. Therefore operation in quadrant II is known as forward braking. Similarly operation in quadrant III and IV can be identified as reverse motoring and reverse braking since speed in these quadrants is negative. For better understanding of the above notations, let us consider operation of hoist in four quadrants as shown in the figure. Direction 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 from 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 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. Load torque line in quadrants I and IV represents speed-torque characteristics of the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight.

The load torque in quadrants II and III is the speed torque characteristics for an empty hoist. This torque is the difference of torques due to counter weight and the empty hoist. Its sigh is negative because the counter weight is always higher than that of an empty cage.

The quadrant I operation of a hoist requires movement of cage upward, which corresponds to the positive motor speed which is in counter clockwise direction here. This motion will be obtained if the motor products positive torque in CCW direction equal to the magnitude of load torque T_{L1}. Since developed power is positive, this is forward motoring operation. Quadrant IV is obtained when a loaded cage is lowered. Since the weight of the loaded cage is higher than that of the counter weight .It is able to overcome due to gravity itself.

In order to limit the 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. Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weigh is heavier than an empty cage, its 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 direction. Since speed is positive and developed power is negative, it"s forward braking operation.

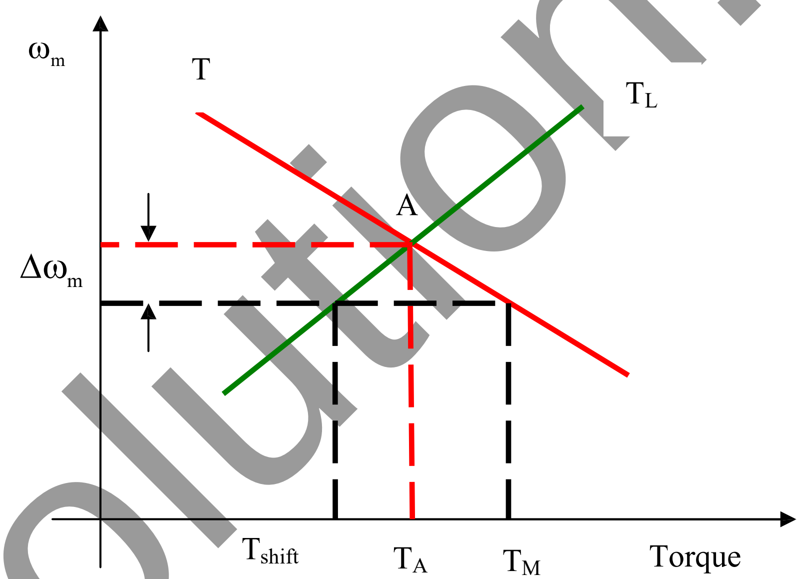
Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in CW direction. Since speed is negative and developed power is positive, this is reverse motoring operation.

Steady State Stability:

Equilibrium speed of motor-load system can be obtained when motor torque equals the load torque. Electric drive system will operate in steady state at this speed, provided it is the speed of stable state equilibrium. Concept of steady state stability has been developed to readily evaluate the stability of an equilibrium point from the steady state speed torque curves of the motor and load system.

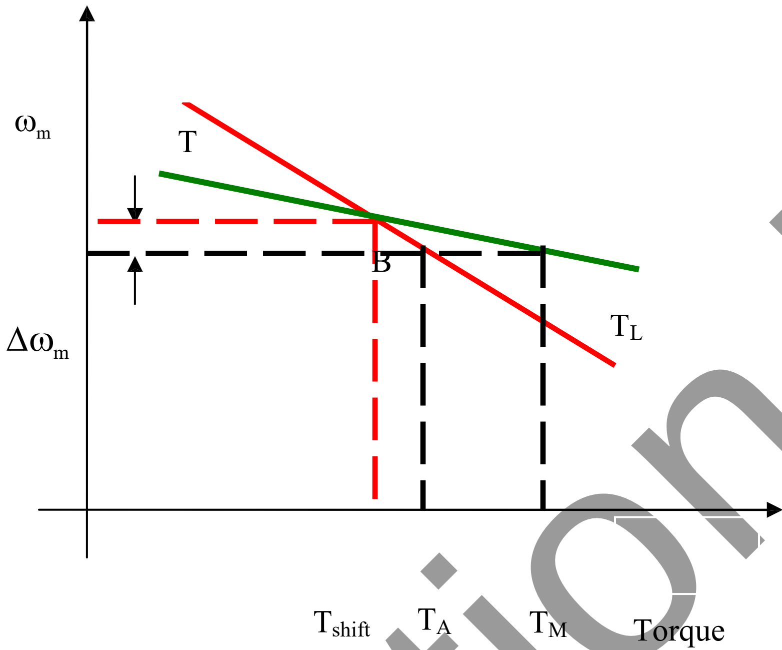
In most of the electrical drives, the electrical time constant of the motor is negligible compared with the mechanical time constant. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient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

Now, consider the steady state equilibrium point A shown in figure below



The equilibrium point will be termed as stable state when the operation will be restored to it after a small departure from it due to disturbance in the motor or load. Due to disturbance a reduction of $\Delta\omega_m$ in speed at new speed, electrical motor torque is greater than the load torque, consequently motor will accelerate and operation will be restores to point A. similarly an increase in $\Delta\omega_m$ speed caused by a disturbance will make load torque greater than the motor torque, resulting into deceleration and restoring of operation to point A.

Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure. A decrease in speed causes the load torque to become greater than the motor torque, electric drive decelerates and operating point moves away from point B. Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B



From the above discussions, 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 conditions is satisfied.

$$\frac{dT_L}{d\omega_m} > \frac{dT}{d\omega_m} \text{ --------------- } (1)$$

Inequality in the above equation can be derived by an alternative approach. Let a small perturbation in speed, $\Delta\omega_m$ results in ΔT and ΔT_l perturbation in T and T_l respectively. Therefore the general load-torque equation becomes

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

$$= T + \Delta T = T_l + \Delta T_l + \frac{J d\omega_m}{dt} + J\frac{d\Delta\omega_m}{dt} \text{ ----} (2)$$

The general equation is

$$T = T_l + J\frac{d\omega_m}{dt} \text{-------}(3)$$

Subtracting (3) from (2) and rearranging

$$J\frac{d\omega_m}{dt} = \Delta T - \Delta T_l \text{----------}(4)$$

From small perturbations, the speed –torque curves of the motor and load can be assumed to be straight lines, thus

$$\Delta T = \left(\frac{dT}{d\omega_m}\right)\Delta\omega_m \text{-------}(5)$$

$$\Delta T_l = \left(\frac{dT_l}{d\omega_m}\right)\Delta\omega_m \text{-------}(6)$$

Where $\frac{dT}{d\omega_m}$ and $\frac{dT_l}{d\omega_m}$ are respectively slopes of the steady state speed torque curves of motor and load at operating point under considerations. Substituting (5) and (6) in (4) we get,

$$J\frac{d\Delta\omega_m}{dt} + \left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)\Delta\omega_m = 0 \text{-----}(7)$$

This is a first order linear differential equation. If initial deviation in speed at t=0 be $(\Delta\omega_m)_0$ then the solution of equation (7) is

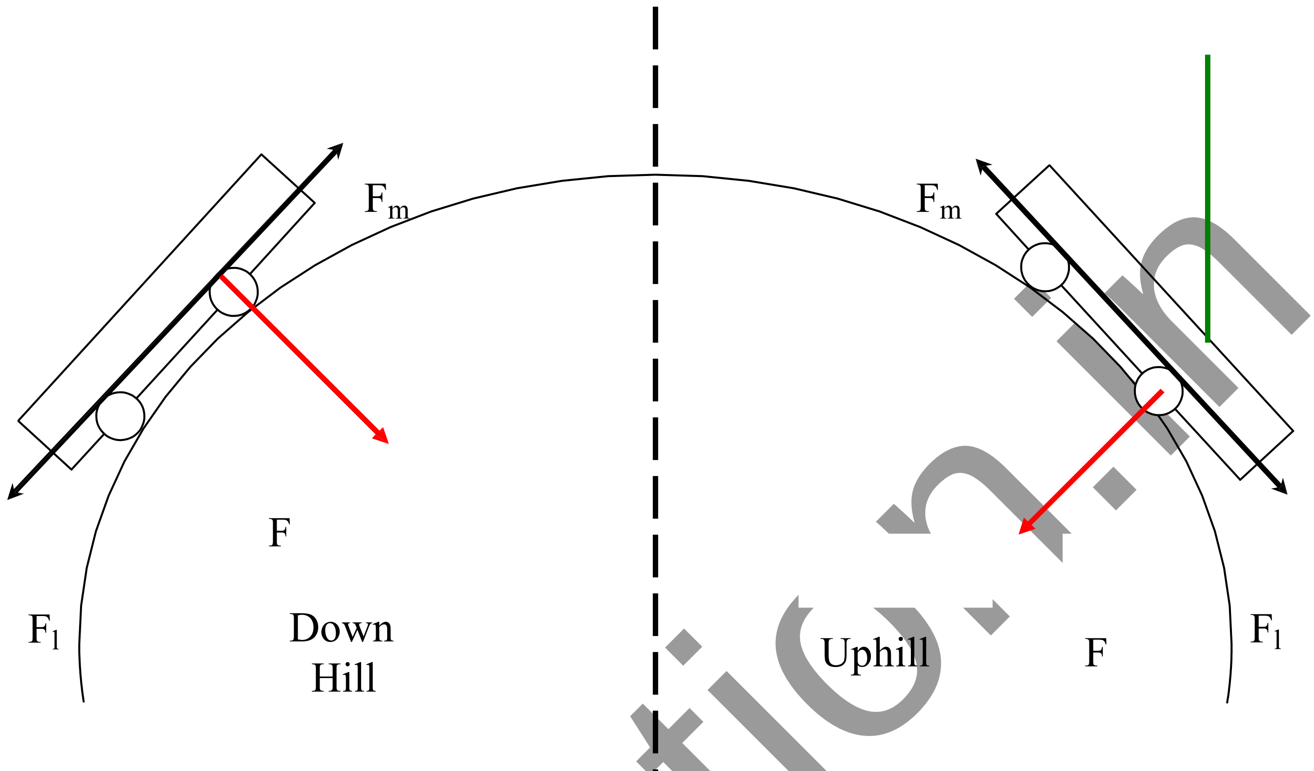
$$\Delta\omega_m = (\Delta\omega_m)_0 \exp\left\{-\frac{1}{J}\left(\frac{dT_l}{d\omega_m} - \frac{dT}{d\omega_m}\right)t\right\} \text{-----}(8)$$

An operating point will be stable when $\Delta\omega_m$ approaches zero as t approaches infinity. For this to happen exponential term in equation (8) should be negative.

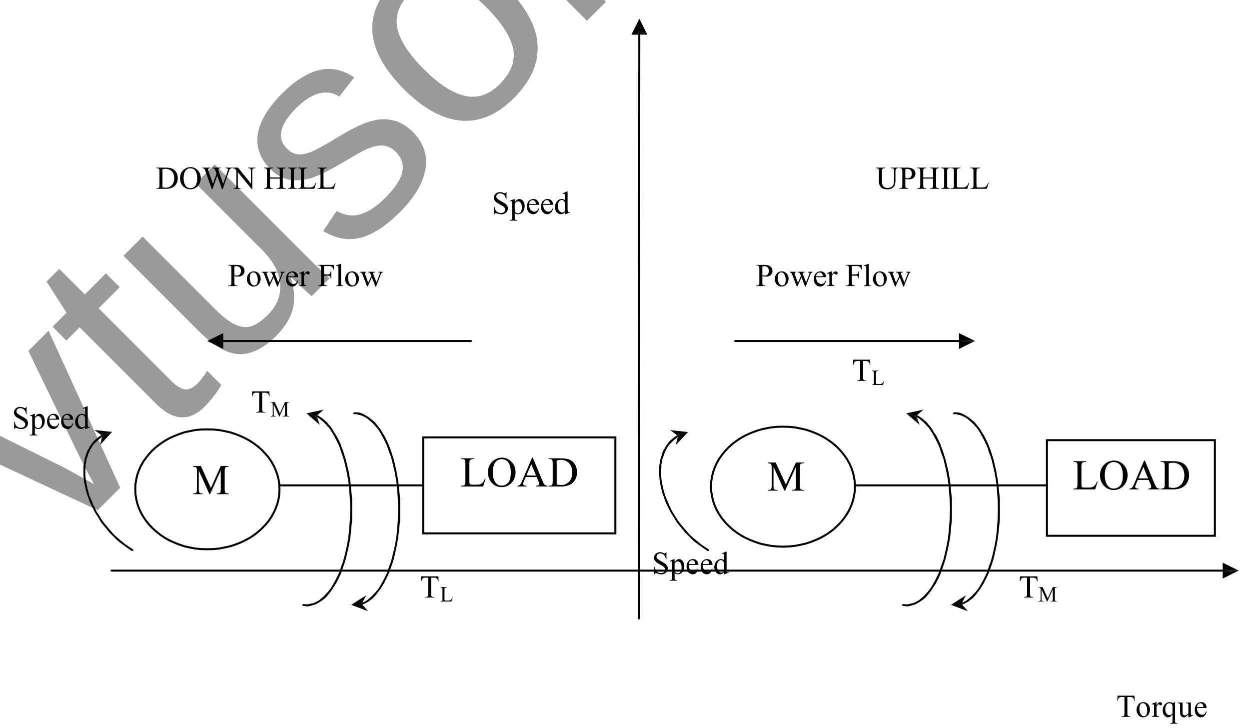
Load equalization

In the regenerative braking operation, the motor operates as generator, while it is still connected to the supply. Here, the motor speed is greater than the synchronous speed. Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven by the load.

An example of regenerative braking is shown in the figure below. Here an electric motor is driving a trolley bus in the uphill and downhill direction. The gravity force can be resolved into two components in the uphill direction. One is perpendicular to the load surface (F) and another one is parallel to the road surface F_l. The parallel force pulls the motor towards bottom of the hill. If we neglect the rotational losses, the motor must produce force F_m opposite to F_l to move the bus in the uphill direction.



This operation is indicated as shown in the figure below in the first quadrant. Here the power flow is from the motor to load.



Now we consider that the same bus is traveling in down hill, the gravitational force doesn‟t change its direction but the load torque pushes the motor towards the bottom of the hill. The motor produces a torque in the reverse direction because the direction of the motor torque is always opposite to the direction of the load torque. Here the motor is still in the same direction on both sides of the hill. This is known as regenerative braking. The energy is exchange under regenerative braking operation is power flows from mechanical load to source. Hence, the load is driving the machine and the machine is generating electric power that is returned to the supply.

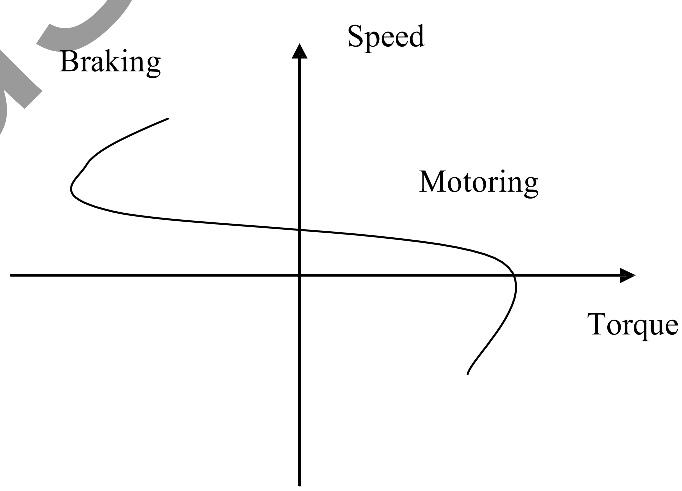
Regenerative braking of Induction motor:

An induction motor is subjected to regenerative braking, if the motor rotates in the same direction as that of the stator magnetic field, but with a speed greater than the synchronous speed. Such a state occurs during any one of the following process.

Downward motion of a loaded hoisting mechanism

During flux weakening mode of operation of IM.

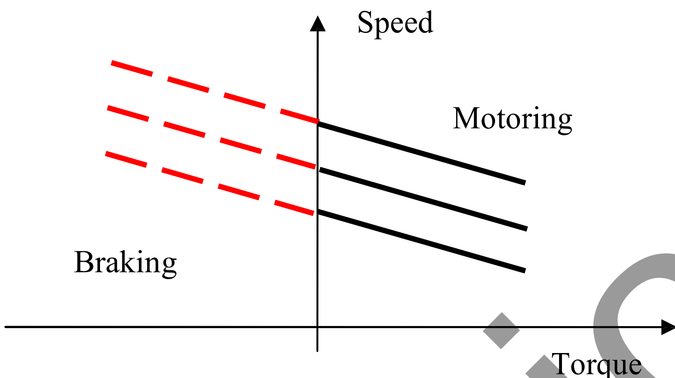
Under regenerative braking mode, the machine acts as an induction generator. The induction generator generates electric power and this power is fed back to the supply. This machine takes only the reactive power for excitation. The speed torque characteristic of the motor for regenerative braking is shown in the figure.



Regenerative Braking for DC motor:

In regenerative braking of dc motor, generated energy is supplied to the source. For this the following condition is to be satisfied.

$E > V$ and I_a should be negative



Calculation of time and energy loss in transient operations

Modes of Operation

An electrical drive operates in three modes:

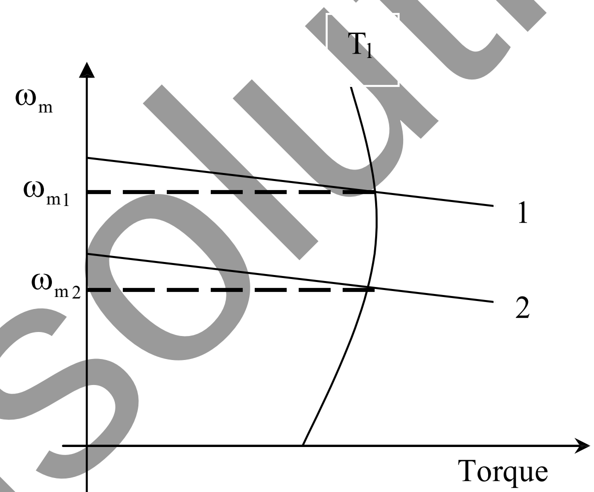
Steady state

Acceleration including Starting

Deceleration including Stopping

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. The steady state operation for a given speed is realized by adjustment of steady state motor speed torque curve such that the motor and load torques are equal at this speed. 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 below when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed.Speed is changed to 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.

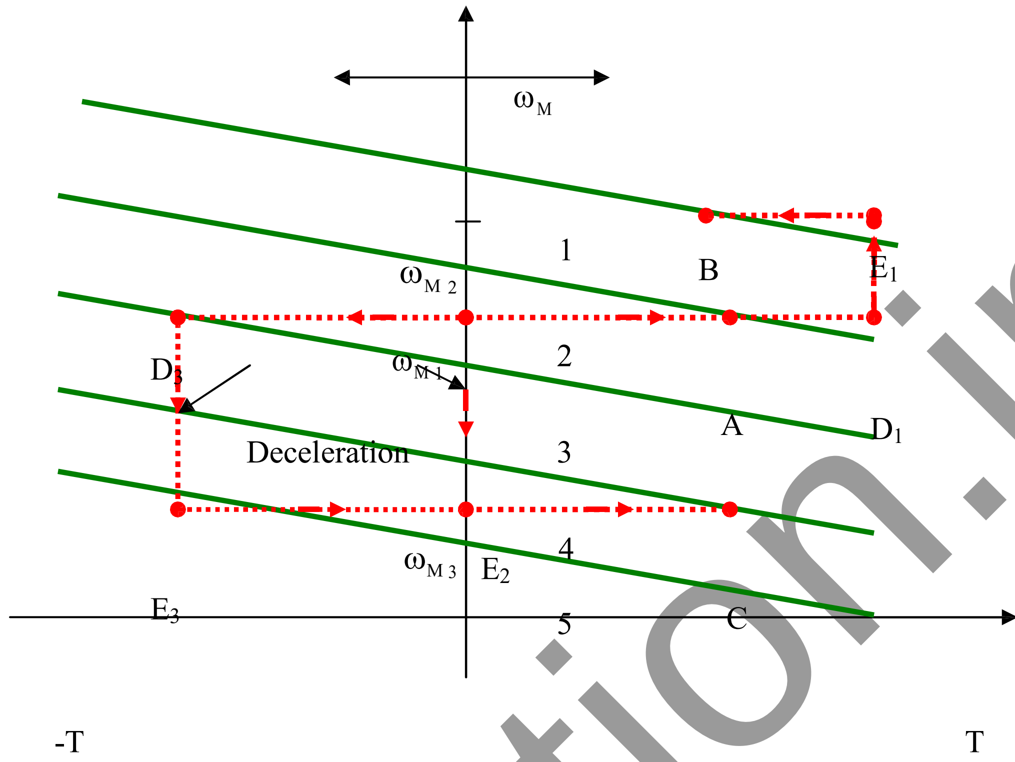


Acceleration and Deceleration modes are transient modes. Drive operates in acceleration mode whenever an increase in its speed is required. For this motor speed torque curve must be changed so that motor torque exceeds the load torque. Time taken for a given change in speed depends on inertia of motor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

Figure shown below shows the transition from operating point A at speed

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 figure below, 1 to 5 are motor speed torque curves. Starting is a special case of acceleration where a speed change from 0 to a desired speed takes place. 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.



Motor operation in deceleration mode is required when a decrease in its speed is required. According to the equation $T = T_l + J\frac{d\omega_m}{dt}$, deceleration occurs when load torque exceeds the motor torque. In those applications where load torque is always present with substantial magnitude, enough deceleration can be achieved by simply reducing the motor torque to zero. In those applications where load torque may not always have substantial amount or where simply reducing the motor torque to zero does not provide enough deceleration, mechanical brakes may be used to produce the required magnitude of deceleration. 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. Appropriate changes are made to ensure that the current is restricted within the safe limit.

UNIT 2

SELECTION OF MOTOR POWER RATING

- Thermal model of motor for heating and cooling
- Classes of motor duty
- Determination of motor rating.

INTRODUCTION

1. When a motor operates, heat is produced (losses) in the machine and its temperature rise.

2. As the temperature increases beyond the limit, a portion of heat flows out to the surrounding medium.

3. When temperature reaches a steady state. (i.e. steady state value depends on power loss and output power of the machine).

4. Therefore, temperature rise has a direct relationship with the output power and is termed as thermal loading on the machine.

5. Steady state temperature is not the same at various parts of the machine. It is highest in the windings. (loss density in conductors is high and dissipation is slow)

6. Also because windings are not exposed to cooling air, wrapped with the insulation material and partly exposed in slots.

7. Among the various materials used in machine, the insulation has lowest temperature limit.

When operating for a specific application, motor rating should be carefully chosen to ensure that the insulation temperature never exceeds the prescribed limit. 2. If not lead to thermal breakdown causing short circuit and damage to winding. 3. For loads which operate at a constant power and speed, determination of motor power rating is simple and straightforward.4. Most of the loads operate at variable power and speed and are different for different applications. This chapter has three objectives:

1. Obtain thermal model for the machine – calculation of motor ratings for various classes of motor duty.

2. Categorization of load variation with time. (Classes of duty of motor)

3. Methods for calculating motor ratings for various classes of duty.

CLASSES OF MOTOR DUTY

IEC (the International Electro technical Commission) uses eight duty cycle designations to describe electrical motors operating conditions:

S1 – CONTINUOUS DUTY (A)- The motor works at a constant load for enough time to reach temperature equilibrium. Characterized by a constant motor loss.

Examples: paper mill drives, compressors, pumps.

S2 – SHORT TIME DUTY (B) – it denotes the operation at constant load during a given time, less than that required to reach thermal equilibrium, followed by a rest of sufficient duration to re-establish equality of temperature with the cooling medium.

Examples: motors used for opening and closing lock gates and bridges, motors employed in battery-charging units etc, are rated for such a duty.

S3 - INTERMITTENT PERIODIC DUTY – it denotes a sequence of identical duty cycles, each consisting of a period of operation at constant loadand a rest period, these periods being too short to obtain thermal equilibrium during one duty cycle.

Examples: motors that are used in different kinds of hoisting mechanisms and those used in trolley buses etc. are subjected to intermitted periodic duty.

S4- INTERMITTENT PERIODIC DUTY WITH STARTING – this is intermitted periodic duty cycles where heat losses during starting cannot be ignored. Thus, it consisting of a period of starting, a period of operation at constant load and a rest period, the operating and rest periods being too short to attain thermal equilibrium during one duty cycle.

Exampesl*:* motors that drive metal cutting and drilling tool, certain auxiliary equipment of rolling mills.

S5- INTERMITTENT PERIODIC DUTY WITH STARTING AND BRAKING – it denotes a sequence of identical duty cycles each consisting of a period of starting, a period of operation at a constant load, a period of braking and rest period. The operating and rest periods are too short to obtain thermal equilibrium during one duty cycle. In this duty braking is rapid and is carried out electrically.
Examples*:* certain auxiliary equipment used in rolling mills and metal cutting metal lathes offer such operating conditions.

S6- CONTINUOUS DUTY WITH INTERMITTENT PERIODIC LOADING: it denotes a sequence of identical duty cycles each consisting of a period of operation of constant load and a period of operation at not load, with normal voltage across the exciting windings. The operation and no load periods are too short to attain thermal equilibrium during one duty cycle.

This type of duty is distinguished from intermittent periodic duty by the fact that after a period of operation at constant load follows a period of no load operation instead of rest.
Examples: Pressing, cutting and drilling machine drives are the examples

S7- CONTINUOUS OPERATION WITH STARTING AND BRAKING – it denotes a sequence of identical duty cycles each consisting of a period of starting, a period of operation at constant load and a period of electrical braking. There is no period of rest.
Examples*:* blooming mill

S8- CONTINUOUS DUTY WITH PERIODIC SPEED CHANGES – it consists of periodic duty cycle, each having a period of running at one load and speed, and another period of running at different speed and load; the operating periods being too short to attain thermal equilibrium during one duty cycle. There is no rest period.

Heating and Cooling Curves In many of the industrial applications, electric motors are widely used. During the operation of motor, various losses such as copper loss, iron loss and windage loss etc. take place. Due to these losses, heat is produced inside the machine. This increases the temperature of the motor. The temperature when reaches beyond the ambient value, a part of heat produced starts flowing to the surrounding medium. This outflow of heat is function of temperature rise of the motor above the ambient value. Key Point: With increase in temperature, the heat outflow rises and the equilibrium is achieved when heat generated is equal to heat dissipated to the surrounding. The temperature of motor then attains steady state value. This steady state temperature depends on power loss which in turn depends on power output of the motor. As the temperature rise and power output are directly related, it is called thermal loading on the machine. The heat flow and the temperature distribution within a motor is very difficult to predict because of complexity in the motor geometry. The calculations are also complicated because of loading of the motor. The heat flow direction does not remain same at all loading conditions. The steady state temperature is different at various parts of the motor. It is highest in the windings as loss density in conductors is high and dissipation is slow. A simple thermal model of the motor can be obtained by assuming motor as a homogeneous body with uniform temperature gradient. The heat which is generated at all points has same temperature. The points at which heat is dissipated to the cooling medium are also at same temperature. The heat dissipation is proportional to the difference of the temperatures of the body and surrounding medium. No heat is radiated. Similarly it is also assumed that heat dissipation rate is constant at all temperature. If cooling is not provided then motor can not dissipate heat to surrounding medium. This will increase temperature to a very high value.

Heating Curves

Let W = Loss taking place in a machine in watts

G = Mass of the machine in kg

S = Specific heat in watt-sec/kg °C

θ = Rise in temperature above ambient temperature in °C

θ_F = Final temperature rise with continuos load in °C

A = Area of cooling surface in m^2

λ = Rate of heat dissipation in watts/sq meter/°C rise in temperature.

Let us consider the small time interval dt in which temperature rise of the machine is $d\theta$ due to the losses taking place in the machine. Total losses in machine during

time interval dt = W dt

Heat dissipation from surface during the same time interval = $A\,\lambda\theta\cdot dt$

Additional heat stored in the machine = $G.S.d\theta$

We have, heat developed = heat absorbed + heat dissipated

$$W\cdot dt = G.S.d\theta + A\lambda\theta\cdot dt \qquad \text{...(i)}$$

$$\therefore \quad W\cdot dt - A\lambda\theta\cdot dt = G.S.d\theta$$

$$\therefore \quad (W - A\lambda\theta)\,dt = G.S.d\theta$$

$$\frac{dt}{G.S.} = \frac{d\theta}{W - A\lambda\theta}$$

$$\frac{dt}{\left(\frac{GS}{A\lambda}\right)} = \frac{d\theta}{\left(\frac{W}{A\lambda} - \theta\right)} \qquad \text{...(ii)}$$

When final temperature is reached, there is no heat absorbed. The heat which is generated is totally dissipated.

$$\therefore \quad W\cdot dt = A\,\lambda\,\theta_F\,dt$$

$$\therefore \quad W = A\,\lambda\,\theta_F$$

$$\therefore \quad \theta_F = \frac{W}{A\,\lambda} \qquad \text{...(iii)}$$

Substituting equation (iii) in equation (ii) we get,

$$\frac{dt}{\left(\frac{GS}{A\lambda}\right)} = \frac{d\theta}{\theta_F - \theta}$$

Integrating both sides of above equation

$$\int \frac{dt}{\left(\frac{GS}{A\lambda}\right)} = \int \frac{d\theta}{\theta_F - \theta}$$

$$\frac{A\lambda}{GS} \cdot t = -ln(\theta_F - \theta) + K \qquad \ldots(iv)$$

where K = constant of integration

To find out value of K, let us use initial condition

At t = 0, $\theta = \theta_1$

$$\therefore \quad 0 = -ln(\theta_F - \theta_1) + K$$

$$\therefore \quad K = ln(\theta_F - \theta_1)$$

Substituting this value of K in equation (iv),

$$\frac{A\lambda}{GS} \cdot t = -ln(\theta_F - \theta) + ln(\theta_F - \theta_1)$$

$$\therefore \quad \frac{A\lambda}{GS} \cdot t = ln\left(\frac{\theta_F - \theta_1}{\theta_F - \theta}\right)$$

$$\therefore \quad e^{\frac{A\lambda}{GS} t} = \frac{\theta_F - \theta_1}{\theta_F - \theta}$$

$$\therefore \quad \theta_F - \theta = (\theta_F - \theta_1)\, e^{-\frac{A\lambda}{GS} t}$$

$$\therefore \quad \theta = \theta_F - (\theta_F - \theta_1)\, e^{-\frac{A\lambda}{GS} t}$$

The term $GS/A\lambda$ is called **heating time constant** of the machine and is denoted by τ.

$$\therefore \quad \boxed{\theta = \theta_F - (\theta_F - \theta_1)\, e^{-t/\tau}}$$

If the machine is started from ambient temperature $\theta_1 = 0\,°C$ then above equation becomes,

$$\therefore \quad \boxed{\theta = \theta_F\,(1 - e^{-t/\tau})}$$

Let us consider time period $t = \tau$ then

Heating of Electric Motors

An electric motor has various power losses, mainly copper losses in the winding and core losses due to the hysteresis losses and eddy current losses, in the core. These losses appear in the form of heat. The mechanical losses due to the friction and windage also contribute to such heat development. There are some cooling methods provided in an electric motor. The ventilation causes heat to dissipate to the outside media such as air, oil or solids, or cooling medium. However some heat gets stored in the material, causing the temperature rise of an electric motor. Key Point: Under steady state conditions, the final temperature rise is reached when the rate of production of heat and rate of heat dissipation are equal. There is always some limited temperature rise specified for an electric motor. If temperature rises beyond the specified limit, motor is likely to be damaged. The insulating material may get damaged, which may cause a short circuit. Such a short circuit may lead to a fire. If immediate thermal breakdown of insulating material may not occur, the quality of insulation starts deteriorating such that in future for a normal load also thermal breakdown may occur. Hence while selecting an electric motor, such thermal restriction must be considered. Key Point: In fact the continuous rating of a machine is that rating for which the final temperature rise is just below the permissible value of ternperature rise. The insulating material used to protect the conductors decides the permissible temperature rise for an electric motor. The following table gives various classes of insulating materials and the corresponding permissible temperatures.

Heating and Cooling Curves In many of the industrial applications, electric motors are widely used. During the operation of motor, various losses such as copper loss, iron loss and windage loss etc. take place. Due to these losses, heat is produced inside the machine. This increases the temperature of the motor. The temperature when reaches beyond the ambient value, a part of heat produced starts flowing to the surrounding medium. This outflow of heat is function of temperature rise of the motor above the ambient value. Key Point: With increase in temperature, the heat outflow rises and the equilibrium is achieved when heat generated is equal to heat dissipated to the surrounding. The temperature of motor then attains steady state value. This steady state temperature depends on power loss which in turn depends on power output of the motor.

As the temperature rise and power output are directly related, it is called thermal loading on the machine. The heat flow and the temperature distribution within a motor is very difficult to predict because of complexity in the motor geometry. The calculations are also complicated because of loading of the motor. The heat flow direction does not remain same at all loading conditions. The steady state temperature is different at various parts of the motor. It is highest in the windings as loss density in conductors is high and dissipation is slow. A simple thermal model of the motor can be obtained by assuming motor as a homogeneous body with uniform temperature gradient The heat which is generated at all points has same temperature. The points at which heat is dissipated to the cooling medium are also at same temperature. The heat dissipation is proportional to the difference of the temperatures of the body and surrounding medium. No heat is radiated. Similarly it is also assumed that heat dissipation rate is constant at all temperature. If cooling is not provided then motor can not dissipate heat to surrounding medium. This will increase temperature to a very high value. Key Point: Thus cooling is important to limit the maximum temperature rise to a permissible value depending upon class of insulation employed. It is important to know about the heating and cooling curves. The detailed analysis about these curves is made in subsequent sections.

Heating Curves Consider a homogenous machine developing heat internally at a uniform rate and gives it to the surroundings proportional to temperature rise. It can be proved that the temperature rise of a body obeys exponential law.

Determination of motor rating

For a drive motor which is driving a constant load for sufficiently longer period till it reaches thermal equilibrium, its rating must be sufficient to drive it without exceeding the specified temperature. The rating of the motor selected for such type of duty is called continuous or design rating. The continuous rating specifies the maximum load that the motor can take over a period of time without exceeding the temperature rise. It is also expected that the motor should carry momentary overloads. Hence the motor which is selected sometimes has a rating slightly more than the power required by the load.

The efficiency of motor varies considerably with type of drive, bearings etc. Centrifugal pumps, fans, conveyors and compressors are some types of loads where the continuous duty at constant load is required. Selection of motor for such duty class is simple. Based on the load characteristics or specific requirements, the continues input required for mechanical load can be obtained. A suitable motor can be then selected from manufacture‟s catalogue. The thermal or overload capacities for selected motors should not be checked again as the design rating takes care of heating and temperature rise and the motor normally has short time overloading capacity. In case of such motors, the losses occurring during starting even though more than at rated load should not be given much importance as such motors does not require frequent starting. But it should be checked that whether the motor is able to provide enough starting torque or not if the load has considerable moment of inertia.

Method based on Average Losses

A method based on average losses of motor is suitable for selecting a motor for continuous duty, variable load. In this case, the motor having its rated losses equal to the average of the losses of the motor for variable load cycle is selected for driving the load. Here the final steady state temperature rise under variable load is same as the temperature rise with constant load. Let us consider a load-time graph as shown in the Fig. 1.10. The load torque goes on varying as per different intervals of time. In the last time period motor is de-energized from supply which is period of rest. T,

Key Point: The losses are zero in the last interval as motor is disconnected from supply. Consider equivalent constant current Li which causes same average losses over the time period considered. Average losses = W, c+1, .2.q12 where Wc, are core losses and R is the resistance of armature. LolI1 be current in time interval t 1, 12 be current in time interval 12 and so on.

UNIT 3 & 4

D C MOTOR DRIVES:

- Starting braking, transient analysis, single phase fully controlled rectifier
- Control of dc separately excited motor
- Single-phase half controlled rectifier control of dc separately excited motor.
- Three phase fully controlled rectifier control of dc separately excited motor
- Three phases half controlled rectifier control of dc separately excited motor Multiquadrant operation of dc separately excited motor fed form fully controlled rectifier. Rectifier control of dc series motor
- Chopper controlled dc drives, chopper control of separately excited dc motor.
- Chopper control of series motor.

Introduction

It is seen that due to various advantages, electric motors are used as drive motors in various industrial applications. The various industrial loads have different types of mechanical characteristics, which mainly include speed-torque characteristics. When an electric motor is to be selected as a drive motor, first the speed-torque requirement of the load is determined. Then an electric motor is selected having speed-torque characteristics same as that required by the load. Thus it is necessary to know the various types of electric motors used as drive motors and their mechanical characteristics. This helps to select the proper motor for driving the load. The electric motors are classified based on the nature of the electric supply used to drive the motor. Accordingly, the electric motors are basically classified as, 1. D.C. Motors which require d.c. supply. 2. AC. motors which require a-c. supply. This chapter explains the various types of electric motors and their characteristics.

D.C. Motors

The motors which require d.c. supply to drive them are called d.c. motors. In d.c. motors, there are two types of windings, 1. Field winding: 'this is used to produce the main operating flux. This is also called exciting winding. The dc. supply is used to pass exciting current through the field winding. The field current products necessary working flux. Key Point: Before saturation, the flux ON produced by the field winding is directly proportional to the field current (lf) 2. Armature winding: The armature winding is placed on armature, which is a rotating part of the d.c. motor. The armature winding is connected to the commutator and the supply to the armature winding is given through the bushes which are resting against the commutator. When supply is given to the armature, it carries an armature current (I„) and produces the flux called armature flux.

Principle of Operation

DC motor operates on the principle that when a current carrying is placed in a magnetic field, it experiences a mechanical force given by F = BIL newton. Where the current and „L" is the length of the conductor. The direction of force can be found by left hand rule. Constructionally, there is no difference between a DC generator and DC motor. Conductors. The collective force produces a driving torque which sets the armature into rotation.The function of a commutator in DC motor is to provide a continIn DC generator the work done in overcoming the magnetic drag is converted into electrical energy.
Conversion of energy from electrical form to mechanical form by a DC motor takes place by the work done in overcoming the opposition which is called the BACK EMF: is the dynamically induced emf in the armature conductors of a dc motor when the armature is rotated. The direction of the induced emf as found by Flemings right hand rule is in Opposition to the applied voltage. Its value is same as that this emf is called as back opposition is converted into mechanical energy.

Starting braking

DC motor operates on the principle that when a current carrying is placed in a magnetic field, it experiences a mechanical force given by F = BIL newton. Where „B‟ = flux density in wb/ is the length of the conductor. The direction of force can be found by left hand rule. Constructionally, there is no difference between a DC generator and DC motor. Armature conductors are carrying current downwards under North Pole and upwards under South Pole. When the field coils are excited, with current carrying armature conductors, a force is experienced by each armature conductor whose direction can be found by Fleming‟s left hand rule. This is shown by arrows. The collective force produces a driving torque which sets the armature into rotation. The function of a commutator in DC motor is to provide a continuous and unidirectional torque.

In DC generator the work done in overcoming the magnetic drag is converted into electrical energy. Conversion of energy from electrical form to mechanical form by a DC motor takes place by the work done in overcoming the opposition which is called the „back emf‟. is the dynamically induced emf in the armature conductors of a dc motor when the armature is rotated. The direction of the induced emf as found by Flemings right hand rule is in opposition to the applied voltage. Its value is same as that of the induced emf in a DC generator volts. This emf is called as back emf'. The work done in overcoming this opposition is converted into mechanical energy.

The direction of force can be found by Fleming‟s left hand rule. Constructionally, there is no difference between a DC generator and DC motor. Shows a multipolar DC motor. Armature conductors are carrying current downwards under North Pole and upwards under South Pole. When the field coils are excited, with current carrying armature conductors, a force is experienced by each armature hose direction can be found by Fleming‟s left hand rule. This is shown by arrows on top of the. The collective force produces a driving torque which sets the armature into rotation

In DC generator the work done in overcoming the magnetic drag is converted into electrical energy.

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armature is rotated. The direction of the induced emf as found by Flemings right hand rule is in of the induced emf in a DC generator. The work done in overcoming this
The rotating armature connected across a supply voltage of „V". Direct current (dc) motors have variable characteristics and are used extensively in variable-speed drives.

• DC motors can provide a high starting torque and it is also possible to obtain speed control over a wide range.

• The methods of speed control are normally simpler and less expensive than those of AC drives.

• DC motors play a significant role in modern industrial drives.

• Both series and separately excited DC motors are normally used in variable- speed drives, but series motors are traditionally employed for traction applications.

• Due to commutators, DC motors are not suitable for very high speed applications and require more maintenance than do AC motors.

• With the recent advancements in power conversions, control techniques, and microcomputers, the ac motor drives are becoming increasingly competitive with DC motor drives.

• Although the future trend is toward AC drives, DC drives are currently used in many might be a few decades Controlled rectifiers provide a variable dc output voltage from a fixed ac voltage, whereas a dc-dc converter can provide a variable dc voltage from a fixed dc voltage.

• Due to their ability to supply a continuously variable dc voltage, controlled rectifiers and dc-dc converters made a revolution in modern industrial control equipment and variable-speed drives, with power levels ranging from fractional horsepower to several megawatts.

• Controlled rectifiers are generally used for the speed control of dc motors.

• The alternative form would be a diode rectifier followed by dc-dc converter.

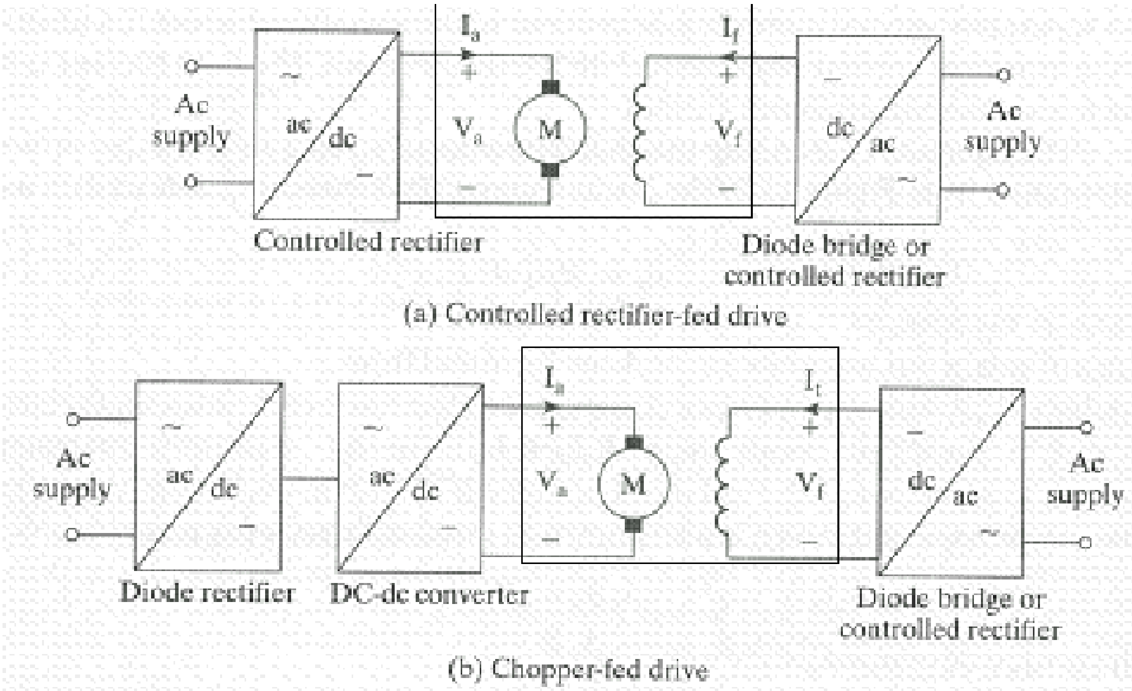
• DC drives can be classified, in general, into three types:

– 1. Single-phase drives

– 2. Three-phase drives

– 3. DC-DC converter drives

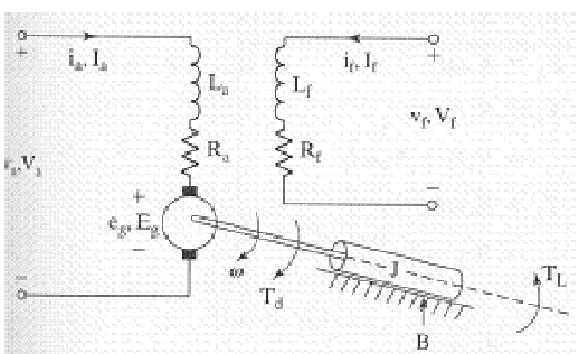
Single phase fully controlled rectifier



(a) Controlled rectifier-fed drive

(b) Chopper-fed drive

Control of dc separately excited motor



$$\omega = \frac{V_a - R_a I_a}{K_v I_f} = \frac{V_a - R_a I_a}{K_v V_f / R_f}$$

The motor speed can be varied by

– controlling the armature voltage Va, known as voltage control;

– controlling the field current If, known as field control; or

– torque demand, which corresponds to an armature current Ia, for a fixed field current If.

The speed, which corresponds to the rated armature voltage, rated field current and rated armature current, is known as the rated (or base) speed.

In practice, for a speed less than the base speed, the armature current and field currents are maintained constant to meet the torque demand, and the armature voltage Va is varied to control the speed. For speed higher than the base speed, the armature voltage is maintained at the rated value and the field current is varied to control the speed. However, the power developed by the motor (= torque X speed) remains constant.

Figure below shows the characteristics of torque, power, armature current, and field current against the speed.

Operating Modes

In variable-speed applications, a dc motor may be operating in one or more modes:

motoring,

Regenerative braking,

Dynamic braking,

Plugging

Motoring: The arrangements for motoring are shown in Figure 15.7a. Back emf Eg is less than supply voltage Vy. Both armature and field currents are positive. The motor develops torque to meet the load demand.

Regenerative braking:

• The motor acts as a generator and develops an induced voltage E g. Eg must be greater than supply voltage Va.

• The armature current is negative, but the field current is positive.

• The kinetic energy of the motor is returned to the supply.

• A series motor is usually connected as a self-excited generator.

• For self-excitation, it is necessary that the field current aids the residual flux. This is normally accomplished by reversing the armature terminals or the field terminals.

Dynamic braking:

• The arrangements shown in Figure 15.7c are similar to those of regenerative braking, except the supply voltage Va is replaced by a braking resistance Rb,.

• The kinetic energy of the motor is dissipated in Rb.

Plugging:

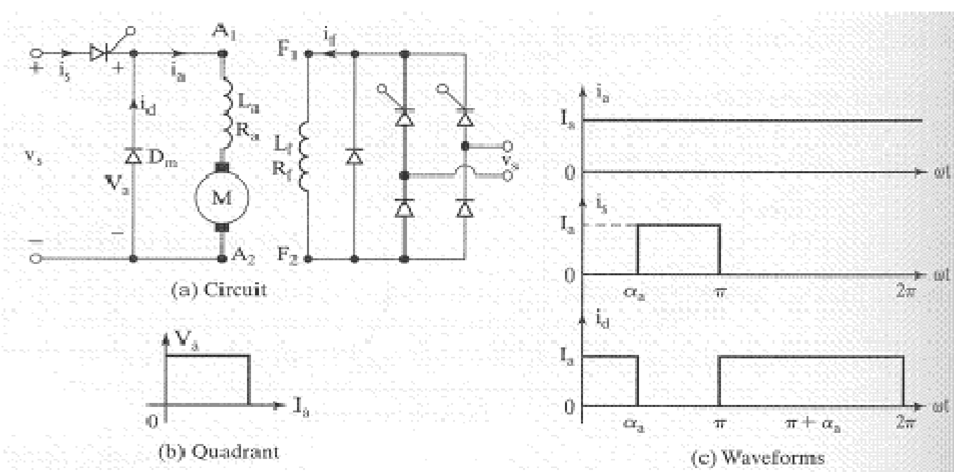
• Plugging is a type of braking. The connections for plugging are simple

• The armature terminals are reversed while running. The supply voltage Va and the induced voltage Eg act in the same direction.

• The armature current is reversed, thereby producing a braking torque. The field current is positive.

• For a series motor, either the armature terminals or field terminals should be reversed, but not both.

Single-phase half controlled rectifier control of dc separately excited motor



A single-phase half-wave converter feeds a dc motor, as shown

• The armature current is normally discontinuous unless a very large inductor is connected in the armature circuit.

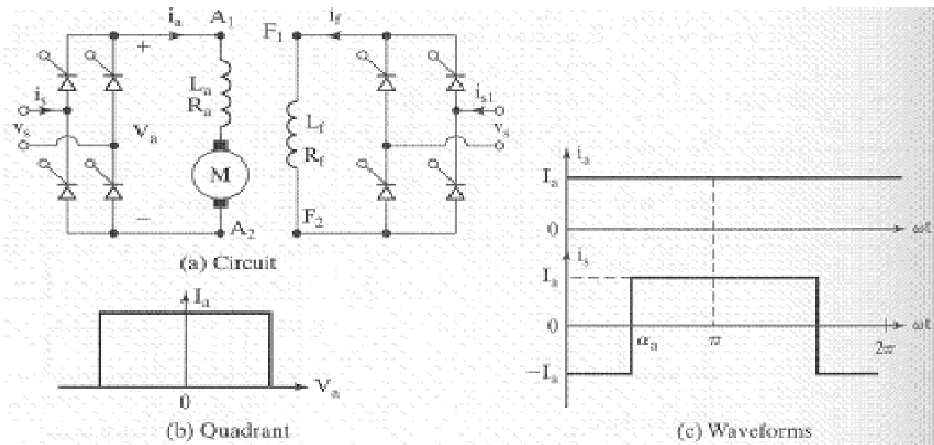
• A freewheeling diode is always required for a dc motor load and it is a one-quadrant drive.

• The applications of this drive are limited to the 0.5 kW power level.

• Figure shows the waveforms for a highly inductive load.

• A half-wave converter in the field circuit would increase the magnetic losses of the motor due to high ripple content on the field excitation current.

Single-Phase Full-Wave-Converter Drives

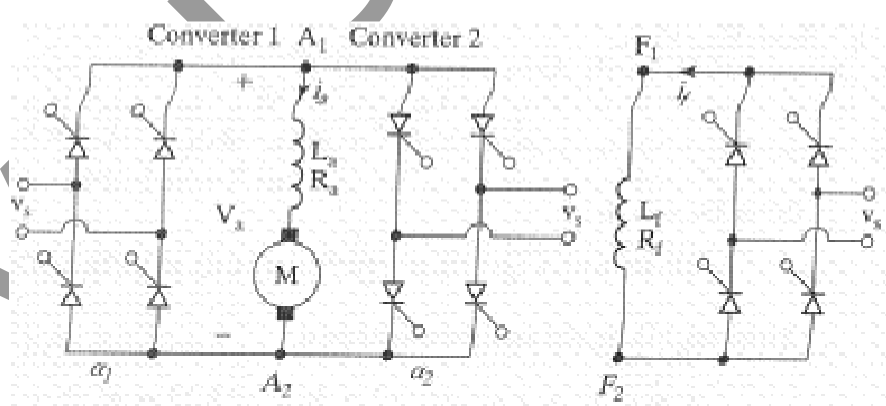


The converter in the field circuit could be a full, or even a dual converter.

• The reversal of the armature or field allows operation in the second and third quadrants.

• The current waveforms for a highly inductive load are shown in Figure for powering action.

Single-Phase Dual-Converter Drives



• Two single-phase full-wave converters are connected.

• Either converter 1 operates to supply a positive armature voltage, Va, or converter 2 operates to supply a negative armature voltage, - Va.

• Converter 1 provides operation in the first and fourth quadrants, and converter 2, in the second and third quadrants.

• It is a four-quadrant drive and permits four modes of operation: forward powering, forward braking (regeneration), reverse powering, and reverse braking (regeneration).

• It is limited to applications up to 15 kW. The field converter could be a fill-wave or a dual converter.

Chopper controlled dc drives

DC to DC converters operating under certain conditions. The use of such converters is extensive in automotive applications, but also in cases where a DC voltage produced by rectification is used to supply secondary loads. The conversion is often associated with stabilizing, i.e. the input voltage is variable but the desired output voltage stays the same. The converse is also required, to produce a variable DC from a fixed or variable source. The issues of selecting component parameters and calculating the performance of the system will be addressed here. Since these converters are switched mode systems, they are often referred to as choppers. The basic circuit of this converter is shown in figure connected first to a purely resistive load. If we remove the low pass filter shown and the diode the output voltage vo(t) is equal to the input voltage Vd when the switch is closed and to zero when the switch is open, giving an average output voltage Vo: Ts = D, the duty ratio. The low pass filter attenuates the high frequencies (multiples of the switching frequency) and leaves almost only the DC component. The energy stored in the filter inductor (or the load inductor) has to be absorbed somewhere other than the switch, hence the diode, which conducts when the switch is open. We‟ll study this converter in the continuous mode of operation i.e. the current through the inductor never becomes zero. As the switch opens and closes the circuit assumes one of the topologies of figures.

If the source of supply is dc. a chopper-type converter is The basic operation of a single-switch chopper and Drives ,where it was shown that the average output voltage could be varied by periodically switching the battery voltage on and off for varying intervals. The principal difference between the thyristor-controlled rectifier and the chopper is that in the forrner the motor current always flows through the supply, whereas in the latter, the motor current only flows from the supply terminals for part of each cycle. A single-switch chopper using a transistor, IvIOSFET or IGBT can only supply positive voltage and current to a dc. Motor, and is therefore restricted to quadrant 1 motoring operation.

UNIT - 5 & 6

INDUCTION MOTOR DRIVES

- Operation with unbalanced source voltage and single phasing
- Operation with unbalanced rotor impedances
- Analysis of induction motor fed from non-sinusoidal voltage supply
- Starting braking, transient analysis.
- Stator voltage control variable voltage frequency control from voltage sources
- Voltage source inverter control, closed loop control current source inverter control current regulated voltage source inverter control
- Rotor resistance control, slip power recovery

An induction or asynchronous motor is a type of AC motor where power is supplied to the rotor by means of electromagnetic, rather than a commutator or slip rings as in other types of motor. These motors are widely used in industrial drives, particularly polyphase induction motors, because they are rugged and have no brushes. Single-phase versions are used in small appliances. Although most AC motors have long been used in fixed-speed load drive service, they are increasingly being used in variable-frequency drive (VFD) service, variable-torque centrifugal fan, pump and compressor loads being by far the most important energy saving applications for VFD service. Squirrel cage induction motors are most commonly used in both fixed-speed and VFD applications.

In both induction and synchronous motors, the AC power supplied to the motor's stator creates a magnetic field that rotates in time with the AC oscillations. Whereas a synchronous motor's rotor turns at the same rate as the stator field, an induction motor's rotor rotates at a slower speed than the stator field. The induction motor stator's magnetic field is therefore changing or rotating relative to the rotor. This induces an opposing current in the induction motor's rotor, in effect the motor's secondary winding, when the latter is short-circuited or closed through external impedance. The rotating magnetic flux induces currents in the windings of the rotor;[14] in a manner similar to currents induced in transformer's secondary windings. These currents in turn create magnetic fields in the rotor that react against the stator field. Due to Lenz's Law, the direction of the magnetic field created will be such as to oppose the change in current through the windings. The cause of induced current in the rotor is the rotating stator magnetic field, so to oppose this rotor will start to rotate in the direction of the rotating stator magnetic field. The rotor accelerates until the magnitude of induced rotor current and torque balances the applied load. Since rotation at synchronous speed would result in no induced rotor current, an induction motor always operates slower than synchronous speed. The difference between actual and synchronous speed or slip varies from about 0.5 to 5% for normal Design A and B torque curve induction motors.[15] The induction machine's essential character is that it is created solely by induction instead of being separately excited as in synchronous or DC machines or being self-magnetized as in permanent magnet motors.

For these currents to be induced, the speed of the physical rotor must be lower than that of the stator's rotating magnetic field (n_s), or the magnetic field would not be moving relative to the rotor conductors and no currents would be induced. As the speed of the rotor drops below synchronous speed, the rotation rate of the magnetic field in the rotor increases, inducing more current in the windings and creating more torque. The ratio between the rotation rate of the magnetic field as seen by the rotor (slip speed) and the rotation rate of the stator's rotating field is called "*slip*". Under load, the speed drops and the slip increases enough to create sufficient torque to turn the load. For this reason, induction motors are sometimes referred to as asynchronous motors.[16] An induction motor can be used as an induction generator, or it can be unrolled to form the motor which can directly generate linear motion.

Operation with unbalanced source voltage and single phasing

A single phase induction motor is not self-starting; thus, it is necessary to provide a starting circuit and associated start windings to give the initial rotation in a single phase induction motor. The normal running windings within such a motor can cause the rotor to turn in either direction, so the starting circuit determines the operating direction.

A polyphase induction motor is self-starting and produces torque even at standstill. Available squirrel cage induction motor starting methods include direct on-line starting and reduced-voltage starting methods based on classical reactor, auto-transformer and star-delta assemblies, or, increasingly, new solid-state soft assemblies and, of course, VFDs.[22] Unlike with the wound-rotor motor, it is not possible to connect the cage rotor to external resistance for starting or speed control.

For small single-phase shaded-pole motor of a few watts, starting is done by a shaded pole, with a turn of copper wire around part of the pole. The current induced in this turn lags behind the supply current, creating a delayed magnetic field around the shaded part of the pole face. This imparts sufficient rotational character to start the motor. These motors are typically used in applications such as desk fans and record players, as the starting torque is very low and low efficiency is not objectionable.

Larger single phase motors have a second stator winding fed with out-of-phase current; such currents may be created by feeding the winding through a capacitor or having it have different values of inductance and resistance from the main winding. In some designs, the second winding is disconnected once the motor is up to speed, usually either by a centrifugal switch acting on weights on the motor shaft or a thermistor which heats up and increases its resistance, reducing the current through the second winding to an insignificant level. Other designs keep the second winding on when running, improving torque.

Polyphase motors have rotor bars shaped to give different speed/torque characteristics. The current distribution within the rotor bars varies depending on the frequency of the induced current. At standstill, the rotor current is the same frequency as the stator current, and tends to travel at the outermost parts of the squirrel-cage rotor bars (the skin effect). The different bar shapes can give usefully different speed/torque characteristics as well as some control over the inrush current at startup. Polyphase motors can generate torque from standstill, so no extra mechanism is required to initiate rotation.

In a wound rotor motor, slip rings are provided and external resistance can be inserted in the rotor circuit, allowing the speed/torque characteristic to be changed for purposes of acceleration control and speed control. Generally, maximum torque is delivered when the reactance of the rotor circuit is equal to its resistance.

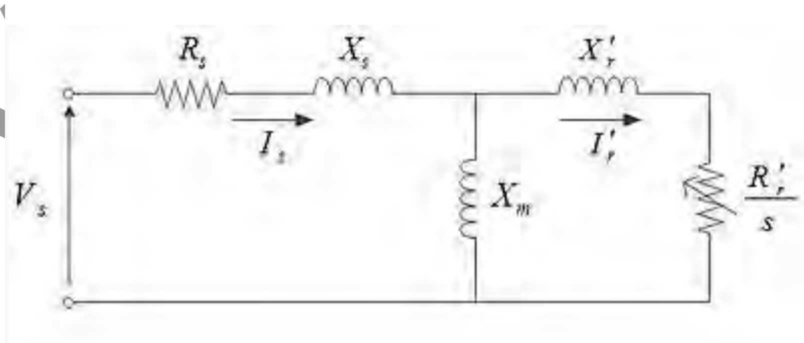
Starting braking, transient analysis

Any useful motor relationships between time, current, voltage, speed, power factor and torque can be obtained from equivalent circuit analysis. The equivalent circuit is a mathematical model used to describe how an induction motor's electrical input is transformed into useful mechanical energy output. A single-phase equivalent circuit representation of a multiphase induction motor is sufficient in steady-state balanced-load conditions.

Neglecting mechanical inefficiencies, the basic components of the induction motor equivalent circuit are:

- Stator resistance and leakage reactance (R_s, X_s)
- Rotor resistance and leakage reactance (R_r, X_r or R_r', X_r')
- Rotor slip (s)
- Magnetizing reactance (X_m)
- Inertia of the motor and mechanical load.

Paraphrasing from Alger in Knowlton, an induction motor is simply an electrical transformer the magnetic circuit of which is separated by an air gap between the stator winding and the moving rotor winding.[13] It is accordingly customary to either separate equivalent circuit components of respective windings by an ideal transformer or refer the rotor components to the stator side as shown in the following simplified equivalent circuit and associated table of equations and symbols:



Need of using starters for Induction motor

• Two (Star Delta and Auto-transformer) types of starters used for Squirrel cage Induction motor

• Starter using additional resistance in rotor circuit, for Wound rotor (Slip-ring) Induction motor. The sketches of the different torque-slip (speed) characteristics, with the variations in input (stator) voltage and rotor resistance, are presented, along with the explanation of their features. Lastly, the expression of maximum torque developed and also the slip, where it occurs, have been derived. In this lesson, starting with the need for using starters in IM to reduce the starting current, first two (Star-Delta and Auto-transformer) types of starters used for Squirrel cage IM and then, the starter using additional resistance in rotor circuit, for Wound rotor (Slip-ring) IM, are presented along with the starting current drawn from the input (supply) voltage, and also the starting torque developed using the above starters. Direct-on-Line (DOL) starter, Star-delta starter, auto-transformer starter, rotor resistance starter, starting current, starting torque, starters for squirrel cage and wound rotor induction motor, need for starters.

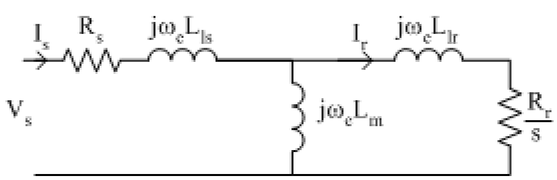
We have seen the speed torque characteristic of the machine. In the stable region of operation in the motoring mode, the curve is rather steep and goes from zero torque asynchronous speed to the stall torque at a value of slip s = ^s. Normally ^s may be such that stall torque is about three times that of the rated operating torque of the machine, and hence may be about 0.3 or less. This means that in the entire loading range of the machine, the speed change is quite small. The machine speed is quite with respect to load changes. The entire speed variation is only in the range ns to (1 _ ^s) ns, ns being dependent on supply frequency and number of poles. The foregoing discussion shows that the induction machine, when operating from mains is essentially a constant speed machine. Many industrial drives, typically for fan or pump applications, have typically constant speed requirements and hence the induction machine is ideally suited for these. However, the induction machine, especially the squirrel cage type, is quite rugged and has a simple construction. Therefore it is good candidate for variable speed applications if it can be achieved. From the torque equation of the induction machine, we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in Fig. These curves show that the slip at maximum torque ^s remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same. Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed

Inverter control, closed voltage source loop control, current source inverter control

The torque speed curves for a drive with a variable voltage supply do not obviously indicate how a variable voltage supply system may provide speed control. In order to use this approach for speed control, it is important to realize that the speed of an induction motor is dependent of the mechanical load: steady state operation is reached when motor torque equals load torque. In the diagram below, a mechanical torque curve for a fan load is plotted on top of the motor torque curves. Fans typically have a torque speed curve where torque is proportional to speed squared or speed cubed, depending on the mechanical design. In the diagram below, the points where the motor torque equals the load torque are highlighted, indicating the resulting speed range Variable Voltage Fixed Frequency Sinusoidal Supply

Circuit Review

Prior to analyzing the performance of a machine under variable voltage and fixed frequency conditions, it is helpful to review the equivalent circuit and induction machine torque equation, as applicable to all operating conditions



Using the above circuit and writing the torque in terms of electrical supply frequency and slip

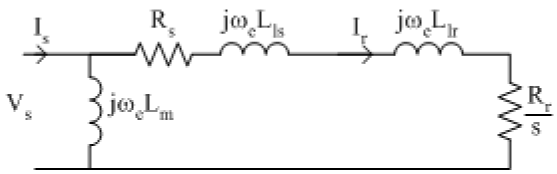
$$\tau = 3\frac{p}{2}\frac{I_r^2 R_r}{s\omega_e}$$

$$\tau = 3\frac{p}{2}\frac{I_r^2 R_r}{\omega_{sl}}$$

The torque equation and circuit shown above are valid for all supply and operation conditions. Much of the work with drives in steady state relates to how to simplify the analysis such that the full equivalent circuit model does not need to be analyzed for each operating condition. Fundamentally, the torque equation above is used in many cases, with different substitutions for rotor current.

Approximation: Low stator voltage drop

If the voltage drop across the stator is negligible relative to the voltage drop across the magnetizing reactance, it is reasonable to re-draw the equivalent circuit with the magnetizing branch at the terminals of the circuit.



The primary advantage of using the approximate circuit shown above is that the calculation of rotor current is greatly simplified.

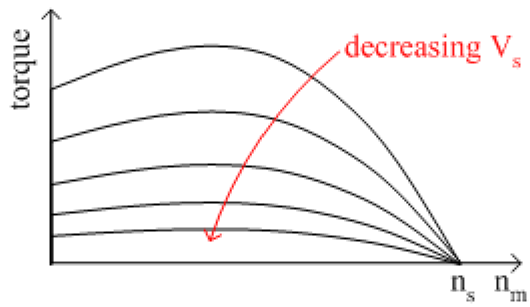
$$I_r = \frac{V_s}{R_r + \frac{R_r}{s} + j\omega_e\left(L_{lr} + L_{ls}\right)}$$

Substituting into the torque equation

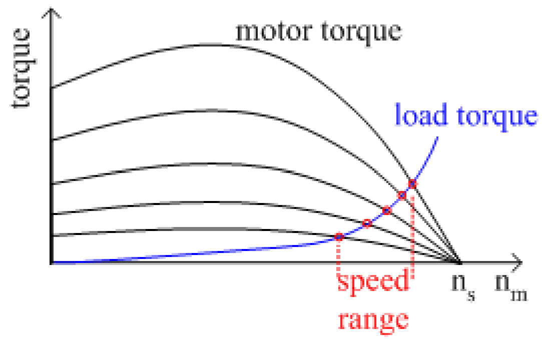
$$\tau = 3\frac{p}{2}\frac{R_r}{\omega_{sl}}\frac{V_s^2}{\left(R_r + \frac{R_r}{s}\right)^2 + j\omega_e^2\left(L_{lr} + L_{ls}\right)^2}$$

Fixed Frequency Operation

If the stator supply frequency is held at the rated value $f_{e\ b}$, the stator voltage cannot be increased above the rated value$V_{s\ b}$, it can only be reduced. Considering the torque equation above, it can be seen that the magnitude of torque is proportional to voltage squared. The shape of the torque-speed curve will be independent of voltage. Torque speed curves for an induction motor with a variable voltage supply are sketched in the figure below.



Speed Control.



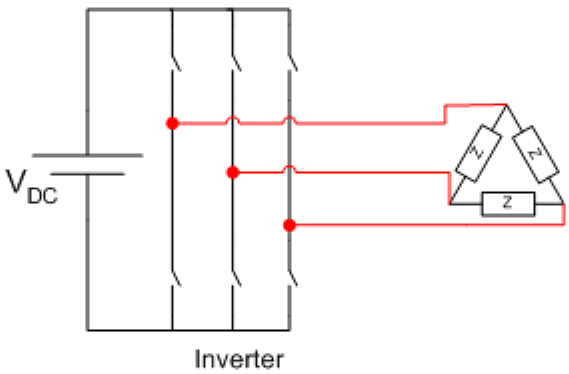
It is important to realise that the above torque curves are typical for a class D induction motor, with high slip for pull out torque. A machine with a low pull out slip will not provide the speed control required.

Variable voltage control can be easily achieved in practice by chopping the input sine wave, using anti-parallel thyristors, or triacs in low power applications. As a result, the control is cheap, but introduces significant harmonic content into the supply and motor circuit, reducing efficiency and power factor.

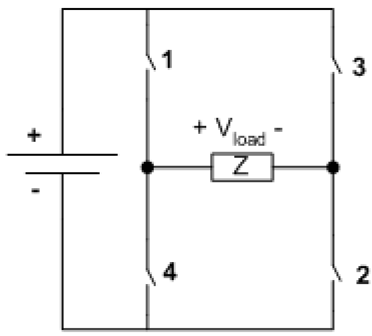
Voltage Sourced Options

This section of the course considers voltage sourced drives. Essentially this type of drive uses voltage to supply the machine, with currents being a result of the applied voltage. This is the usual way of viewing a machine to those used to standard fixed frequency bus supplies. It is also possible to supply machines form a current source, considered later.

To begin this section of the course, assume that the motor is supplied via a drive with a DC link. The drive can be thought of as an inverter fed from a DC supply. In the diagram below, a simple 3-phase inverter is shown connected to a delta load.



The voltage applied to one phase of the load can be seen as the difference between the output voltages of two of the three inverter legs.



Considering a single phase of the load, the phase voltage can be made to switch between the full positive dc link voltage, zero, or the negative dc link voltage, depending on inverter switching.

If switches 1 and 2 are closed, the load voltage is $+V_{DC}$. If switches 3 and 4 are closed, the load voltage is $-V_{DC}$.

If both switches 1 and 3 are closed while 2 and 4 are open, the load voltage is zero. (Similarly the load voltage is zero when 1 and 3 are open and 2 and 4 are closed.

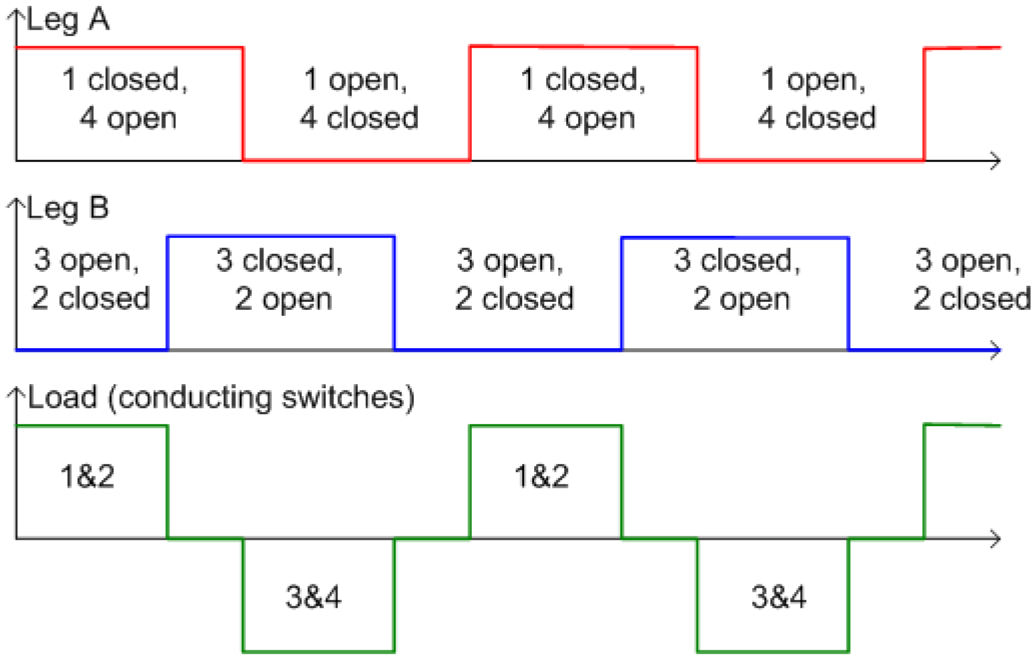
Basic Options

With the basic information about voltage supplied to a single phase of the output, a decision can be made about how to best operate the inverter. Three basic options are:

- Square Wave Supply
- Pulse Width Modulation Supply
- Current Source Supply

Square Wave

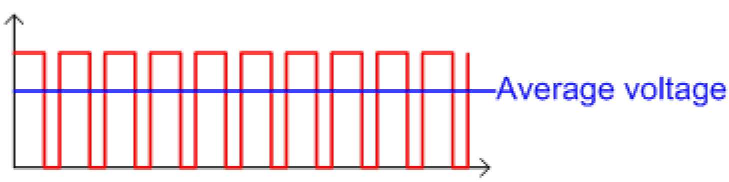
The most basic inverter operation, square wave output involves switching such that each leg has 180° conduction for each switch. The resulting waveforms are shown below:



It can be seen that the output line-line voltage (load switches between positive, zero and negative. Changing the switching frequency will change the fundamental supply frequency. However, the fundamental voltage is fixed by the DC voltage. This makes square wave switching unsuitable below rated speed. To use square wave switching below rated speed, a variable DC link voltage would be needed. It is better to use an inverter switching strategy that can provide variable voltage and frequency output from a constant DC voltage.

Pulse Width Modulation (PWM)

The basic idea behind PWM is to rapidly switch between positive and zero voltage to get an average voltage output that is somewhere between the positive value and zero. In the diagram below, the voltage is positive for two thirds of the switching cycle, therefore the average voltage is two thirds of the DC value.



In an AC drive, the switching frequency is much higher than the fundamental frequency (typically 2kHz-10kHz). Effectively, the average value of the voltage over one switching cycle is made to vary to produce a sinusoidal fundamental output signal.

Current Control

In a voltage sources current controlled drive, the output currents are measured and compared to a desired reference. If the current is too low, the voltage is switched high. If the currents are too low, the voltage is switched low. In this closed loop control scheme, the switching pattern cannot be determined in advance.

From the perspective of the motor, current sourced drives operate on the same principle as current controlled voltage sourced drives. i.e. the drive operates to maintain magnetising current, which in turn maintains rated flux in the machine, allowing control with torque proportional to slip speed, independent of synchronous speed.

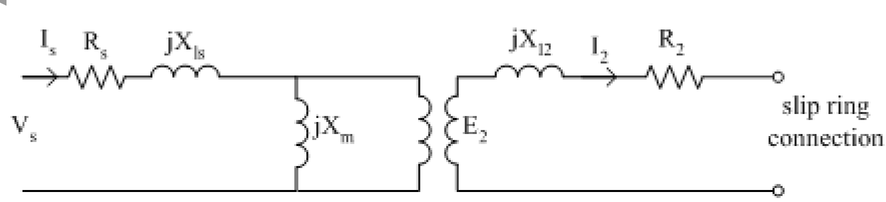
From the perspective of the drive, current sourced drives are very different to voltage sourced drives. There is no fixed relationship between voltage and frequency and in many cases the stator voltage does not need to be known. Current sourced drives have a similar topology to voltage sourced drives, with a rectifier, DC link and inverter. Unlike voltage sourced drives, the DC link has a very large inductance to maintain constant DC link current, providing a current source to the inverter.

Slip power recovery

Slip Control

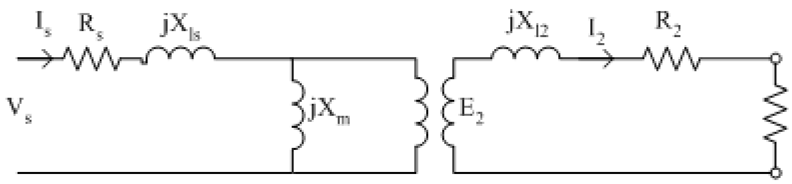
Slip control is only possible with wound rotor induction motors. The principle of slip control is to control the speed of the motor by adjusting the rotor circuit, while the stator supply voltage and frequency remain constant.

Consider the equivalent circuit of a wound rotor induction machine with the rotor circuit not referred to the stator.

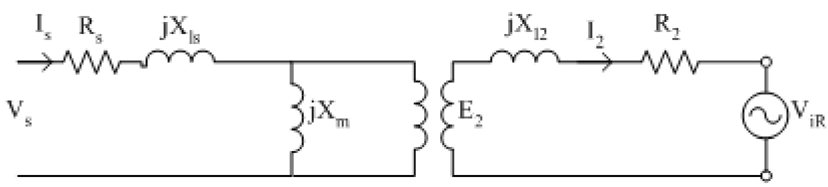


Note that to maintain the drives notation of subscript "r" to denote rotor variables referred to the stator, subscript "2" is used for actual rotor circuit parameters. This is the reverse of the standard machines notation used in the machines course.

Applying slip control, airgap power is diverted from the mechanical system to an external rotor circuit. This can be achieved with an external resistance:



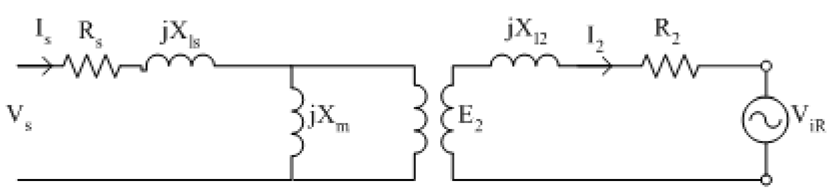
or by applying a voltage to the rotor slip rings



Slip Energy Recovery

A major drawback of rotor resistance control is that the available power of the machine is being reduced by diverting power to additional losses. Ideally, the power diverted from the mechanical system is recovered, reducing total energy consumption. This approach is called slip energy recovery.

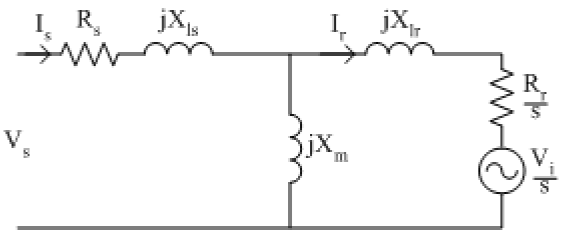
In slip energy recovery, a voltage is applied to the slip ring terminals, in phase with the rotor current.:



The injected voltage can be referred to the stator

$$V_i = \frac{V_{iR}}{a_{eff}}$$

giving the equivalent circuit:

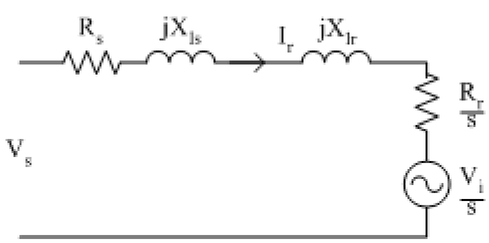


Principle of Operation

Considering the equivalent circuit, if the injected voltage is increased, the rotor current will be reduced, resulting in a reduction in the available torque generated by the motor. If there is a load applied to the motor, the rotor will slow down, resulting in an increase in slip. As slip increases, the effective voltage seen by the stator will be reduced (the actual voltage physically induced in the rotor, due to the stator, will increase). As a result, rotor current will increase. This process allows the machine to find a new steady state where the induced rotor current produces enough torque to equal the load torque.

Analysis of operation

In order to simplify the analysis, assume that the magnetising reactance can be moved to the terminals of the equivalent circuit. (If this is not the case, the stator phase voltage, stator impedance and magnetising reactance can be replaced by a Thevenin source and impedance. Simply replace subscript "s" in the following analysis with subscript "TH").



If the injected voltage is in phase with the rotor current, then the voltages in the equivalent circuit may be written as

$$V_s = \vec{I}_R\left(R_{s+}\frac{R_R}{s}\right)+\frac{\vec{V_i}}{s}+j\vec{I}_R\left(X_{Ls}+X_{Lr}\right)$$

$$V_s = \frac{I_r R_r + V_i}{s}\angle\theta_r + I_r\left(X_{Ls}+X_{Lr}\right)\angle\left(\theta_r+90^\circ\right)$$

$$V_s^2 = \left(I_r R_s + \frac{I_r R_r + V_i}{s}\right)^2 + I_r^2\left(X_{Ls}+X_{Lr}\right)^2$$

rearranging, the slip may be found as

$$s = \frac{V_i + I_r R_r}{\left(V_s^2 - I_r^2 \left(X_{Ls} + X_{Lr}\right)^2\right)^{1/2} - I_r R_s}$$

Power and Torque

The air gap power of the machine may be written as

$$P_{gap} = 3 I_r \frac{\left(I_r R_r + V_i\right)}{s}$$

Breaking this equation into parts, it can be seen that the air gap power is the sum of resistive losses, power recovered through the slip rings and the mechanical power.

$$P_{gap} = 3 I_r^2 R_r + 3 I_r V_i + 3 I_r \left(I_r R_r + V_i\right) \frac{(1-s)}{s}$$

Using the expression for air gap power, the torque may be written as

$$\tau = 3 I_r \frac{\left(I_r R_r + V_i\right)}{s \omega_s}$$

Now, substituting the slip expression into the torque expression gives the result that torque is only a function of rotor current, not slip or injected voltage:

$$\tau = \frac{3 I_r}{\omega_s} \left[\left(V_s^2 - I_r^2 \left(X_{Ls} + X_{Lr}\right)^2\right)^{1/2} - I_r R_s \right]$$

The expression above means that for a given torque, the rotor current will always be the same, independent of speed. Analysing the torque equation, this in turn means that for a given constant value of torque

$$\frac{\left(I_r R_r + V_i\right)}{s}$$

will be constant. The injected voltage required to adjust the slip at a given load can be found from this expression.

No-Load Condition

Consider again the expression for slip:

$$s = \frac{V_i + I_r R_r}{\left(V_s^2 - I_r^2 \left(X_{Ls} + X_{Lr}\right)^2\right)^{1/2} - I_r R_s}$$

If the torque is zero, then the rotor current will also be zero and at zero torque, the slip is given by

$$s_0 = \frac{V_i}{V_s}$$

Efficiency

Since some of the power supplied to the motor is recovered from the rotor circuit, the efficiency cannot be calculated as simply output power over input power. Instead, in a slip energy recovery drive the efficiency is

$$\eta = \frac{P_{out}}{P_{in} - P_{recovered}}$$

Speed control of single phase induction motors

We have seen the speed torque characteristic of the machine. In the stable region of operation in the motoring mode, the curve is rather steep and goes from zero torque asynchronous speed to the stall torque at a value of slip s = ^s. Normally ^s may be such that stall torque is about three times that of the rated operating torque of the machine, and hence may be about 0.3 or less. This means that in the entire loading range of the machine, the speed change is quite small. The machine speed is quite with respect to load changes. The entire speed variation is only in the range ns to (1 _ ^s)ns, ns being dependent on supply frequency and number of poles. The foregoing discussion shows that the induction machine, when operating from mains is essentially a constant speed machine. Many industrial drives, typically for fan or pump applications, have typically constant speed requirements and hence the induction machine is ideally suited for these. However, the induction machine, especially the squirrel cage type, is quite rugged and has a simple construction. Therefore it is good candidate for variable speed applications if it can be achieved.

Speed control by changing applied voltage

From the torque equation of the induction machine, we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in Fig. These curves show that the slip at maximum torque ^s remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same. Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed

Rotor resistance control

The reader may recall the expression for the torque of the induction machine. Clearly, it is dependent on the rotor resistance. Further, that the maximum value is independent of the rotor resistance. The slip at maximum torque dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shift to higher slip values, while retaining a constant torque. Figure shows family of torque-speed characteristic obtained by changing the rotor resistance. Note that while the maximum torque and synchronous speed remain constant, the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque. Whether the load is of constant torque type or fan-type, it is evident that the speed control range is more with this method. Further, rotor resistance control could also be used as a means of generating high starting torque. For all its advantages, the scheme has two serious drawbacks. Firstly, in order to vary the rotor resistance, it is necessary to connect external variable resistors (winding resistance itself cannot be changed). This, therefore necessitates a slip-ring machine, since only in that case rotor terminals are available outside. For cage rotor machines, there are no rotor terminals. Secondly, the method is not very efficient since the additional resistance and operation at high slips entails dissipation resistors connected to the slip-ring brushes should have good power dissipation capability. Water based rheostats may be used for this. A `solid-state' alternative to a rheostat is a chopper controlled resistance where the duty ratio control of the chopper presents a variable resistance load to the rotor of the induction machine

Cascade control The power drawn from the rotor terminals could be spent more usefully. Apart from using the heat generated in meaning full ways, the slip ring output could be connected to another induction machine. The stator of the second machine would carry slip frequency currents of the first machine, which would generate some useful mechanical power. A still better option would be to mechanically couple the shafts of the two machines together. This sort of a connection is called cascade connection and it gives some measure of speed control as shown below. Let the frequency of supply given to the first machine be f1, its number poles bep1, and its slip of operation be s1. Let f2; p2 and s2 be the corresponding quantities for the second machine. The frequency of currents owing in the rotor of the first machine and hence in the stator of the second machine is s1f1. Therefore f2 = s1f1. Since the machines are coupled at the shaft, the speed of the rotor is common for both. Hence, if n is the speed of the rotor

Pole changing Schemes

Einstein College of Engineering Sometimes induction machines have a special stator winding capable of being externally connected to form two different number of pole numbers. Since the synchronous speed of the induction machine is given by ns = fs=p (in rev./s) where p is the number of pole pairs, this would correspond to changing the synchronous speed. With the slip now corresponding to the new synchronous speed, the operating speed is changed. This method of speed control is a stepped variation and generally restricted to two steps. If the changes in stator winding connections are made so that the air gap flux remains constant, then at any winding connection, the same maximum torque is achievable. Such winding arrangements are therefore referred to as constant-torque connections. If however such connection changes result in air gap flux changes that are inversely proportional to the synchronous speeds, then such connections are called constant-horsepower type. The following figure serves to illustrate the basic principle. Consider a magnetic pole structure consisting of four poles faces A, B, C, D in fig. Coils are wound on A & C in the directions shown. The two coils on A & C may be connected in series in two different ways | A2 may be connected to C1 or C2. A1 with the other terminal at C then form the terminals of the overall combination. Thus two connections result, for a given direction of current flow at terminal A1, say into terminal A1,the flux directions within the poles are shown in the figures. In case (a), the flux lines are out of the pole A (seen from the rotor) for and into pole C, thus establishing a two-pole structure

Stator frequency control

The expression for the synchronous speed indicates that by changing the stator frequency also it can be changed. This can be achieved by using power electronic circuits called inverters, which convert dc to ac of desired frequency. Depending on the type of
control scheme of the inverter, the ac generated may be variable-frequency-fixed-amplitude or variable-frequency- variable-amplitude type. Power electronic control achieves smooth variation of voltage and frequency of the ac output. This when fed to the machine is capable of running at a controlled speed. However, consider the equation fort the induced emf in the induction machine. Figure : Pole change example: three phase where N is the number of the turns per phase, _m is the peak flux in the air gap and f

is the frequency. Note that in order to reduce the speed, frequency has to be reduced. If the frequency is reduced while the voltage is kept constant, thereby requiring the amplitude of induced emf to remain the same, flux has to increase. This is not advisable since the machine likely to enter deep saturation. If this is to be avoided, then flux level must be maintained constant which implies that voltage must be reduced along with frequency. The ratio is held constant in order to maintain the flux level for maximum torque apability. Actually, it is the voltage across the magnetizing branch of the exact equivalent circuit that must be maintained constant, for it is that which determines the induced emf. Under conditions where the stator voltage drop is negligible compared the applied voltage, is valid. In this mode of operation, the voltage across the magnetizing inductance in the ‚exact' equivalent circuit reduces in amplitude with reduction in frequency and so does the inductive reactance. This implies that the current through the inductance and the flux in the machine remains constant. The speed torque characteristics at any frequency may be estimated as before. There is one curve for every excitation frequency considered corresponding to every value of synchronous speed. The curves are shown below. It maybe seen that the maximum torque remains constant.

UNIT - 7

SYNCHRONOUS MOTOR DRIVES

- Operation form faced frequency supply, synchronous motor variable speed drives
- Variable frequency control of multiple synchronous motors
- Self-controlled synchronous motor drive employing load commutated thruster inverter.

Introduction: AC Motor Drives

•Ac motors exhibit highly coupled, nonlinear, and multivariable structures as opposed to much simpler decoupled structures of separately excited de motors

• The control of or drives generally requires complex control algorithms that can be performed by microprocessors or microcomputers along with fast-switching power converters.

• The ac motors have a number of advantages, they are lightweight (20 to 40% higher than equivalent de motors), are inexpensive, and have low maintenance compared with dc motors.

• They require control of frequency, voltage, and current for variable-speed applications.

• The power converters, inverters, undue voltage controllers can control the frequency, voltage, or current to meet the drive requirements. AC drives, inverters, and adjustable frequency drives are all terms that are used to refer to equipment designed to control the speed of an AC motor. The term SIMOVERT is used by Siemens to identify a SIemens MOtor inVERTer (AC drive). AC drives receive AC power and convert it to an adjustable frequency, adjustable voltage output for controlling motor operation. A typical inverter receives 480 VAC, three-phase, 60 Hz input power and in turn provides the proper voltage and frequency for a given speed to the motor. The three common inverter types are the variable voltage inverter (VVI), current source inverter (CSI), and pulse width modulation (PWM). Another type of AC drive is a cycloconverter. These are commonly used for very large motors. All AC drives convert AC to DC, and then through various switching techniques invert the DC into a variable voltage, variable frequency output.

The variable voltage inverter (VVI) uses an SCR converter Inverter (VVI) bridge to convert the incoming AC voltage into DC. The SCRs provide a means of controlling the value of the rectified DC voltage from 0 to approximately 600 VDC. The L1 choke and C1 capacitor(s) make up the DC link section and smooth the converted DC voltage. The inverter section consists of six switching devices. Various devices can be used such as thyristors, bipolar transistors, MOSFETS, and IGBTs. The following schematic shows an inverter that utilizes bipolar transistors. Control logic (not shown) uses a microprocessor to switch the transistors on and off providing a variable voltage and frequency to the motor.

Operation form fixed frequency supply

Generator Action

If an induction motor is forced to run at speeds in excess of the synchronous speed, the load torque exceeds the machine torque and the slip is negative, reversing the rotor induced EMF and rotor current. In this situation the machine will act as a generator with energy being returned to the supply. If the AC supply voltage to the stator excitation is simply removed, no generation is possible because there can be no induced current in the rotor.

Regenerative braking

Thus in traction applications, regenerative braking is not possible below synchronous speed in a machine fed with a fixed frequency supply. If however the motor is fed by a variable frequency inverter then regenerative braking is possible by reducing the supply frequency so that the synchronous speed becomes less than the motor speed.AC motors can be microprocessor controlled to a fine degree and can regenerate current down to almost a stop whereas DC regeneration fades quickly at low speeds.

Dynamic Braking: Induction motors can be brought rapidly to a stop (and / or reversed) by reversing one pair of leads which has the effect of reversing the rotating wave. This is known as "plugging". The motor can also be stopped quickly by cutting the AC supply and feeding the stator windings instead with a DC (zero frequency) supply. With both of these methods, energy is not returned to the supply but is dissipated as heat in the motor. These techniques are known as dynamic braking.

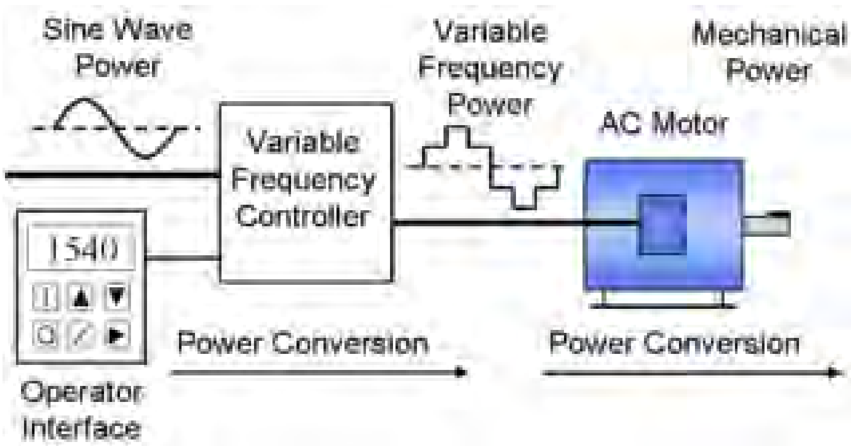
Starting

Three phase induction motors and some synchronous motors are not self starting but design modifications such as auxiliary or "damper" windings on the rotor are incorporated to overcome this problem. Usually an induction motor draws 5 to 7 times its rated current during starting before the speed builds up and the current is modified by the back EMF. In wound rotor motors the starting current can be limited by increasing the resistance in series with the rotor windings. In squirrel cage designs, are used to control the current to prevent damage to the motor or to its power supply. Even with current control the motor can still overheat because, although the current can be limited, the speed build up is slower and the inrush current, though reduced, is maintained for a longer period.

Power Factor

The current drawn by an induction motor has two components, the current in phase with the voltage which governs the power transfer to the load and the inductive component, representing the magnetizing current in the magnetic circuit, which lags 90° behind the load current. The power factor is defined as cosΦ where Φ is the net lag of the current behind the applied voltage due to the in phase and out of phase current components. The net power delivered to the load is VAcosΦ where V is the applied voltage; A is the current which flows. Various methods of power factor correction are used to reduce the current lag in order to avoid losses due to poor power factor. The simplest is to connect a capacitor of suitable size across the motor terminals. Since the current through a capacitor leads the voltage, the effect of the capacitor is to counter-balance the inductive element in the motor canceling out the current lag.power factor correction can also be accomplished in the motor controller

Synchronous motor variable speed drives



The variable frequency drive controller is a solid state power electronics conversion system consisting of three distinct sub-systems: a rectifier bridge converter, a direct current (DC) link, and an inverter. Voltage-source inverter (VSI) drives (see 'Generic topologies' sub-section below) are by far the most common type of drives. Most drives are AC-AC drives in that they convert AC line input to AC inverter output. However, in some applications such as common DC bus or solar applications, drives are configured as DC-AC drives. The most basic rectifier converter for the VSI drive is configured as a three-phase, six-pulse, full-wave diode bridge. In a VSI drive, the DC link consists of a capacitor which smooths out the converter's DC output ripple and provides a stiff input to the inverter. This filtered DC voltage is converted to quasi-sinusoidal AC voltage output using the inverter's active switching elements. VSI drives provide higher power factor and lower harmonic distortion than phase-controlled current-source inverter (CSI) and load-commutated inverter (LCI) drives (see 'Generic topologies' sub-section below). The drive controller can also be configured as a phase converter having single-phase converter input and three-phase inverter output.

Controller advances have exploited dramatic increases in the voltage and current ratings and switching frequency of solid state power devices over the past six decades.

Introduced in 1983,[8] the insulated-gate bipolar transistor (IGBT) has in the past two decades come to dominate VFDs as an inverter switching device.

In variable-torque applications suited for Volts per Hertz (V/Hz) drive control, AC motor characteristics require that the voltage magnitude of the inverter's output to the motor be adjusted to match the required load torque in a linear V/Hz relationship. For example, for 460 volt, 60 Hz motors this linear V/Hz relationship is 460/60 = 7.67 V/Hz. While suitable in wide ranging applications, V/Hz control is sub-optimal in high performance applications involving low speed or demanding, dynamic speed regulation, positioning and reversing load requirements. Some V/Hz control drives can also operate in quadratic V/Hz mode or can even be programmed to suit special multi-point V/Hz paths.

The two other drive control platforms, vector control and direct torque control (DTC), adjust the motor voltage magnitude, angle from reference and frequency[14] such as to precisely control the motor's magnetic flux and mechanical torque. Although space vector pulse-width modulation (SVPWM) is becoming increasingly popular,[15] sinusoidal PWM (SPWM) is the most straightforward method used to vary drives' motor voltage (or current) and frequency. With SPWM control (see Fig. 1), quasi-sinusoidal, variable-pulse-width output is constructed from intersections of a saw-toothed carrier frequency signal with a modulating sinusoidal signal which is variable in operating frequency as well as in voltage (or current). Operation of the motors above rated nameplate speed (base speed) is possible, but is limited to conditions that do not require more power than the nameplate rating of the motor. This is sometimes called "field weakening" and, for AC motors, means operating at less than rated V/Hz and above rated nameplate speed. Permanent magnet synchronous motors have quite limited field weakening speed range due to the constant magnet flux linkage. Wound rotor synchronous motors and induction motors have much wider speed range. For example, a 100 hp, 460 V, 60 Hz, 1775 RPM (4 pole) induction motor supplied with 460 V, 75 Hz (6.134 V/Hz), would be limited to 60/75 = 80% torque at 125% speed (2218.75 RPM) = 100% power. At higher speeds the induction motor torque has to be limited further due to the lowering of the breakaway torque[a] of the motor. Thus rated power can be typically produced only up to 130...150% of the rated nameplate speed. Wound rotor synchronous motors can be run at even higher speeds. In rolling mill drives often 200...300% of the base speed is used. The mechanical strength of the rotor limits the maximum speed of the motor.

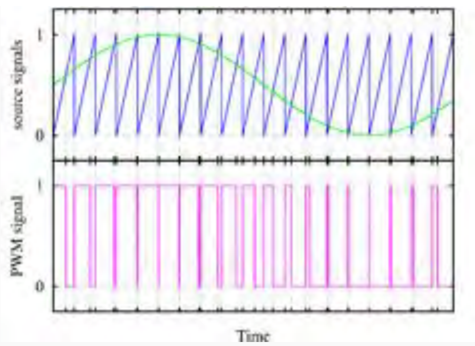


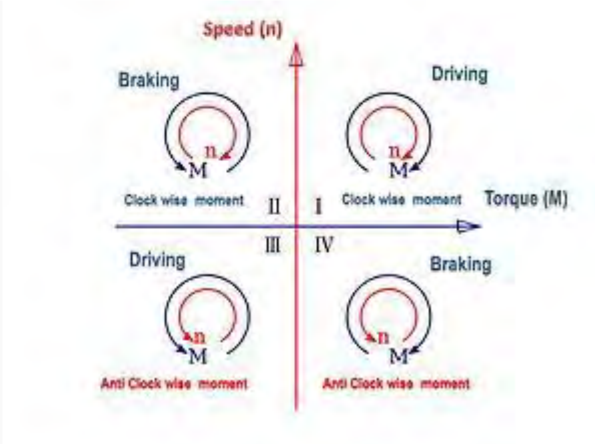
Fig. 1: SPWM carrier-sine input & 2-level PWM output

An embedded microprocessor governs the overall operation of the VFD controller. Basic programming of the microprocessor is provided as user inaccessible firmware. User programming of display, variable and function block parameters is provided to control, protect and monitor the VFD, motor and driven equipment.[9][19]

The basic drive controller can be configured to selectively include such optional power components and accessories as follows:

- Connected upstream of converter - circuit breaker or fuses, isolation contactor, EMC filter, line reactor, passive filter
- Connected to DC link - braking chopper, braking resistor
- Connected downstream of inverter - output reactor, sine wave filter, dV/dt

Drive operation



Electric motor speed-torque chart

Referring to the accompanying chart, drive applications can be categorized as single-quadrant, two-quadrant or four-quadrant; the chart's four quadrants are defined as follows

- Quadrant I - Driving or motoring,forward accelerating quadrant with positive speed and torque
- Quadrant II - Generating or braking, forward braking-decelerating quadrant with positive speed and negative torque
- Quadrant III - Driving or motoring, reverse accelerating quadrant with negative speed and torque
- Quadrant IV - Generating or braking, reverse braking-decelerating quadrant with negative speed and positive torque.

Most applications involve single-quadrant loads operating in quadrant I, such as in variable-torque (e.g. centrifugal pumps or fans) and certain constant-torque (e.g. extruders) loads.

Certain applications involve two-quadrant loads operating in quadrant I and II where the speed is positive but the torque changes polarity as in case of a fan decelerating faster than natural mechanical losses. Some sources define two-quadrant drives as loads operating in quadrants I and III where the speed and torque is same (positive or negative) polarity in both directions.

Certain high-performance applications involve four-quadrant loads (Quadrants I to IV) where the speed and torque can be in any direction such as in hoists, elevators and hilly conveyors. Regeneration can only occur in the drive's DC link bus when inverter voltage is smaller in magnitude than the motor back-EMF and inverter voltage and back-EMF are the same polarity.

In starting a motor, a VFD initially applies a low frequency and voltage, thus avoiding high inrush current associated with direct on line starting. After the start of the VFD, the applied frequency and voltage are increased at a controlled rate or ramped up to accelerate the load. This starting method typically allows a motor to develop 150% of its rated torque while the VFD is drawing less than 50% of its rated current from the mains in the low speed range. A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed.[29] However, motor cooling deteriorates and can result in overheating as speed decreases such that prolonged low speed motor operation with significant torque is not usually possible without separately-motorized fan ventilation.

With a VFD, the stopping sequence is just the opposite as the starting sequence. The frequency and voltage applied to the motor are ramped down at a controlled rate. When the frequency approaches zero, the motor is shut off. A small amount of braking torque is available to help decelerate the load a little faster than it would stop if the motor were simply switched off and allowed to coast. Additional braking torque can be obtained by adding a braking circuit (resistor controlled by a transistor) to dissipate the braking energy. With a four-quadrant rectifier (active-front-end), the VFD is able to break the load by applying a reverse torque and injecting the energy back to the AC line.

Self-controlled synchronous motor drive employing load commutated thruster inverter

For high performance dynamic applications the most suitable solution is the vector controlled AC drive fed by a static frequency converter (SFC). The wound-excited synchronous motor (Ex-SyM) is the only machine capable to operate at unity or leading power factor (PF). The structure of the vector control system is determined by the combination between the types of the SFC used including the pulse width modulation (PWM) procedure, the orientation field and its identification method .The rigorous control of the PF can be made only with the resultant stator field orientation. If the PF is maximum, there is no reactive energy transfer between the armature and the three-phase power source. Some motor-control-oriented digital signal processing (DSP) equipment‟s present on the market don‟t dispose over implementation possibility of the current-feedback PWM, suitable for current-controlled VSIs, consequently in the control structure it is necessary the computation of the voltage control variables from the current ones, imposed or directly generated by the controllers. The proposed control structure is based on both types of orientation. The stator-field orientation is used for control of the unity power factor and stator flux, and also for generation of the armature-current control variables. The orientation according to the rotor position (i.e. exciting-field orientation) is applied for self-commutation and for generation of the armature-voltage control variables for the inverter control. The transition between the two orientations is performed by using a coordinate transformation block (which rotates the stator-field oriented reference frame with the value of the load angle ($\delta = \lambda s - \theta$).

The d.c. motors with Ward Leonard speed control or ac. commutator motors can be employed for such mill.

Key Point: In general, the d.c. motors with Ward Leonard speed control, with flywheel arrangement are versatile as motors for mill drives. The d.c. dynamic braking may be employed for quick stopping and controlled braking.

UNIT - 8

INDUSTRIAL DRIVES:

- Rolling mill drives
- Cement mill drives
- Paper mill dries
- Textile mill drives.

Comparison of A.C. and D.C. Drives

In some cases it is possible that both ac. and d.c. motors find their suitability. In such cases comparison of ac. and d.c. drives is helpful to do the final selection.

D.C. Drive A.C. Drive -I Speed-torque curve can be adjusted as per the requirement, very easily This s possible by adding a simple rheostat in armature or fold circuit It S not very easy to adjust speed-torque curves The starting torque cannot be adjusted without special arrangements in sequin& cage motors but can be adjusted for slip ring motel's by 1010r resistance 2, se starling, test acceleration are the leaturee Alt at. motors are not self starting. The synchronous motors are not self starting. Frequent maintenance s required because of commutator and brushes. Less maintenance compared to d.c. motors. 4. The drive motor and as control are costly The squirrel cage motors are cheaper. simple in construction and robust.

Steel Rolling Mill drives

Steel Rolling Mills Steel mills are usually produces slabs, rails, sheets, ships, beams, bars, angles etc. These are classified further as continuous cold rolling mills, reversing cold rolling mills, continuous hot rolling mills and reversing hot rolling mills. A continuous mill consists of several stands, each one of them carrying pressing rolls. The metal passes through all the stands in only one direction and gets rolled simultaneously. While in a reversing mill there is only one stand carrying a pressing roll. The metal is passed through this stand alternately forward and backward several times till it reduces to the desired smaller size. In a continuous cold rolling mills metal passes only in one direction. The roller requires accurate torque and speed control. Low speed operation is required at the time of threading, the steel into rolls. Immediately after threading speed is required to be increased. In a reversing cold rolling mill, the strip to be rolled is received by the mill in the form of a reel. One side of the mill stand, there is delivering reel and on other side there is receiving reel. When the receiving mandrel is empty, the threading of metal is done manually. The required tension and pressure should be maintained by increasing motor speed with uniform acceleration. The drive requirements are that it must be capable of reverse rotation, one or two individually driven motors, inertia of the motor should be low and torque, speed control should be possible to maintain the constant tension of strip. To suit these requirements, a d.c. motor with a Ward Leonard control with flywheel is a proper selection. In a reversing hot rolling mills, slabs from hot steel ingots which come directly from steel making shop, are manufactured. The ingots are passed in mill stand in both the direction till they are pressed to desired thickness. The drive requirements for this mill are wide range of speeds of operation, the duty cycle consists of frequent starts and speed reversals, the direction of rotation must be reversible easily, reliability and accuracy of operation. The power rating of the drive must be capable of driving intermittent continuous load. The d.c. motor with Ward Leonard speed control is again a proper selection for this mill. For fast retardation, armature current control can be employed. Load equalization possible by fly wheel. For reliability and accuracy a closed loop automatic speed control should be employed. In continuous hot rolling mills billets or strips are produced. The operation is only in the forward direction.

The metal is processed simultaneously in the finishing stands. The drive requirements are that while producing strips of various sizes gap between rolls of the mill stand must be adjustable. To reduce the thickness of the metal gradually, the drive must have different speeds. The wide range of accurate speed control is necessary. When metal comes in contact with the roll, speed suddenly drops. So drive must be capable of restoring the speed again very quickly. The d.c. motors with Ward Leonard speed control or ac. commutator motors can be employed for such mill.

Key Point: In general, the d.c. motors with Ward Leonard speed control, with flywheel arrangement are versatile as motors for mill drives. The d.c. dynamic braking may be employed for quick stopping and controlled braking.

Cranes and Hoists The requirements of the drive are as follows The acceleration and retardation must be uniform. For exact positioning of loads creep speeds must be possible. The motion of crane is in all three dimensions. The drive must have high speeds in both the directions horizontal and vertical. The speed must be constant while lowering the loads. Mechanical braking must be available in emergency. Due to heavy inrush of current at starts, fluctuations in supply voltage are possible. The drive motor must be capable of withstanding such fluctuations. Among the d.c. motors, the sense motors are most preferred for crane operations. The motors have good starting torque, high torque capacity at light loads, simple arrangement of braking, electric braking at low speeds is possible. The only disadvantage is that the motors are less stable while the regenerative braking. So additional stabilizing circuits are necessary. Advances made in the technology of solid state devices have enabled the use of thyristor converters and choppers for driving the de. Motors used in cranes and hoists with good accuracy, reliability and efficiency.

Textile mill drives

The textile mill has various processes like ginning. Spinning and looms. The ginning means the separation of seeds from cotton. The process requires standard starting torque and standard overload capacity, at constant speed. No speed control is required. The operation is at constant speed. The standard squirrel cage induction motor is the proper choice. The twisting to produce continuous yam of sufficient strength is called as spinning process. The moderate starting torque and high overload capacity is necessary. Acceleration must be constant or uniform so that there is no breakage of thread. The operation is at constant speed hence no speed control is necessary but two speed motors are preferred. Normally a 4 pole to 6 pole squirrel cage induction motor is used. Before the yarn is actually woven, it is made into a uniform layer. The process is called as weaving and done in a loom. This requires 2 to 2.3 times rated torque at start. There are frequent starts and stops. But operation is at constant speed and no speed control is necessary. The totally enclosed high torque squirrel cage induction motors are preferred. The motors are usually of 6 or 8 poles. The ratings of the motors for light fabrics such as cotton silk, rayon etc. are 0.37, 0.55 to 1.5 kW while for wool it is 2.2 to 3.7 kW.

From the stage cotton is picked in the field to the stage it leaves the mills as finished cloth; it undergoes different processes, viz., cotton to slivers, spinning, weaving and finishing.

Cotton to slivers: The process of separating the seeds from cotton is known as ginning. Ginning mills are usually located in the cotton growing areas. Bales oft ginned cotton are first transported to the textile mills. There, they are opened and the impurities are picked up and removed in the blow room. After further opening and cleaning, cotton is transformed into laps and fed to cording section. Here it is opened completely and is converted into slivers. The slivers are gathered in cans and then processed on a drawing machine, which makes then uniform by straightening the fiber. The slivers are then changed into lap form before feeding them for combing, which parallels the fiber and upgrades it.

Spinning: The sliver at this stage is in a fragile condition and is also bulky. After reducing the diameter in two or three stages, it is processed on 'speed frame', which makes it suitable for final spinning. Due to twisting a continuous yarn of sufficient strength is produced during spinning. This yarn is wound on bobbins located in cone winding machines.

Weaving: Before the yarn is actually woven, it is 'warped', i.e., made into a uniform layer. Weaving consists of joining two sets of threads, one which extends throughout the length of the fabric and the other whose threads go across. This process is done in a loom.

Finishing: This consists of a number of processes like bleaching, dyeing, printing, calendaring, stamping and packing. The impurities like oil and grease are removed and the fabric is made white during bleaching. Dyeing involves giving a colour or shade to the cloth. Printing produces designs and patterns in multicolor.

Motors Used/or Different Textile Processes

All machines used in accomplishing the different processes described above require electric motors as their drives. Special environmental, operating and drive conditions demand specially designed motors for textile industry.

Loom motors; In order to accomplish the 'pick up' process in a short time, the starting torque of the loom motor should be high being essentially a reciprocating mechanism causes both torque and current pulsations. Also, loom motors are subjected to frequent starts and stops, these results in a higher temperature rise and is taken care by having good thermal dissipation capacity of the motor.

Loom motors are either totally enclosed or totally enclosed fan cooled, three phase high torque squirrel cage induction motors. Presence of lot of fluff in the atmosphere requires a smooth surface finish of the housing and end shields so that the fluff does not get collected on the surface of the motor. The insulation of the motor must be able to withstand high moisture content.

The ratings of the motors used for driving looms for light fabrics such as cotton, silk, rayon, nylon etc. are 0.37, 0.55,0.75, 1.1 and 1.5 kW, while those of the motors used for making heavy fabrics (wool and canvas) are 2.2 and 3.7 kW. They are usually of 6 or 8 poles.

Card motors: The general requirement of card motors is almost similar to that of 100m motors except that the former are required to have a very high starting torque and must be able to withstand a prolonged starting period. Both the above requirements for the card motor are due to the very high inertia of the card drum. Once the drum is started, the operation is continuous and un interrupting, unlike that of a loom, where frequent starts and stops are involved.

The commonly used drives for card motors arc again totally enclosed and totally enclosed fan cooled three phase high torque squirrel cage induction motors. The usual ratings of motors for cards of light fabrics are 1.1 and 1.5 kW and those for cards of heavy fabrics are 2.2, 3, 3.7 and 5.5 kW. Here again, the preferred synchronous speeds are 750 and 1000 rpm.

Spinning motors: For good quality spinning, it is essential that the starting torque of spinning motors should be moderate and the acceleration should be smooth. If the starting torque were low, the tension of the yarn would be insufficient and hence the yarn would get entangled and break. If the starting torque were high, the acceleration would be high and the yam would snap.

In general, three types of drives are used for spinning frame operation: single speed motor, two-speed motor and two motor drive.

Normally, a 4 pole or 6 pole squirrel cage induction motor is used as single speed drive.

In order to maximize production with minimum breakage, two speed motors (4/6 or 6/8 poles) are used. Although these motors would be larger in size and costlier, the increased production may compensate for the additional initial outlay.

Cement mill drives

The raw materials for producing cement contain lime and silica as main components and alumina and ferric oxide as fluxing components. The limestone mined from the quarries is crushed and transported to the plant by dumpers wagons, trucks or ropeways depending on the area and distance involved. In fact if the quarry is within 1·2 km from the plant, the crushers might be located right next to the plant and in the line of supply of the limestone. The crushed limestone together with the required proportion of corrective additives like clay bauxite, iron ore etc. is ground in grinding mills. The fine dry powder coming out is homogenized in silos by passage of air from bottom and through the medium. It is then fed into the kiln, which is the heart of the cement plant, for producing cement clinker at high temperatures. If tbe kiln receives finely ground and precisely composed dry feed as mentioned above, the cement plant is called as a dry process one. In wet process, the raw materials are ground with water to produce slurry before entering the kiln feed tank. Dry process is preferred to wet process because less fuel is required by such kilns. Wet process is necessitated sometimes, since, certain materials contain so much water that adding a little more water and using wet process is better than trying to dry the raw materials. The clinker coming out of the kilns is air cooled in special types of coolers and then transported to the storage. After aging in storage for at least three days the clinker, mixed with. The right amount of gypsum is fed to the cement grinding mills and ground to required fineness. The cement is stored in silos, drawn for packing in gunny bags and dispatched by wagons or trucks to the dealers.

Types Drives

The driving motors used in the cement industry can be broadly classified is follows:

Raw mill and cement mill drives

Kiln drives

Crusher drives

Waste gas fan drives Compressor drives etc.

Raw mills and cement mill drives: Slip ring induction motors of 6.6 kV are widely used. In order to improve the power factor of the line current drawn, high voltage capacitors of adequate reliability and automatic capacitor control switchgear and circuit breakers are to be used. Even after adding the price of the capacitors and the control gear, the slipping motor is cheaper than the synchronous motor of the same rating. Liquid resistance starters are, usually employed to start the motor and to bring it up to full speed. Gear boxes are also attached in order to get the desired mill speed of about 15 rpm. From the point of view of voltage dips during starting. The starting current of mill drives for large cement plants is normally restricted to 1.75 times the full load current. The starting torque for the mill motors for large cement plants is limited to 125 per cent of the rated torque and the pull out torque is restricted to nearly 240 per cent of the rated torque.

Normally, the motors should be able to withstand 50 per cent overload for one minute occurring four times per hour at equal intervals. The motors for such drives are generally designed for a duty cycle of three consecutive starts from cold condition and two consecutive starts from hot conditions per hour against full load.

Twin drives: Due to the large ratings (above 3000 kW) required for the raw. And cement mill drives and due to the limitations in the availability of large size gear boxes and motors, twin drives are employed in these mills. The two motors have to be more or less identical to each other and so also their liquid resistance starters.

Gearless drives: In developed countries, gearless drives are being increasingly used for large mills. The rotor is shrunk on to the mill and the air sap between the rotor and the overlapping stator is maintained by Invitation using a sophisticated electronic closed loop control. The supply frequency is rectified into de, which is then inverted to ac of a much lower frequency so as to provide a mill speed of approximately 15 rpm. This arrangement completely dispenses with the gearbox, which is normally the source of maintenance problems. These type of drives would become economically viable in a few years, when power diodes and thyristors would be available in plenty at much lower cost than those prevalent today.

Kiln drives: The rotary kiln is an indispensable part of a cement plant. There are different types of rotary kilns depending on whether the cement is manufactured by means of wet or dry process. But, in general, they are tubular, slightly tilted from the horizontal and have a ring gear fitted around them which engages with one or two pinions. Each pinion drive shaft is driven by a variable speed motor.

The rating of the motors used for driving the kilns vary from 100-1000 kW. The maximum speed of the kiln is about I rpm and the kiln motor has to be designed for a speed range of the order of I: 10. The starting torque required may be between 200 per cent to 250 per cent of full load torque. The motors are also specially designed to pick up speed at full load within the normal time of 15 seconds. Quite often, kiln motors have to cater to overloads to the tune of 200 per cent to 250 per cent for small periods of time. The motor and control equipment have also to be specially designed for inching and spotting of the kiln during maintenance and routine checks.

Twin motor de drives: To cope up with increasing kiln capacities, the modern trend is to use twin motor de drives for kiln application. In this case, two de motors with separate pinions drive the same gear wheel at the periphery of the kiln drum. Although this arrangement has certain advantages for the designer of electric motors, it does involve extra expenditure on the electrical side. The twin motor drive system must be designed such that motive power is supplied in equal parts by the two motors to prevent overloading of either one of them or its mechanical transmission system. The speed of the two motors must necessarily be the same because they are coupled through the gear system. This can be achieved either with series connection of the two de motors or with parallel connection by means of a closed loop control system.

Crusher drives: The motors used in crushers are of the slip ring type. Stalling considerations play a very important part in the design of these motors. Normally, the motors are designed to withstand locked rotor current during running without any external resistance introduced in the rotor circuit, for one minute. This is quite important, since very often the crushers tend to get jammed, when a big sized boulder gets trapped between the jaws of the crushers. Generally, the starting torque for such drives is limited to 160 per cent of the full load torque and the pull out torque is limited to 200 per cent to 250 per cent of the full load torque. The motors are also normally designed for IS per cent overload for 15 seconds and 20 per cent overload for 10 seconds taking into consideration the adverse loading conditions encountered in practice.

Fan drives: The motors used are of the slip ring type with a speed variation, generally, between 1000 and 750 rpm. The cast iron grid resistance controller‟s arc normally used for starting and controlling the speed of these drives. As the motors are located outdoor or in semi-outdoor locations totally enclosed motors of TEFC are employed.

Paper mill drives

Pulp Making

Pulp is made in two ways-purely by mechanical means and by both mechanical and chemical processing. The former involves grinding logs of wood of about a meter length on large grind-stones. Grinders operate at almost constant speed and can be started under light load conditions. Hence, synchronous motors are considered as most suitable for grinder drives. Since they usually work with speeds of 200-300 rpm, geared drives are used, especially when the motors are installed in a' separate room for protection from humid atmosphere. Usually, making pulp by purely mechanical means consumes more than fifty per cent of the total power requirement of a paper mill; hence, large size grinders driven by 3000·4000 kW motors are normally, considered as economical .Pulp can also be made by cutting logs of wood into chips of several centimeters length and treating them with alkalis along with other raw materials like grass, rags etc. During the chemical treatment the material is continuously beaten. Wood choppers have random load characteristics and their inertia is large, depending upon the size of the disc, on which the knives of the chopper are mounted. Beaters usually are required to start with large load. The end products of the grinders as well as beaters are refined and stored in large tanks as pulp ready for making paper. Depending upon the size of a mill, the ratings of motor used for chipping, and beating, refining and storing range from several hundreds to thousand kilowatts. Except for beaters, synchronous motors are used in these drives. Since beaters, very often, require speeds less than 200 rpm and large starting torque, slip-ring induction motor drives are found to be more suitable.

Paper Making

The machine that makes paper in a paper mill has to perform the job of forming sheets, removing water from sheets, drying of sheets, pressing of sheets and reeling up of sheets. Therefore, the paper is made in the following five sections: (i) Couch section (wire section), (ii) Press section, (iii) Dryer section, (iv)Calendar section, and (v) Reel section shows a schematic layout of the different sections that make paper. The paper pulp suspension with a moisture content of 98 per cent to 99 per cent is transferred uniformly to the wire. Most of the quantity of water drips through the wire mesh and the rest is removed by suction. At the end of the wire section, the moisture content would have reduced to about 80 per cent, In the press section, which follows the wire section, sheet is pressed between woolen felts so as to squeeze out water from the wet sheet and the web leaves the press section with a moisture content of 65 to 60 per cent. In dryer section, the sheet is further dried by passing it over and under the heated cylinders until the desired dryness; usually 6 per cent of moisture content is obtained. In calendar section_sheet is subjected to pressure and friction so that a compact and smooth surface of sheet results. In the reel section, the sheet is wound up on a mandrel.

Requirements of Paper Machine Drive

1. For the actual formation and production of sheets and from the point of view of economy, it is necessary to maintain the speed of paper machine constant.
2. For a paper machine to be multipurpose, its speed should be adjustable over a range as large as 10: 1.
3. In the wet end of the paper machine, the web becomes elongated by about 5 percent. Care should be taken to allow for this elongation by varying the speeds of individual sections. As this elongation is a function of the quality of the paper, speeds of sections must be independently adjustable.

In dry end of paper machine, the web hangs freely between sections without any support. Therefore, a definite amount of tension must be set and regulated. This also necessitates a definite difference between the speed. of successive sections.

The relative speeds of two sections have a direct bearing on the pull on the sheet. Hence, steady state accuracy of 0.1 per cent or better is specified for the speed control system so as to avoid tearing and folding of sheet.

4. As web is manually introduced into the calendar, an arrangement to take up sag is a must.
5. In the last two sections, viz., the calendar and the reel, variations in tension in sheet can occur even if the correct relative speeds are maintained due to uneven drying and other factors. It is, therefore, imperative to augment the speed control circuit by an overriding tension control.
6. While cleaning the wire, it has to be moved forward a few centimeters at a time so that it can be cleaned and inspected properly. Hence, the motor should be capable of running at inching speeds of 10.25 m/min as long as a particular button is pressed.
7. Each section should be able to run at the crawling speed of 10-25 m/min for running in felts, wire and heating up of dryer cylinders.
8. Smooth and quick starting of the sections, without causing -excessive starting current, is required.
9. Control system employed should be flexible in nature.

Types of Drives Used for Paper Machine

There are two types of drives employed for making paper from pulp line shaft drive and sectional drive. Line shaft drives; In this form of drive, the various sections of the paper machine are driven from a line shaft running the full length of paper machine. Cone pulleys and belt-combinations drive the various sections of the machine from line shaft through right angled gear reductions. Normally, electric motors are employed to drive the transmission shaft. Both ac and dc drives can be used for practically loss-less speed control. In ac drive only the ac commutator motor with shunt characteristic is of use for obtaining an economic speed control system. Its advantage is in the possibility of connecting the motor directly to a three phase supply, thereby eliminating an ac-dc converter, which would be required if a dc drive were used. However, the speed of an ac commutator motor depends on load and, hence, its use as a paper machine drive with stringent requirements of constant speed is no longer advisable. Also, its speed range (usually of the order 1: 3) as well as the power required greatly affects the size of the motor. The open loop speed control of the ac commutator motor is sluggish in comparison with a dc drive, as speed is varied by adjusting an induction regulator and shifting the brush rocker.

In de drives, the speed of the paper machine is controlled by varying the armature voltage of a separately excited dc motor. The variable de voltage is obtained from alternating voltage supply by means of either rotary conveners or static converters.

Sectional drives: In sectional drive each section of the paper machine has its own electrical motor, All the motors arc operated from a common supply bus. By varying bus bar voltage, the speed of the paper machine can be controlled. By adjusting the field excitation of any motor, it is possible to vary the speed of that particular motor with respect to other motors.

Coal and Mining Industry

The motors used in coal and mining are classified into two groups. The first group are drives for mine accessories such as compressors, pumps etc. While the second motors are used for actual mining process i.e. to drive the cutters, drillers etc. It is necessary that the motors used for coal and mining must be flame proof. The atmosphere is generally hot with high ambient temperature and also humid. The motors should have humid proof insulation. The load diagram discussed earlier, related to the duty cycle must be studied while selecting the motor for the drive. The coal cutting or drilling do not require any speed control as the processes are constant speed processes. High starting torque is necessary. The high starting torque squirrel cage motors with double cage are preferred for these applications. For haulage purpose the motors be able to start large drum. So they must have high starting torque. The speeds required are different at different haulage stages. The frequent starts and stops are required. To meet these requirements the slip ring induction motor with rotor resistance starter is preferred. The mine winder motor may be a d.c. motor with Word Leonard speed control or slip ring motor with rotor resistance starter is preferred. The centrifugal pumps are used in mining for various jobs like pumping water. The high torque squirrel cage motors which do not have any maintenance problems are selected.