A Course Material on

EE 2352 Solid State Drives

By

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EE8601 SOLID STATE DRIVES L T P C 3 0 0 3

AIM

To study and understand the operation of electric drives controlled from a power electronic converter and to introduce the design concepts of controllers.

OBJECTIVES

- ✓ To understand the stable steady-state operation and transient dynamics of a motor-load system.
- ✓ To study and analyze the operation of the converter / chopper fed dc drive and to solve simple problems.
- ✓ To study and understand the operation of both classical and modern induction motor drives.
- ✓ To understand the differences between synchronous motor drive and induction motor drive and to learn the basics of permanent magnet synchronous motor drives.
- ✓ To analyze and design the current and speed controllers for a closed loop solid-state DC motor drive and simulation using a software package

UNIT I DRIVE CHARACTERISTICS 9

Equations governing motor load dynamics - steady state stability - Multi quadrant dynamics - Acceleration, deceleration, starting and stopping - load torque characteristics of various drives.

UNIT II CONVERTER / CHOPPER FED DC MOTOR DRIVE 9

Steady state analysis of the single and three phase fully controlled converter fed separately excited D.C motor drive - Continuous and discontinuous conduction Time ratio and current limit control - 4 quadrant operation of converter.

UNIT III DESIGN OF CONTROLLERS FOR DRIVES 9

Transfer function for DC motor, load and converter – Closed loop control with current and speed feedback - Armature voltage control and field weakening mode control, Design of controllers: Current controller and speed controller - Converter selection and characteristics - Use of simulation software package.

UNIT IV INDUCTION MOTOR DRIVES 9

Stator voltage control – energy efficient drive - v/f control, constant air-gap flux – field weakening mode - voltage/current fed inverters - Block diagram of vector control - closed loop control.

UNIT V SYNCHRONOUS MOTOR DRIVES 9

V/f control and self-control of synchronous motor – Marginal angle control and power factor control - Permanent magnet synchronous motor Black diagram of closed loop control.

TOTAL : 45 PERIODS

TEXT BOOKS:

1. Gopal K.Dubey, “Power Semi conductor controlled drives “ Prentice Hall Inc., New Jersey 1989.
2. Bimal K. Bose. ‘Modern Power Electronics and AC Drives’, PHI / Pearson Education, 2002.

REFERENCES:

1. N.K.De and S.K.Sen Electrical Drices” PHI, 2006 9th print.
2. Murphy J.M.D. and Turnbull, “ Thyristor control of AC Motor” Pergamon Press Oxford 1988.

UNIT-I

DRIVE CHARACTERISTICS

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

They have flexible control characteristics. The steady state and dynamic characteristics of electric drives can be shaped to satisfy the load requirements.

1. 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.
2. They are available in wide range of torque, speed and power.
3. They are adaptable to almost any operating conditions such as explosive and radioactive environments
4. It can operate in all the four quadrants of speed-torque plane
5. They can be started instantly and can immediately be fully loaded
6. 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.

- ✓ 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

- ✓ Transient operation requirements:

Values of acceleration and deceleration, starting, braking and reversing performance.

- ✓ 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

- ✓ Capital and running cost, maintenance needs life.
- ✓ Space and weight restriction if any.
- ✓ Environment and location.
- ✓ 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 sometimes 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.

Classification of Electrical Drives

Another main classification of electric drive is

- ✓ DC drive
- ✓ AC drive

Applications

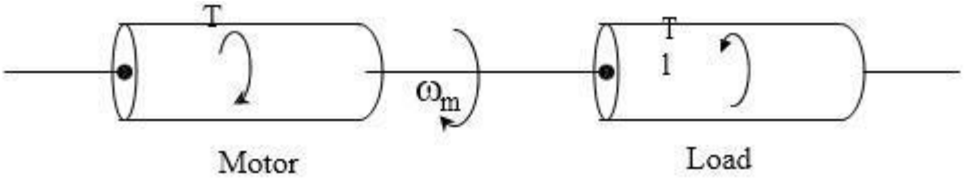
- ✓ Paper mills
- ✓ Cement Mills
- ✓ Textile mills
- ✓ Sugar Mills
- ✓ Steel Mills
- ✓ Electric Traction
- ✓ Petrochemical Industries
- ✓ Electrical Vehicles

1.1 Dynamics of Motor Load System

A motor generally drives a load (Machines) through some transmission system. While motor always rotates, the load may rotate or undergo a translational motion.

Load speed may be different from that of motor, and if the load has many parts, their speed may be different and while some parts rotate others may go through a translational motion.

Equivalent rotational system of motor and load is shown in the figure.



J = Moment of inertia of motor load system referred to the motor shaft kg / m^2

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

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

Tl = 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.

$$T-T_1 = d/dt\,(J\,\omega_m) = J\,d/dt\,(\omega_m) + \omega_m\,dJ/dt \qquad \ldots\ldots\ldots\ldots\ (1)$$

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

For drives with constant inertia

$$\frac{dJ}{dt}=0$$

$$T=T_1+J\,d/dt\,(\omega_m) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

Equation (2) shows that torque developed by motor

1.2 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 Torques:

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

- ✓ Friction Torque (TF):

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

- ✓ Windage Torque (TW)

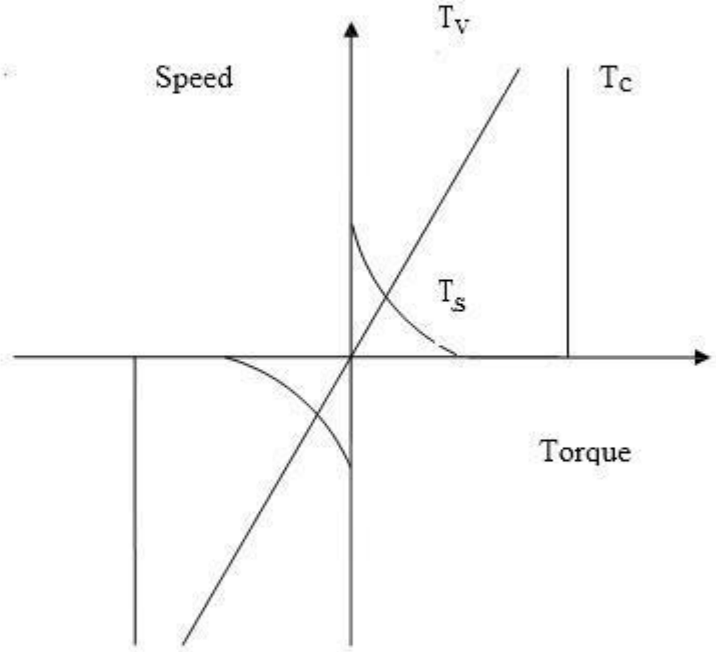
When motor runs, wind generates a torque opposing the motion. This is known as windage torque.

- ✓ 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.

Friction at zero speed is called diction or static friction. In order to start the drive the motor should at least exceeds diction.

Friction torque can also be resolved into three components



Component Tv varies linearly with speed is called VISCOUS friction and is given by

$$T_V = B\,\omega_m$$

Where B is viscous friction co-efficient.

Another component TC, which is independent of speed, is known as COULOMB friction. Third component Ts 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. Wind age torque, TW which is proportional to speed Squared is given by

$$T_W = C\,\omega_m^2$$

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)

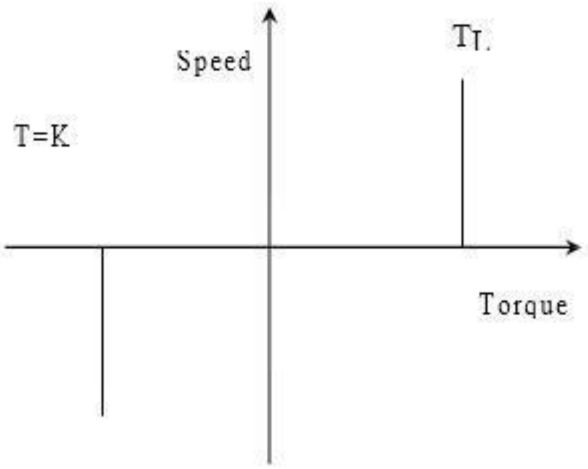
Constant Torque characteristics:

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

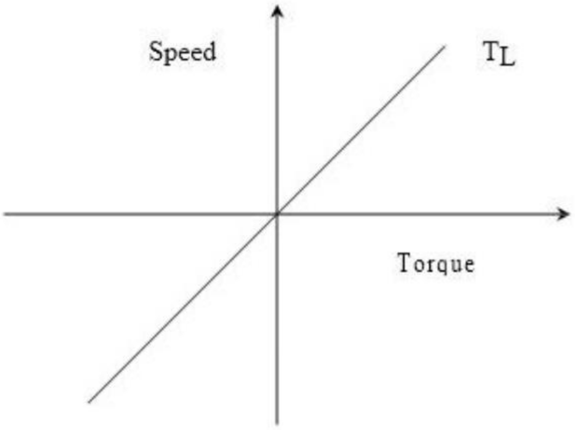


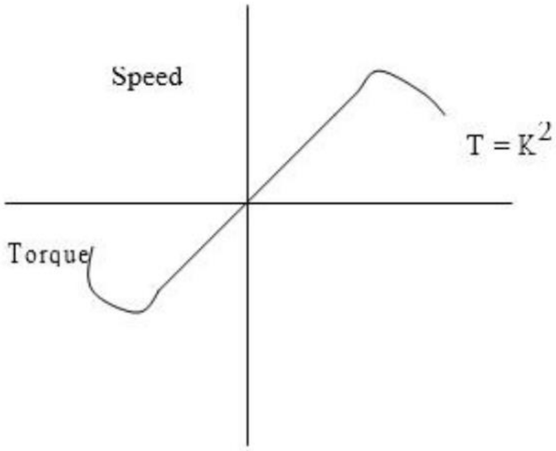
Torque proportional to square of the speed:

Another type of load met in practice is the one in which load torque is proportional to the square of the speed.

Examples:

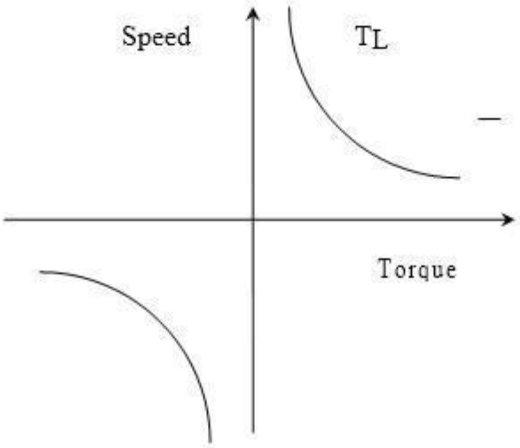
- ✓ Fans rotary pumps,
- ✓ Compressors
- ✓ Ship propellers





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



1.3 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.

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.

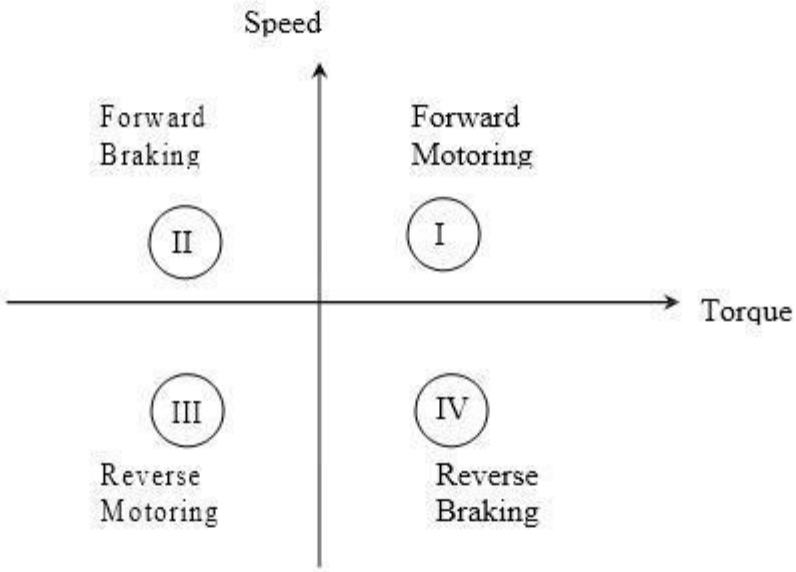
Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B

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

The figure at the right represents a DC motor attached to an inertial load. 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.



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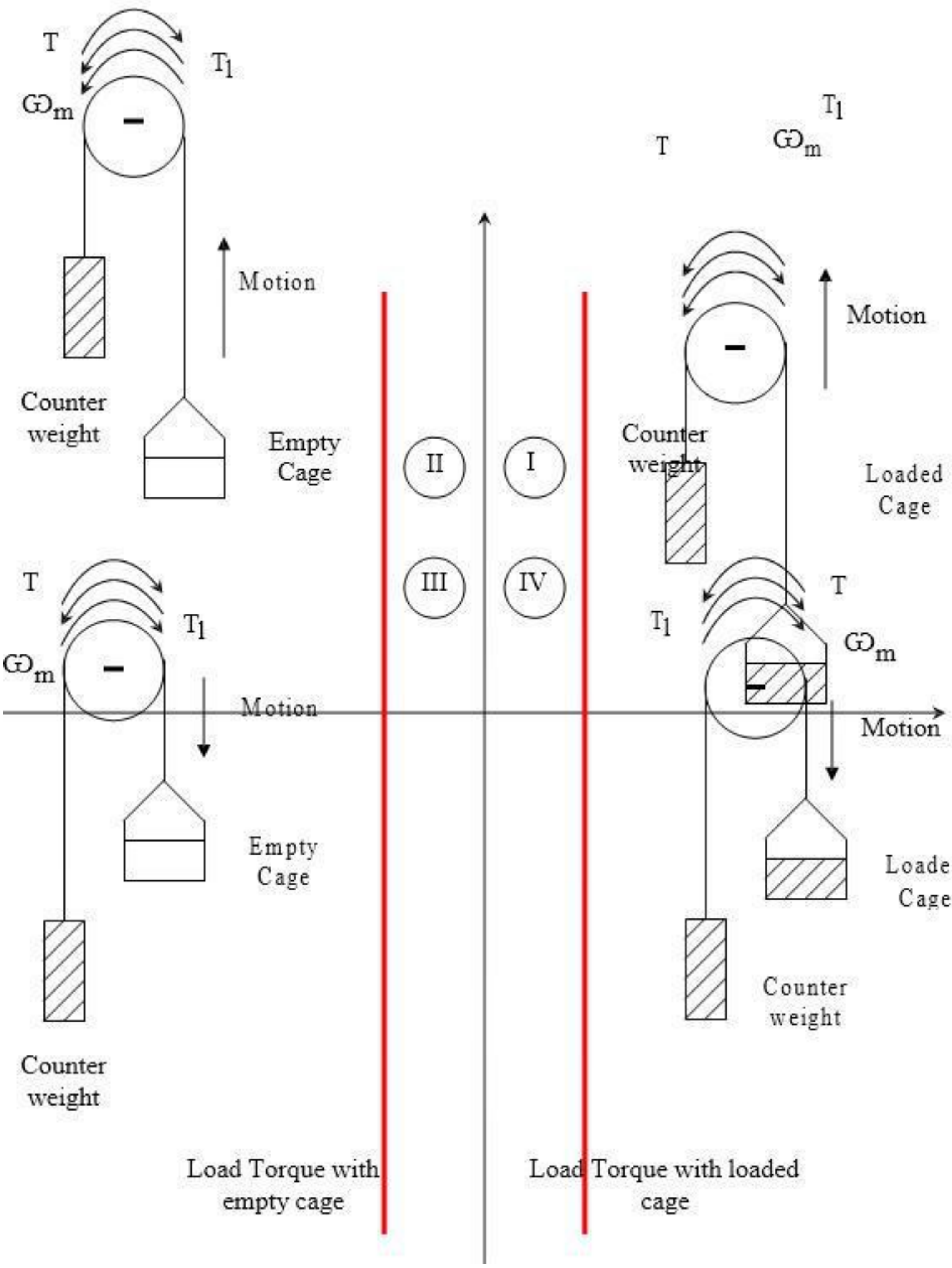


A hoist consists of a rope wound on a drum coupled to the motor shaft one end of the rope is tied to a cage which is used to transport man or material from one level to another level . Other end of the rope has a counter weight. Weight of the counter weight is chosen to be higher than the weight of empty 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 TL1.

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 TL2 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 TL2 in clockwise direction. Since speed is positive and developed power is negative, it’s forward braking operation.

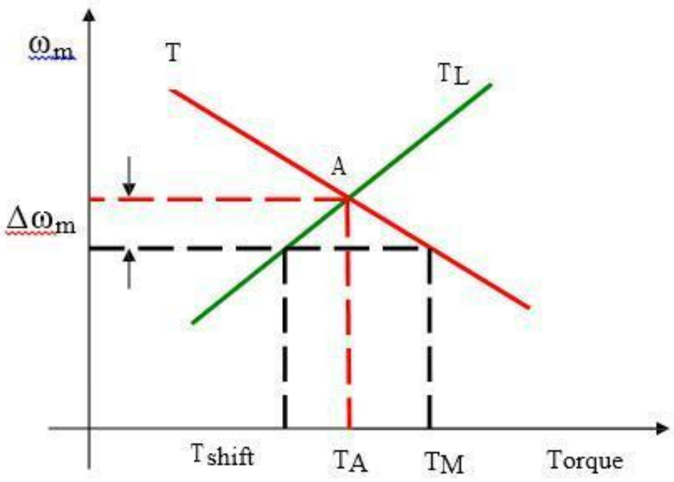
Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in CW direction. Since speed is negative and developed power is positive, this is reverse motoring operation. During transient condition,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

1.4 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



Now consider equilibrium point B which is obtained when the same motor drives another load as shown in the figure.

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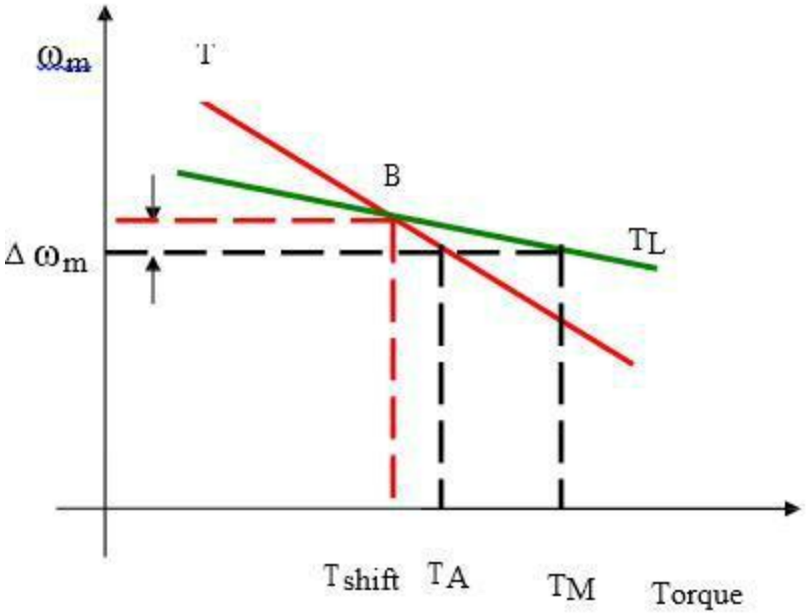
Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B



Basics of Regenerative Braking

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.

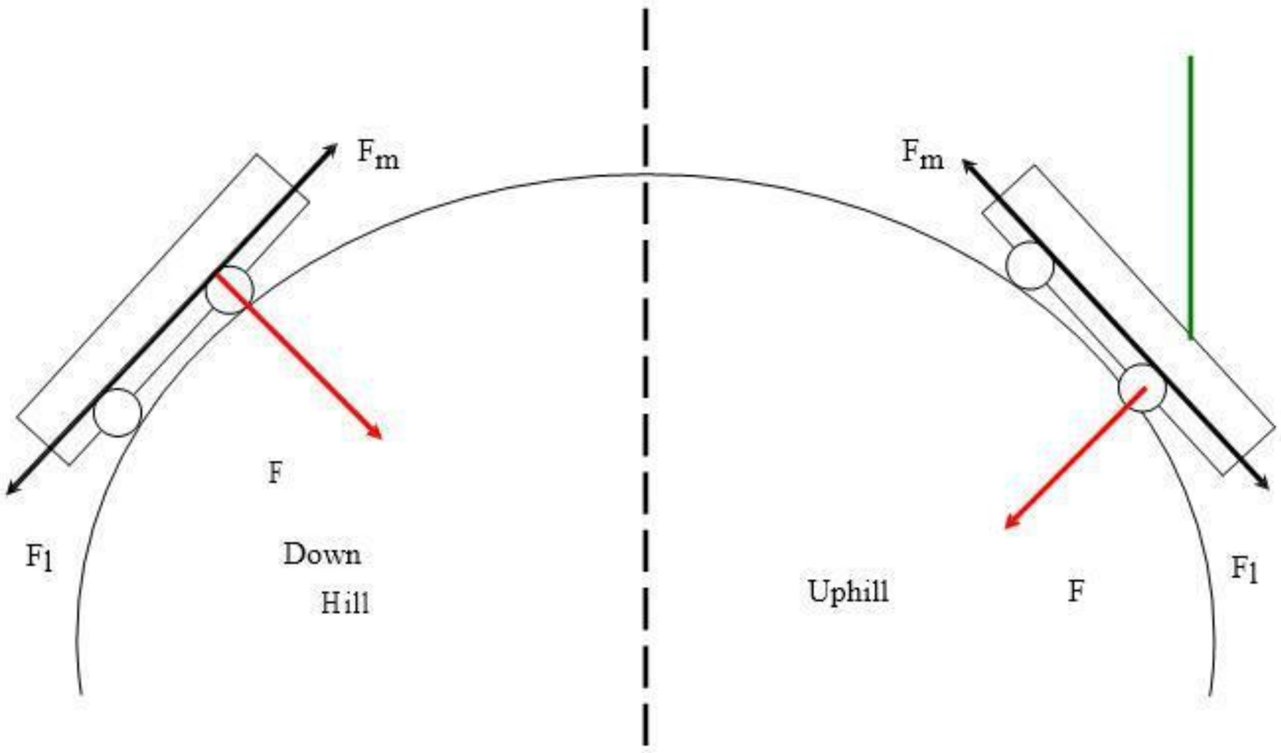
Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven by the load.

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.

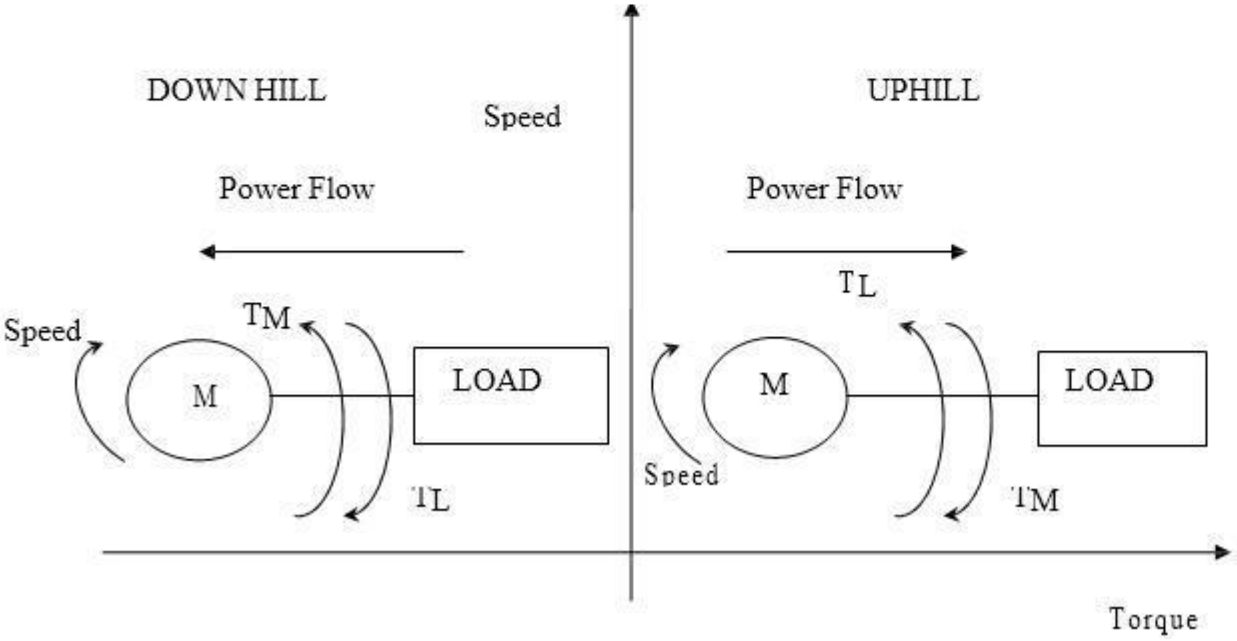
One is perpendicular to the load surface (F) and another one is parallel to the road surface Fl. The parallel force pulls the motor towards bottom of the hill.

If we neglect the rotational losses, the motor must produce force Fm opposite to Fl to move the bus in the uphill direction.

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.



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.

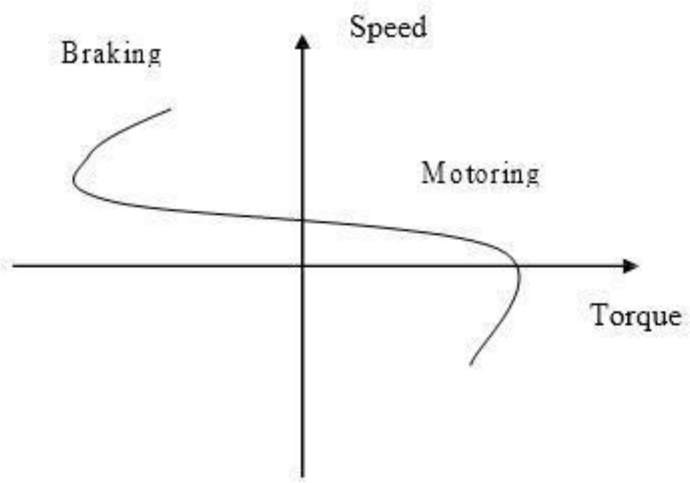
Regenerative braking of Induction motor:

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.

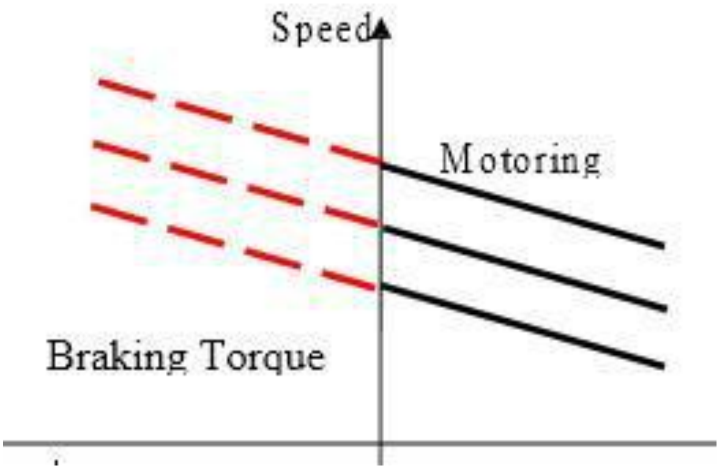
The speed torque characteristic of the motor for regenerative braking is shown in the figure.



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 Ia should be negative



Modes of Operation:

An electrical drive operates in three modes

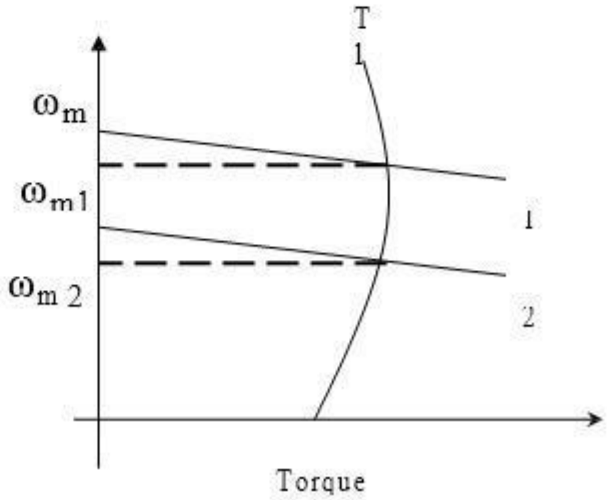
- ✓ Steady state
- ✓ Acceleration including Starting
- ✓ Deceleration including Stopping

We know that

$$T=T_1 +J\, d/dt\, (\omega_m)$$

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 ω_{m1} .

Speed is changed to ω_{m2} when the motor parameters are adjusted to provide speed torque curve 2. When load torque opposes motion, the motor works as a motor operating in quadrant I or III depending on the direction of rotation. When the load is active it can reverse its sign and act to assist the motion. Steady state operation for such a case can be obtained by adding a mechanical brake which will produce a torque in a direction to oppose the motion. The steady state operation is obtained at a speed for which braking torque equal the load torque. Drive operates in quadrant II or IV depending upon the rotation.



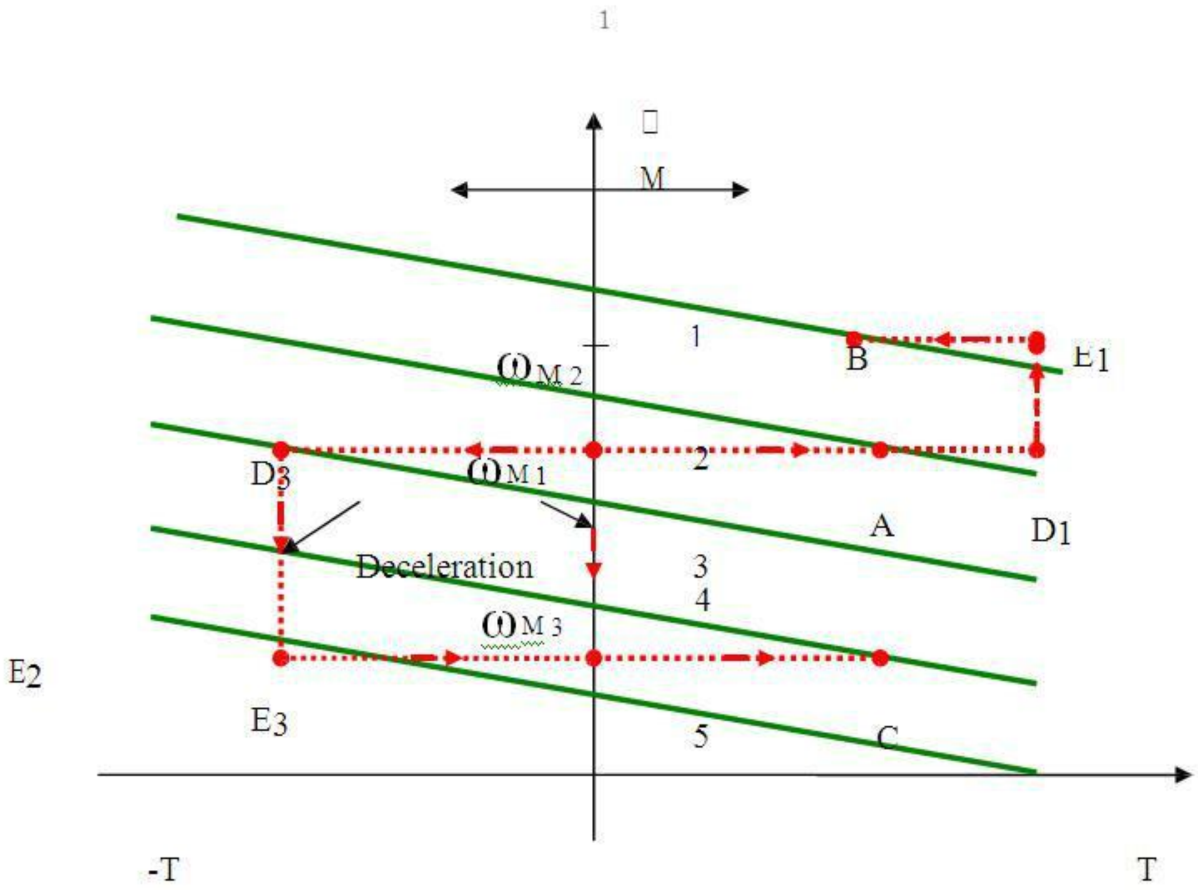
Acceleration and Deceleration modes are transient modes. Drive operates in acceleration mode whenever an increase in its speed is required. For this motor speed torque curve must be changed so that motor torque exceeds the load torque. Time taken for a given change in speed depends on inertia of motor 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 speedωm 2, when the motor torque is held constant during acceleration. The path consists of AD1E1B. 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 step lessly from its zero value. Such a start is known as soft start.



UNIT II

CONVERTER / CHOPPER FED DC MOTOR DRIVE

2.1 Single Phase Fully Controlled Converter Fed Separately Excited D.C Motor Drive

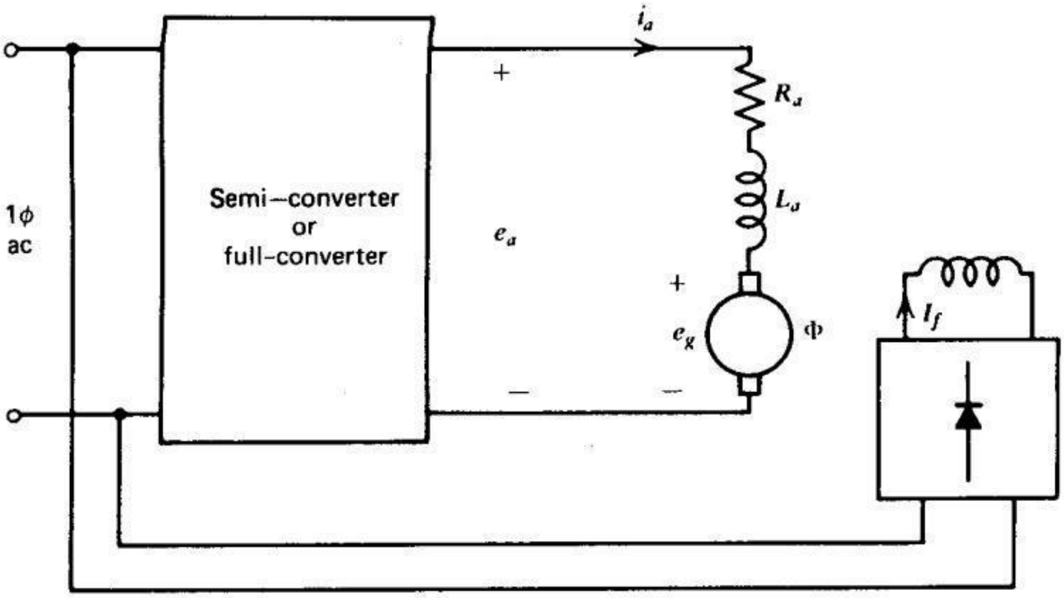


Fig 2.1

The basic circuit for a single-phase separately excited dc motor drive is shown in Fig. 2.1.The armature voltage is controlled by a semi-converter or full-converter and the field circuit is fed from the ac supply through a diode bridge. The motor current cannot reverse due to the thyristors in the converters. If semi-converters are used, the average output voltage (Ea)is always positive. Therefore power flow (Ea1a) is always positive, that is, from the ac supply to the dc load. In drive system semi-converters, regeneration or reverse power flow from motor to ac supply is not possible. In semi-converters free-wheel (i.e., dissipation of armature inductance energy through the free-wheeling path) takes place when the thyristor blocks.

Single-phase full-wave drives are used for low and medium- horsepower applications as indicated infig2.1.Suchdriveshavepoor speed regulation on open-loop firing angle control. However, with armature voltage or tachometer feedback, good regulation can be achieved.

Basic Equation I

The armature circuit of the de motor is represented by its back voltage eg, armature resistance Ra, and armature inductance LaasshowninFig.2.1.

Back voltage:

$$e_g = K_a \Phi n \qquad (1)$$

Average Back Voltage

$$E_g = K_a \Phi N \qquad (2)$$

Developed torque:

$$t = K_a \Phi i_a \qquad (3)$$

Average developed torque:

$$T = K_a \Phi I_a \qquad (4)$$

The armature circuit voltage equation is

$$e_a = R_a i_a + L_a \frac{di_a}{dt} + e_g \qquad (5)$$

Interms of average values,

$$E_a = R_a I_a + E_g \qquad (6)$$

Note that the inductance La does not absorb any average voltage. From equations 2 and 6, the average speed is

$$N = \frac{E_a - R_a I_a}{K_a \Phi}$$

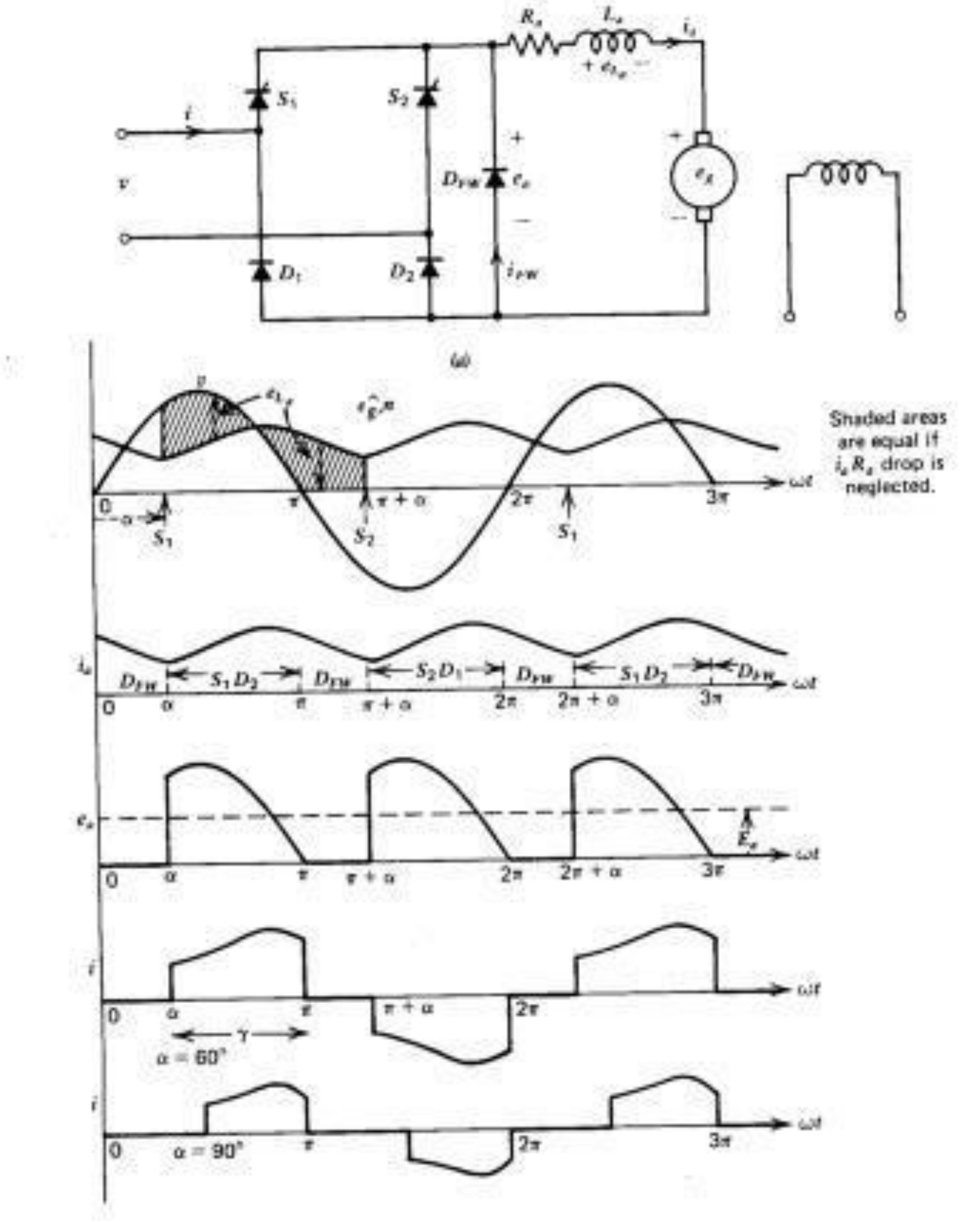
In single-phase converters, the armature voltage ea and current t, change with time. This is unlike the M-G set drive in which both ea and t, are essentially constant. In phase-controlled converters, the armature current ia may not even be continuous. In fact, for most operating conditions, t, is discontinuous. This makes prediction of performance difficult. Analysis is simplified if continuity of armature current can be assumed. Analysis for both continuous and discontinuous current is presented in the following sections

2.2 Continuous Armature Current

Let us assume that the armature current is continuous over the whole range of operation. Typical voltage and current waveforms are shown in Figs.2.2 and 2.3 for semi-converter and full-converter systems, respectively. The thyristors are symmetrically triggered. In the semi-converter systemshowninFig.2.2, thyristor Sl is triggered at an angle a and S2atan anglea+7T with respect to the supply voltage v. In the full-converter systemshowninFig.2.3, thyristors S,and S3 are simultaneously triggered at a, thyristors S2andS4aretriggeredat7T +a.

In Fig. 2.2, the motor is connected to the input supply for the period a<wt<7T through Sl and D2, and the motor terminal voltage ea is the same as the supply input voltage v. Beyond 7T, ea tends to reverse as the input voltage changes polarity. This will forward-bias the free-wheeling diode and DFW will start conducting. The motor current ia, which was flowing from the supply through Sl' is transferred to DFW (i.e., Sl commutates). The motor terminals are shorted through thefree-wheelingdiodeduring7T <wt <(7T +a),making eo zero. Energy from the supply is therefore delivered to the armature

Circuit when the thyristor conducts (a to7T). This energy is partially stored in the inductance, partially stored in the kinetic energy (K.E.) of the moving system, and partially used to supply the mechanical load. During the free-wheeling period, 7T to7T +a, energy is recovered from the inductance and is converted to mechanical form to supplement the K.E.in supplying the mechanical load. The free-wheeling armature current continues to produce electromagnetic torque in the motor. No energy is feedback to the supply during this period.



In Fig.2.3, the motor is always connected to the input supply through the thyristors. Thyristors Sl and S3conduct during the interval a<wt <(7T +a) and connect the motor to the supply. At 7T +a, thyristors S2 and S4aretriggered.Immediately the supply voltage appears across the thyristors Sl and S3asareverse-bias voltage and turns them off. This is called natural or line commutation. The motor current ia, which was flowing from the supply through Sl and S3'istransferred toS2and S4.During ato7T,energy flows from the input supply to the motor (both v and ia repositive, and eo and io are positive, signifying positive power flow). However, during 7T to 7T +a, some of the motor system energy is feedback to the input supply(v and I have opposite polarities and likewise ea and io' signifying reverse power flow).

In Fig.2.3c voltage and current waveforms are shown for a firing angle greater than 90°.The average motor terminal voltage Eo is negative. If the motor back emf Eg is reversed, it will behave as a de-generator and will feed power back to the ac supply. This is known as the inversion operation of the converter, and this mode of operation is used in the regenerative braking of the motor.

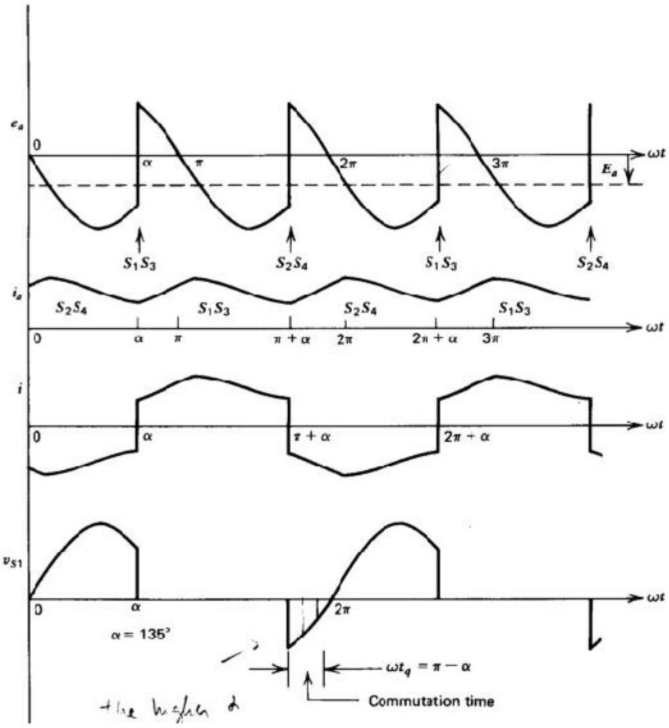


Fig. 2.3 (*Continued*)

Torque Speed Characteristics

For a semi-converter with free-wheeling action the armature circuit equations are:

$$e_a = v = R_a i_a + L_a \frac{di_a}{dt} + e_g \qquad \alpha < \omega t < \pi$$

$$e_a = 0 = R_a i_a + L_a \frac{di_a}{dt} + e_g \qquad \pi < \omega t < \pi + \alpha$$

Single-Phase Separately Excited DC Motor Drives

The armature circuit equation for a full-converter is:

$$e_a = v = R_a i_a + L_a \frac{di_a}{dt} + e_g \qquad \alpha < \omega t < \pi + \alpha$$

$$E_a = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}\, V \sin\theta \, d\theta = \frac{\sqrt{2}\, V}{\pi}(1 + \cos\alpha)$$

With a full-converter:

$$E_a = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} \sqrt{2}\, V \sin\theta \, d\theta = \frac{2\sqrt{2}\, V}{\pi} \cos\alpha$$

2.3 DISCONTINUOUS ARMATURE CURRENT

The torque-speed characteristics shown in Fig.2.4bare drawn on the crude assumption that the armature current is continuous over the whole range of operation. It is very doubtful that the armature current will be continuous at high values of the firing angle a, high speed, and low values of torque. In fact, armature current is discontinuous for these operating conditions. If the armature current is discontinuous, the no-load speeds will be higher than those shown in Fig.2.4b, and the speed regulation will be significantly poor in the region of discontinuous armature current. The motor performance

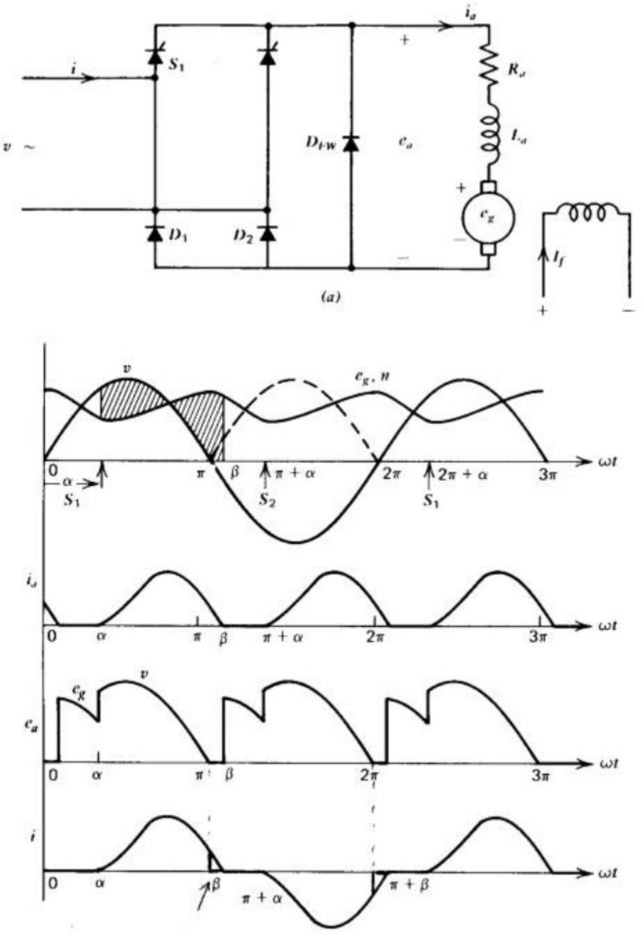
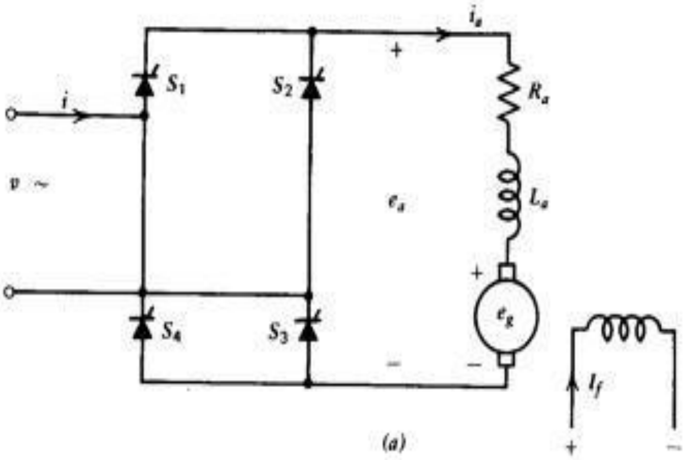
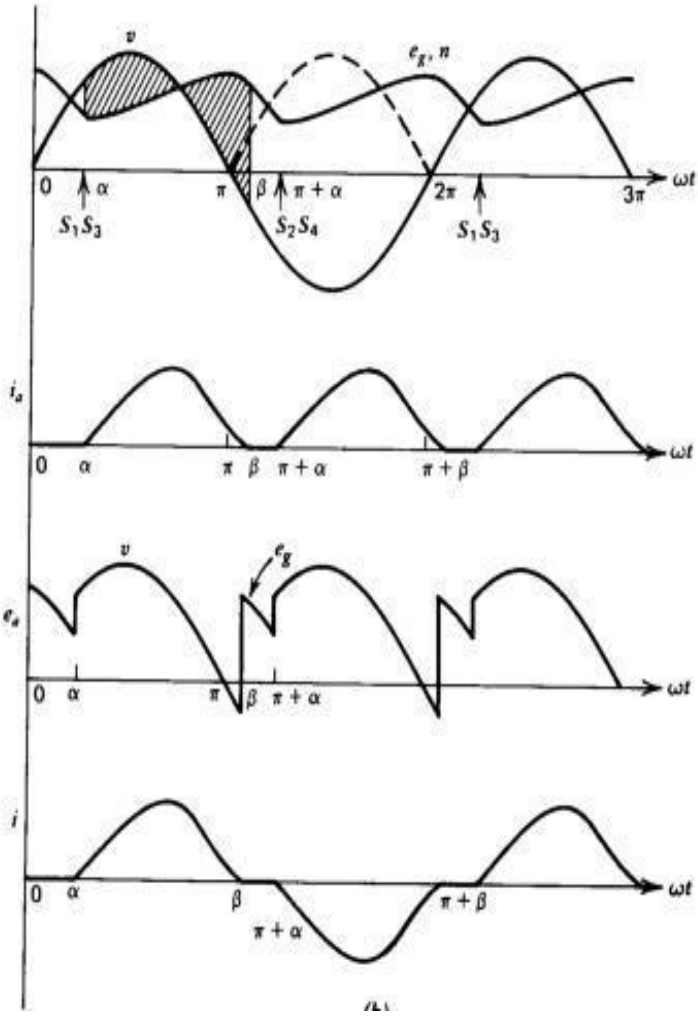


Fig. 2.5 Effects of discontinuous motor current in semi-converter operation. (*a*) Power circuit. (*b*) Voltage and current waveforms.

The waveforms with semi-converter and full-converter with discontinuous armature current areshowninFig.2.5andFig.2.6, respectively.1.



(a)



(b)

In Fig. 2.5, the motor is connected to the input supply for the period a<wI <71' through S, and Dz.Beyond 71', the motor terminal is shorted through the free-wheeling diode DFW' The armature current decays to zero at before the thyristor S2 is triggered at71' +a, thereby making the armature current discontinuous. During a to 71' (i.e., the conduction period of the thyristor S,), motor terminal voltage ea is the same as the supply voltage v. However, during the motor current free-wheels through DFW and so ea s zero. The motor coasts and the motor terminal voltage ea is the same as the back voltage InFig.2.6, the motor is connected to the supply during a<wt<{3 and it Coasts during {3<wI <71' +a. As long as the motor is connected to the supply, its terminal voltage is the same as the input supply voltage.

If the armature current can be assumed to be continuous, the torque-speed characteristics can be calculated merely from average values ofthe motor terminal voltage and current. In the discontinuous current mode, these calculations are cumbersome. The difficulty arises in the calculation of the average motor terminal voltage Ea, because (called the extinction angle, the instant at which the thyristor or motor current becomes zero) depends on, the average speed N, average armature current la' and the firing angle a. A general approach, valid for both continuous and discontinuous armature current, is therefore necessary.

2.4 Three Phase Fully Controlled Converter Fed Separately Excited D.C Motor Drive

Three phase controlled rectifiers are used in large power DC motor drives. Three phase controlled rectifier gives more number of voltage per cycle of supply frequency. This makes motor current continuous and filter requirement also less.

The number of voltage pulses per cycle depends upon the number of thyristors and their connections for three phase controlled rectifiers. In three phase drives, the armature circuit is connected to the output of a three phase controlled rectifier.

Three phase drives are used for high power applications up to megawatts power level. The ripple frequency of armature voltage is greater than that of the single phase drives and its requires less inductance in the armature circuit to reduce the armature current ripple

Three phase full converter are used in industrial application up to 1500KW drives. It is a two quadrant converter.

Principle of Operation

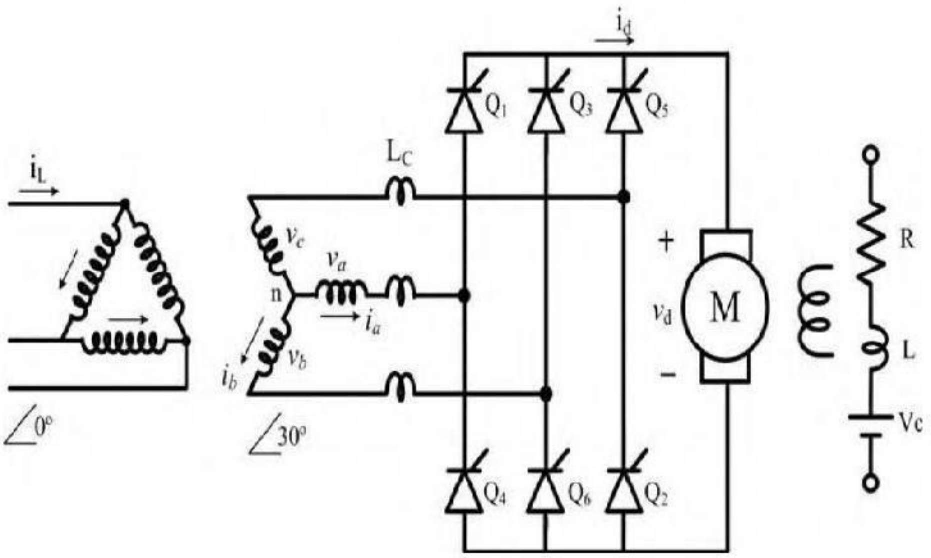


Figure 2.13

Three phase full converter bridge circuit connected across the armature terminals is shown fig. The voltage and current waveforms of the converter. The circuit works as a three AC to DC converter for firing angle delay $0^0 < \alpha < 90^0$ and as a line commutated inverter for $90^0 < \alpha < 180^0$. A three full converter fed DC motor is performed where generation of power is required.

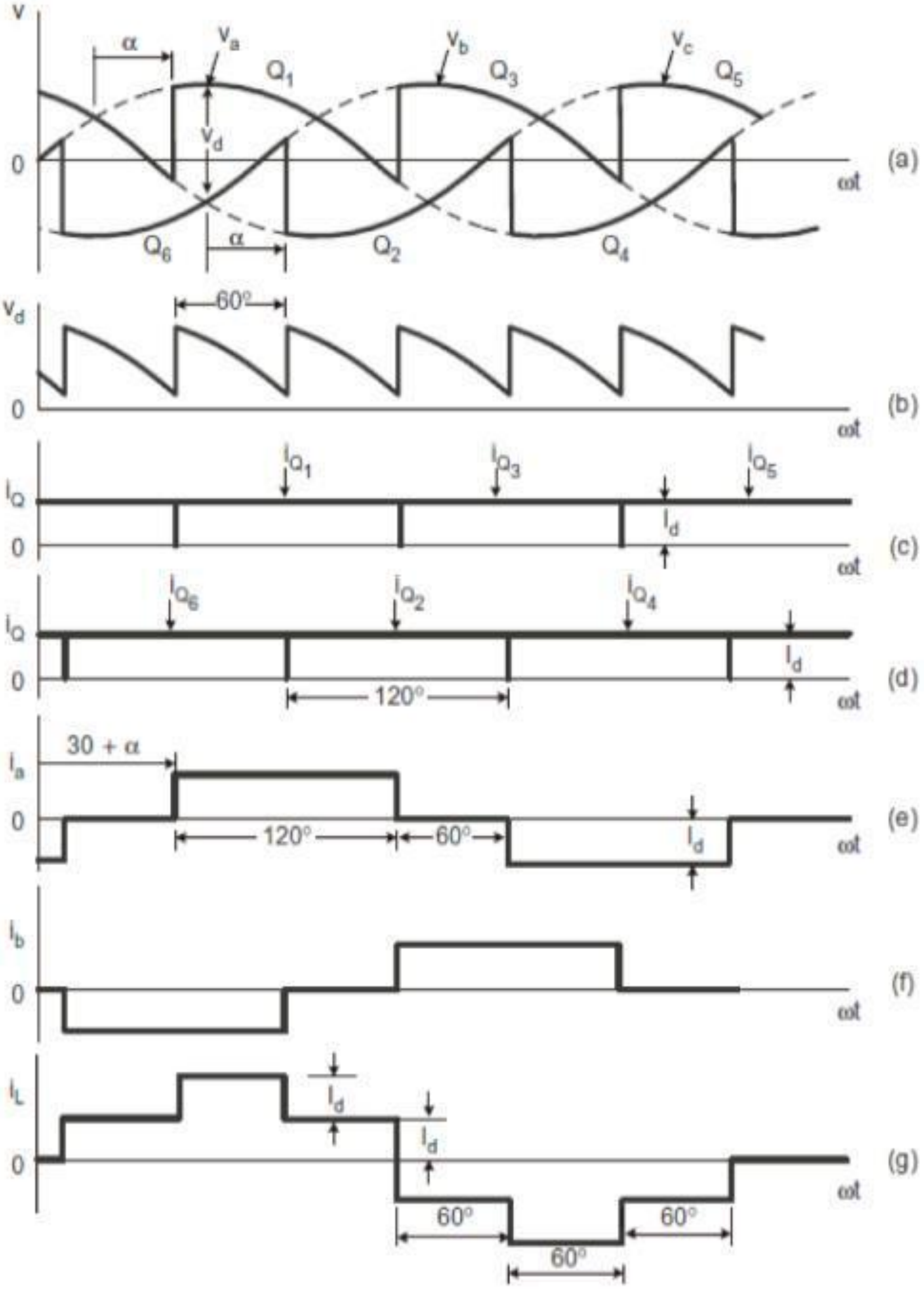


Fig 2.14 Three-phase thyristor bridge waveforms in rectification mode ($\alpha = 40°$)

The average motor armature voltage is given by

$$V_a = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} V_{ab}\, d(\omega t) \qquad (2.49)$$

In the above substitute $V_{ab} = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right) d(\omega t)$ (2.50)

We have $V_a = \frac{3\sqrt{3}}{\pi} V_m \cos\alpha$ (2.51)

2.4.3.2 Speed Torque Relations:

The drive speed is given by

$$V_a = E_b + I_a R_a \qquad \text{Where } E_b = K_a \phi \omega$$

Then $V_a = K_a \phi \omega_m + I_a R_a$

$$\omega_m = \frac{V_a - I_a R_a}{K_a \phi} \qquad (2.52)$$

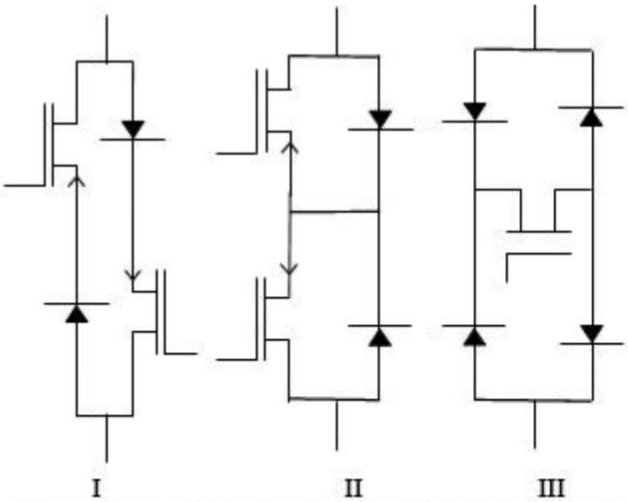
In separately excited DC motor $K_a \phi I_a = T$ therefore (2.52) becomes

$$\omega_m = \frac{V_a}{K_a \phi} - \frac{R_a}{(K_a \phi)^2} T \qquad (2.53)$$

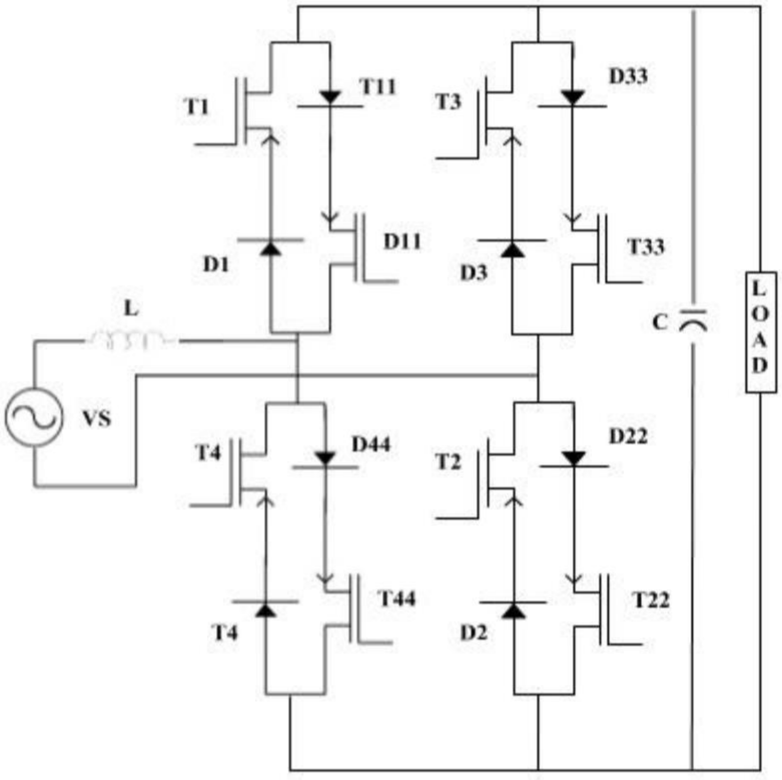
2.5 Four Quadrant Operation of a Converters

The bi-directional boost converter is the IPQC version of the conventional thyristor dual converters. Their topology is derived from ac-ac matrix converters using four quadrant switches (4QSWs). Since no four-quadrant switch is currently commercially available the realized by embedding a transistor inside a diode bridge or by inverse parallel connections of transistors as shown in Fig (1). Power IGBT employed because they have the advantage so high switching frequency and small pulse and notch widths. Topology of a single-phase bi-directional boost converter using typeI 4QSWsis shown in Fig(2).

In the circuit shown in Fig (2), here are four4QSWs, two in each limb. Each 4QSW comprises two 2QSWs (two quadrant switches), each two-quadrant switch consisting of a IGBTT with series diode, connected in inverse-parallel. The operation of the bi -directional boost converter in boost mode and in a particular quadrant in the V-I plane shown in Fig (3) is determined by the conditioning of the switching states of two sets (IandII) of devices. In the single-phase version each set comprises four IGBTs; set(A) IGBTs–T11,T22,T33,T44 and set(B)I GBTTs-T1,T2,T3,T4.corresponding to the four quadrants in the buck and boost modes pertaining to the rectification and inversion operations



Three types of Four-Quadrant Switch (4QSW) realizations



The power circuit diagram of a single phase bi-direction boost rectifier

2.6 Time Ratio Control (TRC)

In this control scheme, time ratio Ton/T (duty ratio) is varied. This is realized by two different ways called Constant Frequency System and Variable Frequency System as described below:

Constant Frequency System

In this scheme, on-time is varied but chopping frequency f is kept constant. Variation of Ton means adjustment of pulse width, as such this scheme is also called pulse-width-modulation scheme.

Variable Frequency System

In this technique, the chopping frequency f is varied and either (i) on-time Ton is kept constant or (ii) off-time Toff is kept constant. This method of controlling duty ratio is also called Frequency-modulation scheme.

2.7 Current- Limit Control

In this control strategy, the on and off of chopper circuit is decided by the previous set value of load current. The two set values are maximum load current and minimum load current.

When the load current reaches the upper limit, chopper is switched off. When the load current falls below lower limit, the chopper is switched on. Switching frequency of chopper can be controlled by setting maximum and minimum level of current.

Current limit control involves feedback loop, the trigger circuit for the chopper is therefore more complex. PWM technique is the commonly chosen control strategy for the power control in chopper circuit

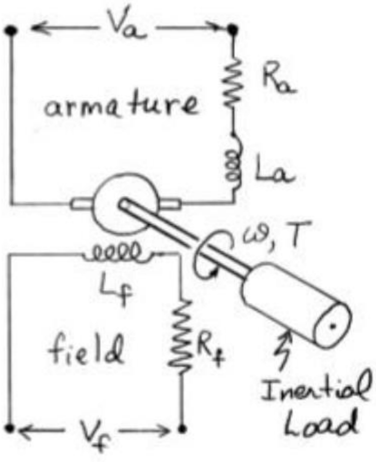
UNIT III

DESIGN OF CONTROLLERS FOR DRIVES

3.1Transfer Function For DC Motor

The figure at the right represents a DC motor attached to an inertial load. The voltages applied to the field and armature sides of the motor are represented by V_f and V_a. The resistances and inductances of the field and armature sides of the motor are represented by R_f, L_f, R_a, and L_a. The torque generated by the motor is proportional to i_f and i_a the currents in the field and armature sides of the motor.

$$\boxed{T_m = K\, i_f\, i_a} \tag{1.1}$$



DC Motor

Field-Current Controlled:

In a field-current controlled motor, the armature current i_a is held constant, and the field current is controlled through the field voltage V_f. In this case, the motor torque increases linearly with the field current. We write

$$T_m = K_{mf}\, i_f$$

By taking Laplace transforms of both sides of this equation gives the transfer function from the input current to the resulting torque.

$$\boxed{\frac{T_m(s)}{I_f(s)} = K_{mf}} \tag{1.2}$$

For the field side of the motor the voltage/current relationship is

$$\begin{aligned} V_f &= V_R + V_L \\ &= R_f i_f + L_f\left(di_f/dt\right) \end{aligned}$$

The transfer function from the input voltage to the resulting current is found by taking Laplace transforms of both sides of this equation.

$$\boxed{\frac{I_f(s)}{V_f(s)} = \frac{\left(1/L_f\right)}{s+\left(R_f/L_f\right)}} \qquad \text{(1}^{\text{st}}\text{ order system)} \qquad (1.3)$$

The transfer function from the input voltage to the resulting motor torque is found by combining equations (1.2) and (1.3).

$$\boxed{\frac{T_m(s)}{V_f(s)} = \frac{T_m(s)}{I_f(s)}\frac{I_f(s)}{V_f(s)} = \frac{\left(K_{mf}/L_f\right)}{s+\left(R_f/L_f\right)}} \qquad \text{(1}^{\text{st}}\text{ order system)} \qquad (1.4)$$

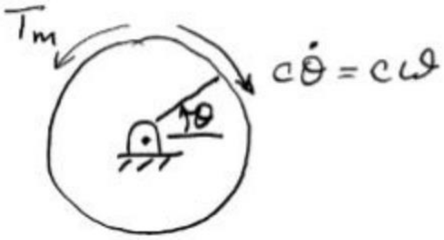
So, a step input in field voltage results in an exponential rise in the motor torque.

An equation that describes the rotational motion of the inertial load is found by summing moments

$$\sum M = T_m - cw = J\dot{w} \qquad \text{(counterclockwise positive)}$$

or

$$\boxed{J\dot{w} + cw = T_m}$$



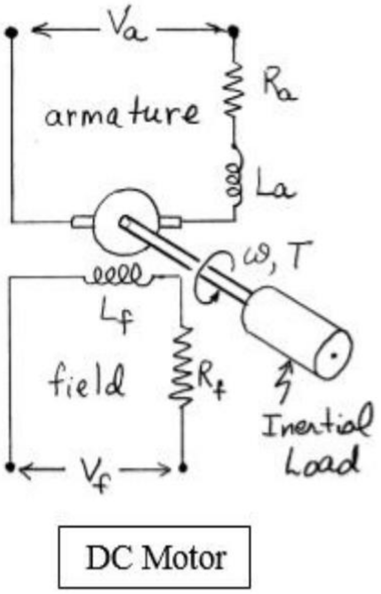
$$\boxed{\frac{w(s)}{T_m(s)} = \frac{\left(1/J\right)}{s+\left(c/J\right)}} \qquad \text{(1}^{\text{st}}\text{ order system)} \qquad (1.5)$$

Combining equations (1.4) and (1.5) gives the transfer function from the input field voltage to the resulting speed change

$$\boxed{\frac{w(s)}{V_f(s)} = \frac{w(s)}{T_m(s)}\frac{T_m(s)}{V_f(s)} = \frac{\left(K_{mf}/L_fJ\right)}{\left(s+c/J\right)\left(s+R_f/L_f\right)}} \qquad \text{(2}^{\text{nd}}\text{ order system)} \qquad (1.6)$$

Finally, since $w = dq/dt$, the transfer function from input field voltage to the resulting rotational position change is

$$\boxed{\frac{q(s)}{V_f(s)} = \frac{q(s)}{w(s)}\frac{w(s)}{V_f(s)} = \frac{\left(K_{mf}/L_fJ\right)}{s\left(s+c/J\right)\left(s+R_f/L_f\right)}} \qquad \text{(3}^{\text{rd}}\text{ order system)} \qquad (1.7)$$



Armature-Current Controlled:

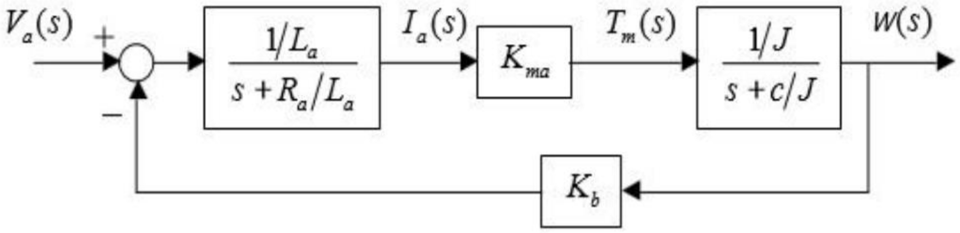
In a armature-current controlled motor, the field current i_f is held constant, and the armature current is controlled through the armature voltage V_a. In this case, the motor torque increases linearly with the armature current. We write

$$T_m = K_{ma}\, i_a$$

The transfer function from the input armature current to the resulting motor torque is

$$\boxed{\frac{T_m(s)}{I_a(s)} = K_{ma}} \tag{1.8}$$

Equations (1.8), (1.11) and (1.12) together can be represented by the closed loop block diagram shown below.



Block diagram reduction gives the transfer function from the input armature voltage to the resulting speed change.

$$\boxed{\frac{W(s)}{V_a(s)} = \frac{(K_{ma}/L_aJ)}{(s+R_a/L_a)(s+c/J)+(K_bK_{ma}/L_aJ)}} \quad (2^{nd} \text{ order system}) \tag{1.13}$$

The transfer function from the input armature voltage to the resulting angular position change is found by multiplying Equation (1.13) by $1/s$.

The voltage/current relationship for the armature side of the motor is

$$V_a = V_R + V_L + V_b \tag{1.9}$$

where V_b represents the "back EMF" induced by the rotation of the armature windings in a magnetic field. The back EMF V_b is proportional to the speed w, i.e. $V_b(s) = K_b w(s)$. Taking Laplace transforms of Equation (1.9) gives

$$\boxed{V_a(s) - V_b(s) = \left(R_a + L_a s\right) I_a(s)} \tag{1.10}$$

or

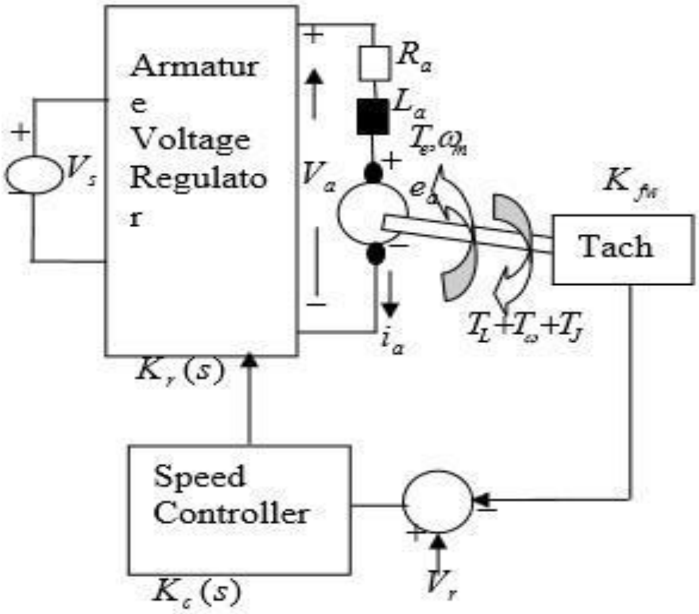
$$\boxed{V_a(s) - K_b w(s) = \left(R_a + L_a s\right) I_a(s)} \tag{1.11}$$

As before, the transfer function from the input motor torque to rotational speed changes is

$$\boxed{\frac{w(s)}{T_m(s)} = \frac{(1/J)}{s + (c/J)}} \qquad \text{(1st order system)} \tag{1.12}$$

3.3 Closed Loop Control With Current And Speed Feedback

Closed loop control improves on the drives performance by increasing speed of response and improving on speed regulation. So the functions of closed loop control is that ω_n is increased, ε is reduced, t_s is reduced, and Speed Regulation (SR) is reduced. A closed loop speed control scheme is shown below



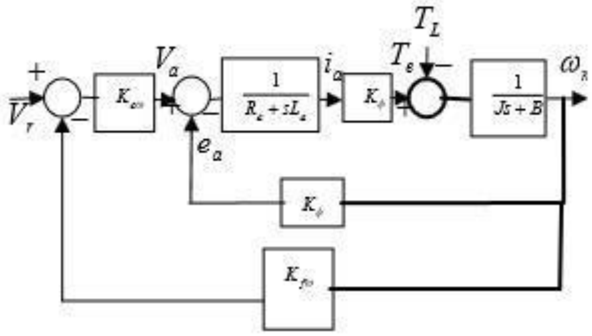
Schematic Diagram of the Closed Loop Speed Control

Where, $K_{f\omega}$ is the tachometer feedback gain

$K_c(s)$ is the speed controller gain

$K_r(s)$ is the armature voltage regulator gain

The block diagram representation of the control configuration is shown below.



Block Diagram of the Closed Loop Speed Control.

The dynamic equation by mason's rule is,

$$\begin{pmatrix}\omega_m\\ i_a\end{pmatrix}=\frac{\begin{pmatrix}K_\phi K_{c\omega}(s) & -(R_a+sL_a)\\ (Js+B)K_{c\omega}(s) & K_\phi K_{f\omega}(s)K_{c\omega}(s)\end{pmatrix}\begin{pmatrix}V_r\\ T_L\end{pmatrix}}{D_o(s)} \qquad (23)$$

Where,

$$D_o(s)=s^2JL_a+(R_aJ+BL_a)s+R_aB+K_\phi^2+K_\phi K_{f\omega}(s)K_{c\omega}(s) \qquad (24)$$

$$D_o(s)=JL_a[s^2+(\frac{R_aJ+BL_a}{JL_a})s+\frac{R_aB+K_\phi^2+K_\phi K_{f\omega}(s)K_{c\omega}(s)}{JL_a} \qquad (25)$$

If the tachometer loop does not contain a filter, the feedback gain can be a constant designated as K_{fw}

$K_{cw}(s) = K_{cwp} + K_{cwI}/ s +sK_{cwd}$

Where,

K_{cwd} is the proportional gain component of $K_{cw}(s)$

K_{cwp} is the integral gain component of $K_{cw}(s)$ & K_{cwd}

Three possible controller configurations are possible:

1.For K_{cwI} & K_{cwd} zero $K_{cw}(S) = K_{cwp}$Which is a Proportional Controller

2. For K_{cwp} & K_{cwd} zero $K_{cw}(S) = K_{cwI/S}$ Which is an Integral Controller

3. For K_{cwd} zero $K_{cw}(S) = K_{cwp} + K_{cwI}/S$ Which is a Proportional Integral Controller

Now taking the Proportional Controller as a case study, with $K_{cw}(S) = K_{cwp}$, the dynamic equation is,

$$\begin{pmatrix}\omega_m\\ i_a\end{pmatrix} = \frac{\begin{pmatrix}K_\phi K_{c\omega p} & -(R_a+sL_a)\\ (Js+B)K_{c\omega p} & K_\phi K_{f\omega}K_{c\omega p}\end{pmatrix}\begin{pmatrix}V_r\\ T_L\end{pmatrix}}{D_o(s)}$$

Where,

$$D_o(s) = s^2 JL_a + (R_aJ + BL_a)s + R_aB + K_\phi^2 + K_\phi K_{f\omega}K_{c\omega p}$$

$$D_o(s) = JL_a[s^2 + (\frac{R_aJ+BL_a}{JL_a})s + \frac{R_aB+K_\phi^2+K_\phi K_{f\omega}K_{c\omega p}}{JL_a}$$

$$D_o(s) = JL_a[s^2 + 2\varepsilon\omega_n s + \omega_n^2]$$

Last Equation is a second order system

The Natural Frequency of Oscillation, ω_n is,

$$\omega_n = \sqrt{\frac{R_aB + K_\phi^2 + K_\phi K_{f\omega}K_{c\omega p}}{JL_a}}$$

This is always higher than the open loop case due to the factor K_ϕ ,$K_{f\omega}$,

$K_{c\omega p}$ The Damping Ratio, ε , is

$$\varepsilon = \frac{R_aJ + BL_a}{2\omega_n JL_a}$$

This is lower than in the open loop case due to the increase in

ω_n Speed Regulation (SR) is also derived as

$$SR = \frac{-R_a}{R_a B + K_\phi^2 + K_\phi K_{f\omega} K_{c\omega p}}$$

,

SR is also lower than in the open loop case due to the factor K_ϕ ,$K_{f\omega}$, $K_{c\omega p}$. This is an indication of a better drive performance.

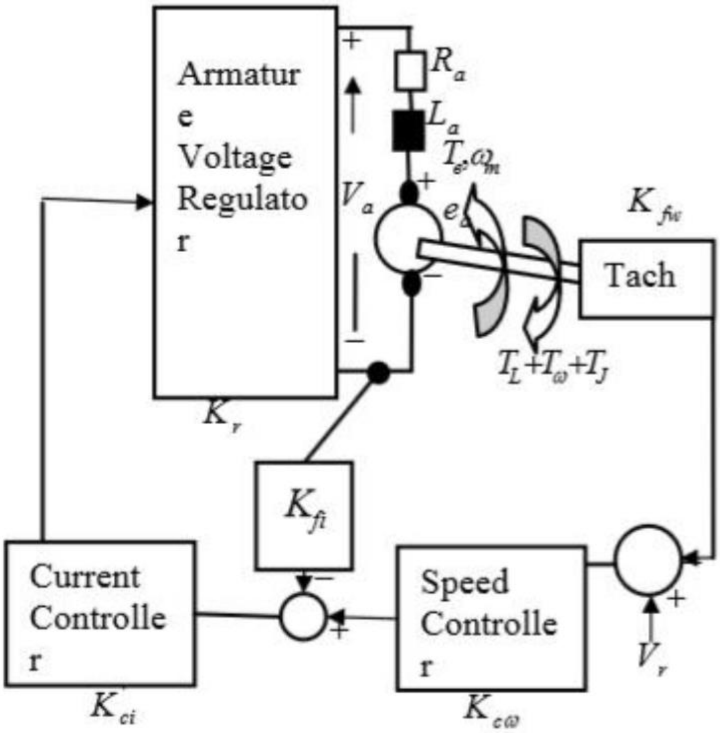
Inner Current Loop Control

Improvement in speed control can be obtained with Inner Current Loop Control method, whereby armature current is fed back to the input. A closed loop speed control scheme with inner current control is shown in Figure.

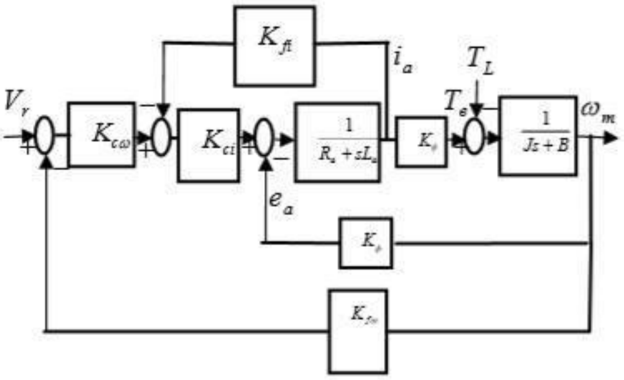
Designating $\mathbf{K^1_{ci}+K_r=K_{ci}}$ the block diagram representation of the control configuration is shown in

Figure. The dynamic equation is,

$$\begin{pmatrix} \omega_m \\ i_a \end{pmatrix} = \frac{\begin{pmatrix} K_\phi K_{ci} K_{c\omega} & -(R_a + sL_a + K_{ci} K_{fi}) \\ (Js+B) K_{c\omega} K_{ci} & K_\phi + K_{f\omega} K_{c\omega} K_{ci} \end{pmatrix} \begin{pmatrix} V_r \\ T_L \end{pmatrix}}{D_o}$$



Schematic Diagram of the Inner Current Loop Control.

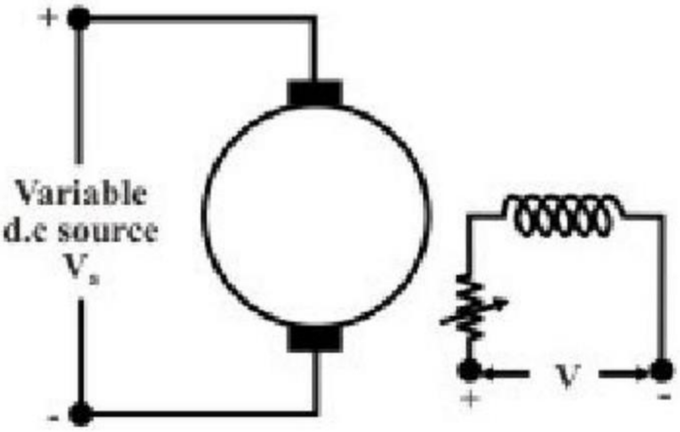


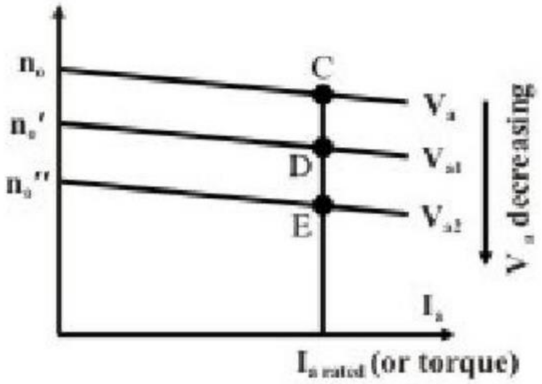
Block Diagram of the Inner Current Loop

Control 3.4 Speed control by armature voltage variation

In this method of speed control, armature is supplied from a separate variable Ac voltage source, while the field is separately excited with fixed rate dc voltage as shown in figure. Here the armature resistance and field current are not varied. Since the no load speed the speed versus *Ia* characteristic will shift parallel as shown in figure for different values of *Va*.

$$n_0 = \frac{V_a}{k\phi},$$





As flux remains constant, this method is suitable for constant torque loads. In a way armature voltage control method dissimilar to that of armature resistance control method except that the former one is much superior as next repower loss takes place in the armature circuit. Armature voltage control method is adopted for controlling speed from base speed down to very small speed, as one should not apply across the armature a voltage, which is higher than the rated voltage.

3.5 Flux-Weakening Control Design and Analysis

In order to produce the maximum torque, which main component is proportional to q-axis component of the armature current, it is convenient to control the inverter-fed PMSM by keeping the direct, *d-axis*, current component to be id as long as the inverter output voltage doesn't reach its limit.

At that point, the motor reaches its maximum speed, so-called *rated speed* (called al so *base speed* when talking about flux-weakening). Beyond that limit, the motor torque decreases rapidly toward its minimum value, which depends on a load torque profile. To expand the speed above the rated value, the motor torque is necessary to be reduced. A common method in the control of synchronous motors is to reduce the magnetizing current, which produces the magnetizing flux. This method is known as *field-weakening*. With PM synchronous motors it is not possible, but, instead, the air gap flux is weakened by producing anegative d-axis current component, id.

Because nothing has happened to the excitation magnetic field and the air gap flux is still reduced, so is the motor torque, this control method is called *flux-weakening*. As a basis for this analysis, the PMSM current and voltage d-q vector diagrams from the previous section Fig are used. During flux-weakening, because the demagnetizing (negative) id current increases, a phase current vector *is* rotates toward the *negative d-semi-axis*. The rotation of the phase voltage vector is determined by a chosen flux weakening strategy, but at the end of flux-weakening it always rotates toward the *positive q- semi axis* because of iq current, i.e vd voltage magnitude decrease.

Hence, the voltage-to-current phase shift decreases to zero and increases in negative direction either to the inverter phase shift limit (usually 30^0), or a load torque dictated steady-state (zero acceleration), or to the zero motor torque condition (no load or generative load). A big concern of flux-weakening control is a danger of permanent demagnetization of magnets. However, large materials such as Samarium-Cobalt, allows significant id current which can extend the motor rated speed up to two times. Three commonly used flux-weakening control strategies are:

1) constant-voltage-constant-power(CVCP)control;

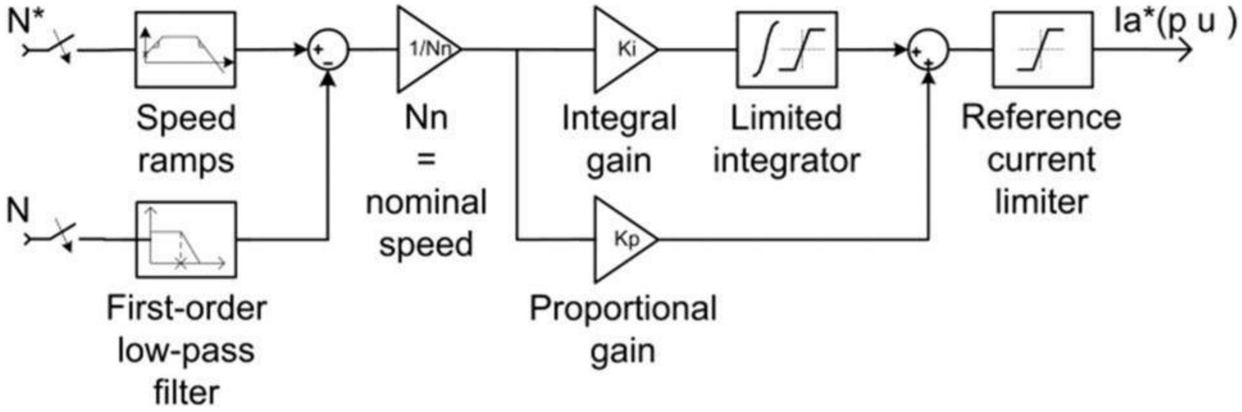
2) constant-current-constant-power(CCCP)control;and

3) optimum-current-vector(OCVorCCCV-constant-current-constant-voltage)control.

3.6 Speed Controller

The speed regulator in the following figure uses a PI controller. The controller outputs the armature current reference (in pu) used by the current controller in order to obtain the electromagnetic torque needed to reach the desired speed. During torque regulation, the speed controller is disabled.

The controller takes the speed reference (in rpm) and the rotor speed of the DC machine as inputs. The speed reference change rate will follow user-defined acceleration and deceleration ramps in order to avoid sudden reference changes that could cause armature over-current and destabilize the system. The speed measurement is filtered by a first-order low-pass filter.

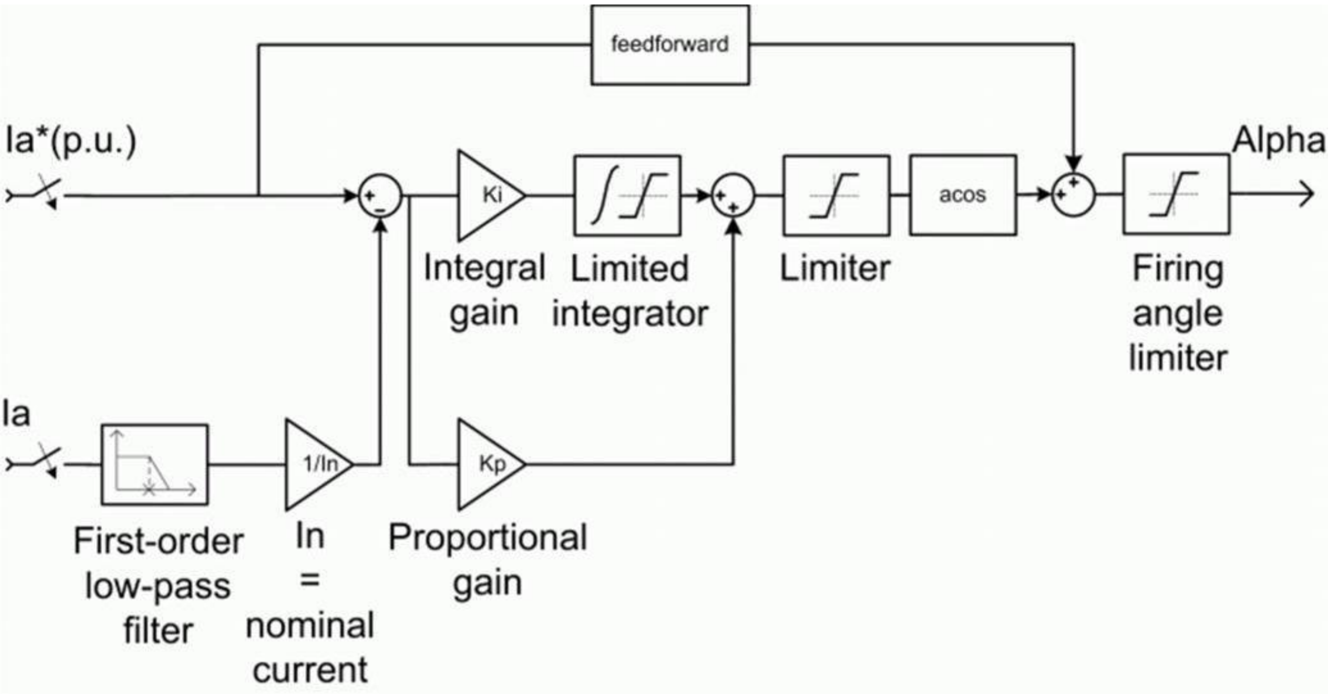


3.7 Current Controller

The armature current regulator in the following figure is based on a second PI controller. The regulator controls the armature current by computing the appropriate thyristor firing angle. This generates the rectifier output voltage needed to obtain the desired armature current and thus the desired electromagnetic torque.

The controller takes the current reference (in pu) and the armature current flowing through the motor as inputs. The current reference is either provided by the speed controller during speed regulation or computed from the torque reference provided by the user during torque regulation. This is managed by the "regulation switch" block.

The armature current input is filtered by a first-order low-pass filter. An arccosine function is used to linearize the control system during continuous conduction. To compensate nonlinearities appearing during discontinuous conduction, a feed forward term is added to the firing angle.



UNIT IV

INDUCTION MOTOR DRIVES

4.1 Stator Voltage Control

In this method of control, back-to-back thyristors are used to supply the motor with variable ac voltage. The analysis implies that the developed torque varies inversely as the square of the input RMS voltage to the motor. This makes such a drive suitable for fan- and impeller-type loads for which torque demand rises faster with speed. For other types of loads, the suitable speed range is very limited. Motors with high rotor resistance may offer an extended speed range. It should be noted that this type of drive with back-to-back thyristors with firing-angle control suffers from poor power and harmonic distortion factors when operated at low speed. If unbalanced operation is acceptable, the thyristors in one or two supply lines to the motor may be bypassed. This offers the possibility of dynamic braking or plugging, desirable in some applications.

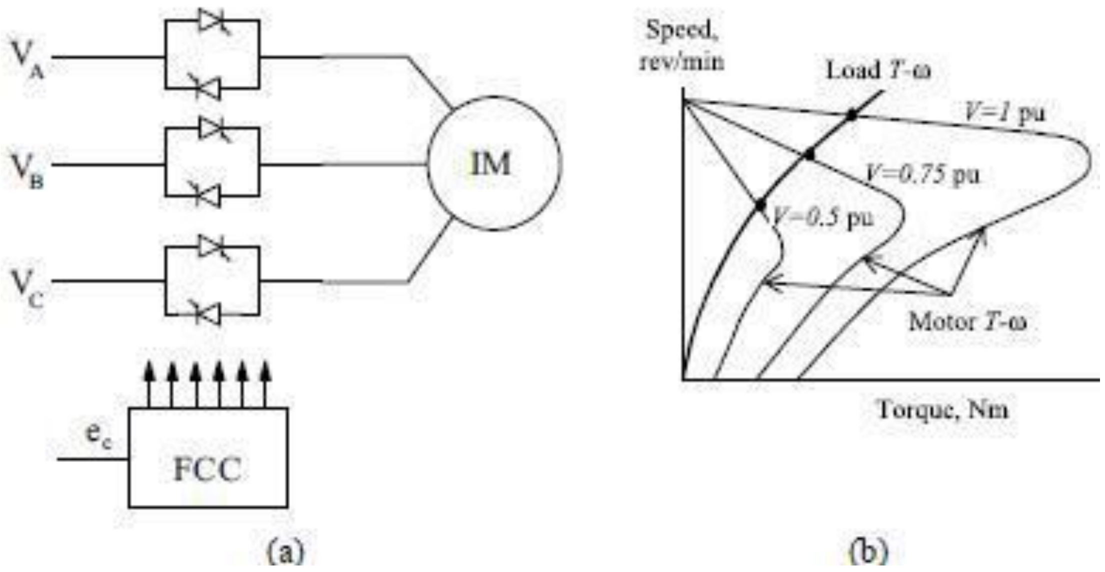
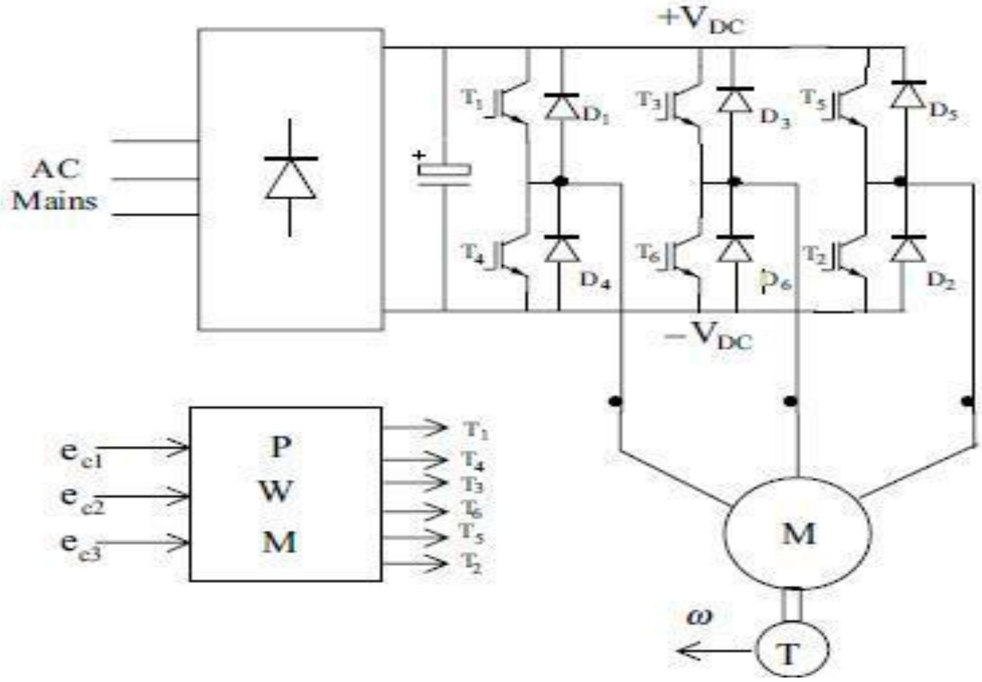


FIGURE (a) Stator voltage controller. (b) Motor and load torque–speed characteristics under voltage control.

The induction motor speed variation can be easily achieved for a short range by either stator voltage control or rotor resistance control. But both of these schemes result in very low efficiencies at lower speeds. The most efficient scheme for speed control of induction motor is by varying supply frequency. This not only results in scheme with wide speed range but also improves the starting performance. If the machine is operating at speed below base speed, then v/f ratio is to be kept constant so that flux remains constant. This retains the torque capability of the machine at the same value. But at lower frequencies, the torque capability decrease and this drop in torque has to be compensated for increasing the applied voltage.



4.2 V/F Control

Open Loop V/F Control

The open loop V/F control of an induction motor is the most common method of speed control because of its simplicity and these types of motors are widely used in industry. Traditionally, induction motors have been used with open loop 50Hz power supplies for constant speed applications. For adjustable speed drive applications, frequency control is natural. However, voltage is required to be proportional to frequency so that the stator flux

$$\Psi_s=V_s/\omega_s$$

Remains constant if the stator resistance is neglected. The power circuit consists of a diode rectifier with a single or three-phase ac supply, filter and PWM voltage-fed inverter. Ideally no feedback signals are required for this control scheme.

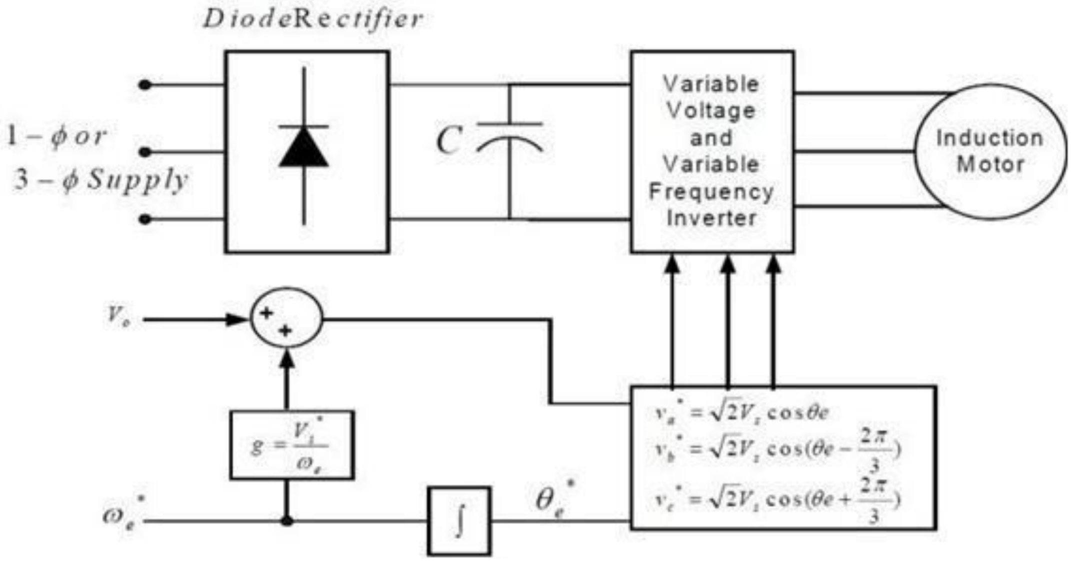
The PWM converter is merged with the inverter block. Some problems encountered in the operation of this open loop drive are the following:

The speed of the motor cannot be controlled precisely, because the rotor speed will be slightly less than the synchronous speed and that in this scheme the stator frequency and hence the synchronous speed is the only control variable.

The slip speed, being the difference between the synchronous speed and the electrical rotor speed, cannot be maintained, as the rotor speed is not measured in this scheme. This can lead to operation in the unstable region of the torque-speed characteristics.

The effect of the above can make the stator currents exceed the rated current by a large amount thus endangering the inverter- converter combination

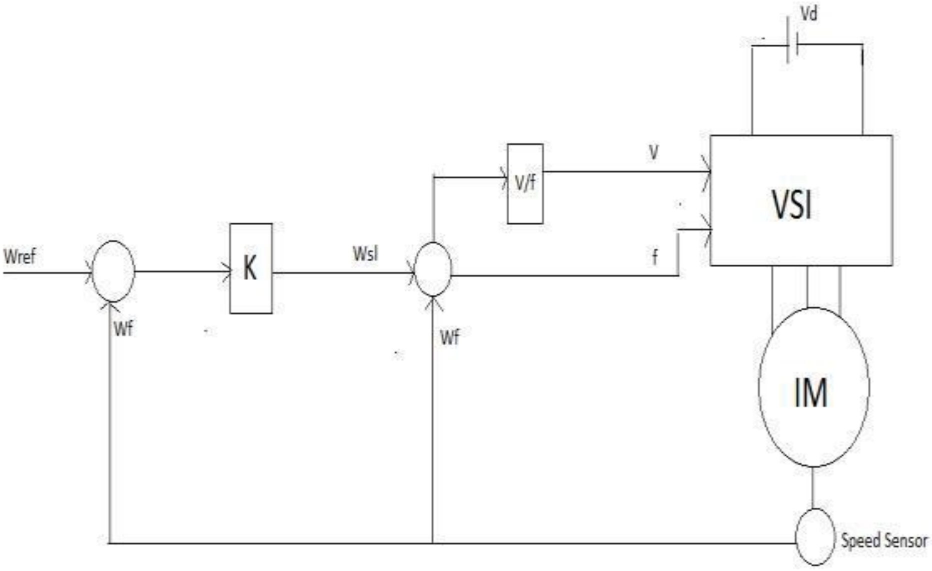
These problems are to be suppress by having an outer loop in the induction motor drive, in which the actual rotor speed is compared with its commanded value, and the error is processed through a controller usually a PI controller and a limiter is used to obtain the slip-speed command



Block diagram of open loop V/F Control for an IM

Closed Loop V/F Control

The basis of constant V/F speed control of induction motor is to apply a variable magnitude and variable frequency voltage to the motor. Both the voltage source inverter and current source inverters are used in adjustable speed ac drives. The following block diagram shows the closed loop V/F control using a VSI



Block diagram for closed loop V/F control for an IM

A speed sensor or a shaft position encoder is used to obtain the actual speed of the motor. It is then compared to a reference speed. The difference between the two generates an error and the error so obtained is processed in a Proportional controller and its output sets the inverter frequency. The synchronous speed, obtained by adding actual speed ω_f and the slip speed ω_{SI}, determines the inverter frequency The reference signal for the closed-loop control of the machine terminal voltage ω_f is generated from frequency

4.3 Field Weakening Mode

In the field of closed loop controlled voltage source inverter- fed induction motors the rotor flux oriented control scheme can be regarded as the state of the art for various applications [6]. In some applications as spindles, traction and electric vehicle drives the availability of constant power operation is very important. A field-oriented induction motor drive is a suitable candidate for such applications because the flux of the induction machine can be easily weakened. In this case the drive operates close to the voltage limit and the reference flux has to be carefully selected to achieve the maximum torque Control of an induction motor with weakened flux has been investigated by many authors and three methods for establishing the flux were suggested

1) The flux reference can be set according to a fixed flux- speed characteristic

2) it can be calculated from simplified motor equations, which can be improved through consideration of additional variables

3) it can be provided by a voltage controller, which sets the flux in such a way that the voltage required by the motor matches the voltage capability of the inverter

The third strategy seems to be optimal because it is not sensitive to parameter variations in a middle speed region. At high speed the current has to be reduced for matching the maxi - mum torque and for avoiding a pull-out. In this is done with a fixed current-speed characteristic which is sensitive to parameter and DC link voltage variations. A remedy is possible if a parameter insensitive feature of the induction machine is used for the current reduction. Such a criterion is presented and an extension of the voltage control is presented in this paper which allows an operation with maximum torque in the whole field weakening region

THE STEADY STATE TORQUE CAPABILITY

The investigation starts with the dynamic model of the induction motor in the rotor flux oriented frame

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} i_{Sd} \\ i_{Sq} \\ \Psi_{Rd} \end{pmatrix} = \begin{pmatrix} -\frac{K_R}{K_L} & \omega_{FS} & \frac{L_m}{L_R K_L}\frac{1}{T_R} \\ -\omega_{FS} & -\frac{K_R}{K_L} & -p\omega_m \frac{L_m}{L_R K_L} \\ \frac{L_m}{T_R} & 0 & -\frac{1}{T_R} \end{pmatrix} \cdot \begin{pmatrix} i_{Sd} \\ i_{Sq} \\ \Psi_R \end{pmatrix} \qquad (1)$$

$$+ \begin{pmatrix} \frac{1}{K_L} & 0 \\ 0 & \frac{1}{K_L} \\ 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} u_{Sd} \\ u_{Sq} \end{pmatrix}$$

$$T_m = \frac{3}{2} p \frac{L_m}{L_R} i_{Sq} \Psi_R \qquad (2)$$

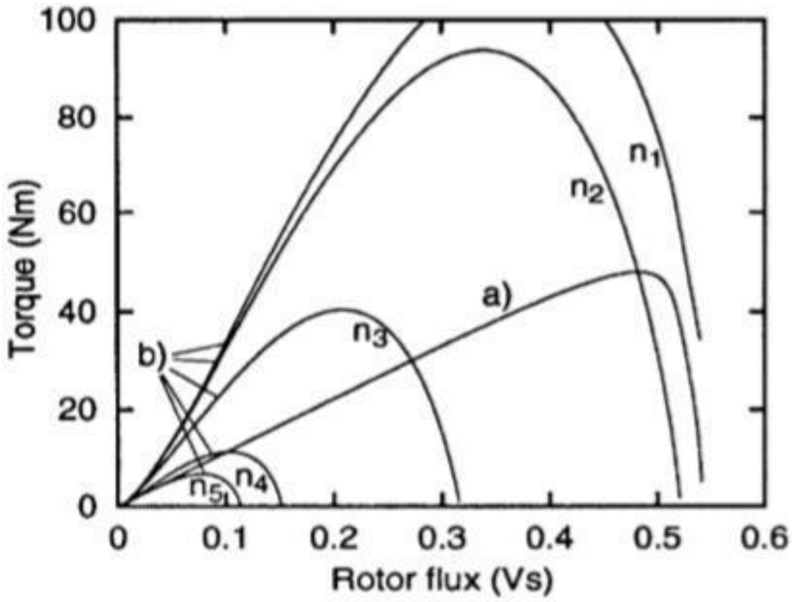
$$T_m = \frac{3}{2}p\frac{L_m}{L_R}i_{Sq}\Psi_R \qquad (2)$$

$$\omega_{FS} = \omega_{FR} + p\omega_m \qquad (3)$$

$$\omega_{FR} = \frac{L_m}{T_R}\cdot\frac{i_{Sq}}{\Psi_R} \qquad (4)$$

$$L_m = f(i_m) \quad \text{with } i_m = i_{Sd}\sqrt{1+\left(\frac{i_{Sq}}{i_{Sd}}\left(1-\frac{L_m}{L_R}\right)\right)^2} \qquad (5)$$

The voltage limitation curves depend on rotor speed. For every rotor speed any operation point below the voltage and the current limitation curve is possible and permissible. Obviously three speed regions have to be distinguished Basic speed region: At low speeds the peak of the cur- rent limit curve is situated below the voltage limit curve (e. g. curve b) with lo00 rpm). The maximum torque is determined by the peak of the current limitation curve and the corresponding rotor flux Root has to chosen.



Lower flux weakening region: At medium speeds the maximum torque is indicated by the crossing of both limitation curves (e. g. curve a) and b) with 2500 rpm). The induction machine has to run with minimum current and maximum voltage.

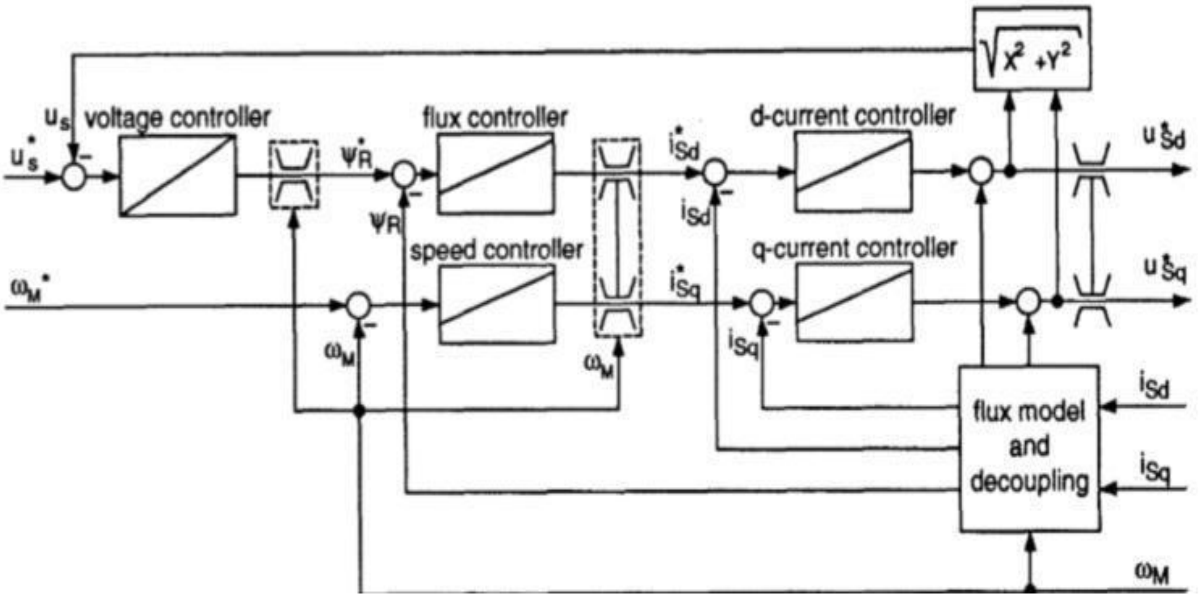
Upper flux weakening region: At high speeds the maxi- mum torque is fixed by the maxima of the voltage limitation curves only. The machine has to run only with maximum voltage but the current has to be reduced.

In the lower flux weakening region the optimum operating point can be adjusted independently of the electrical parameters if the control scheme makes sure that the induction machine runs with maximum current and voltage.

Fig. 2 shows a scheme that keeps these two conditions ([3], [lo]). The voltage controller increases the flux of the induction motor until the voltage matches the reference value us that is nearly the same as the voltage maximum

At the basic speed region the induction motor must not run at the voltage limit. The missing condition to adjust the operating point is replaced by the limitation of the reference flux. This is chosen as that determined the peak of the current limitation curve.

At the upper flux weakening region the limitation of the reference q-current is carried out with a speed depending function is max (am) that is calculated offline in such a way that de reduced current limitation curve crosses the voltage limitation curves at their maxima in Fig



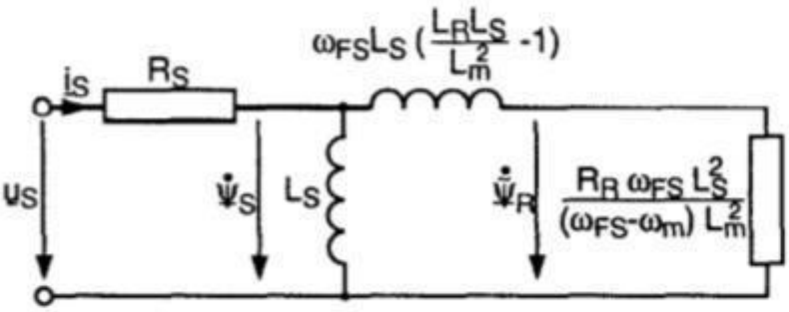
Scheme of rotor flux oriented control with voltage controller

CURRENT REDUCTION IN THE UPPER FLUX WEAKENING REGION

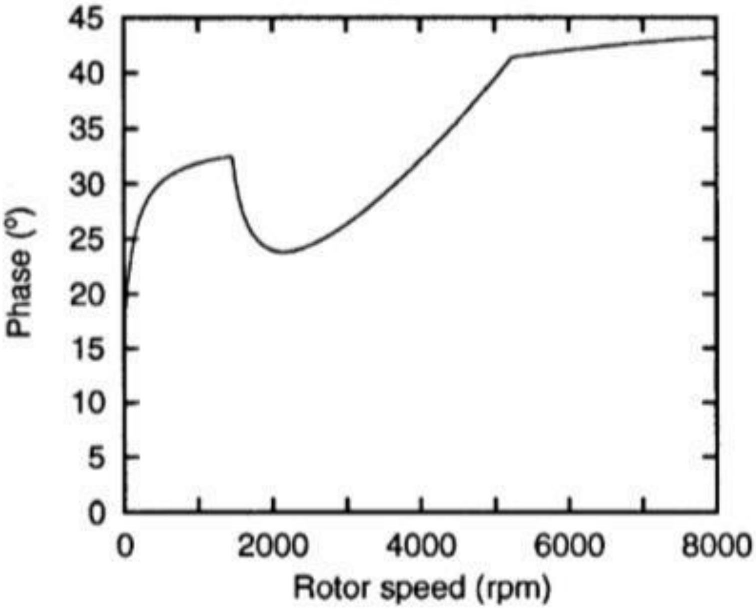
The function Iq max (n) depends on the electrical parameters as well as the DC link voltage. If the uncertainties of the electrical parameters and the variations of u d are taken into account the optimum operating point can be missed. This problem can be solved, if there is a second condition that describes the optimum operating point in the upper flux weakening region independently of the critical parameters. A condition that describes the optimum operating point independent of the electrical parameters can only depend on the measured values of current, voltage and speed. Since the torque has to be optimized for a given speed the measured value of the speed delivers no information.

The amplitudes of the remaining voltage and current values are analyzed by means of Fig. 1 but additional information can be extracted from the angle between these quantities. The angle can be gathered from Fig. 3 that shows the locus of apparent power depends on speed if the motor runs with maximum torque. The three speed regions can be separated in this diagram as well as in Fig Basic speed region (0 rpm ... 1457 rpm): The stator voltage increases with speed and also the active and reactive power. Lower flux weakening region (1457 rpm...5240 rpm): The motor runs with maximum voltage and current. This results in = const. Upper flux weakening region (5240 rpm.. .8000 rpm): The current is reduced and also the apparent power.

Remarkable is the phenomenon that the angle Ψ between u_s and I_s is nearly 45^0 and constant at the upper flux weakening region. This is also true for machines with other parameters. The reason can be deduced from the equivalent circuit of the induction motor at steady state (Fig.). In the upper flux weakening region with the corresponding high excitation frequencies the magnetizing current as well as the influence of the stator resistance can be neglected. The maximum active power for a given voltage and excitation frequency is achieved if leakage reactance and rotor resistance are equal and



Equivalent circuit for induction machine with all leakage on rotor side.



Angle between stator voltage and stator current ϕ.

$\varphi = 45°$. This results in:

$$\omega_{FS} - \omega_{RS} = \frac{R_R}{K_L}. \tag{6}$$

A more exact solution can be found by searching the maximum of

$$P_m(i_{Sd}, i_{Sq}) = T_m \cdot \omega_m = \frac{3L_m^2}{2L_R} \cdot \omega_{RS} \cdot i_{Sd} \cdot i_{Sq} \tag{7}$$

with the constraints:

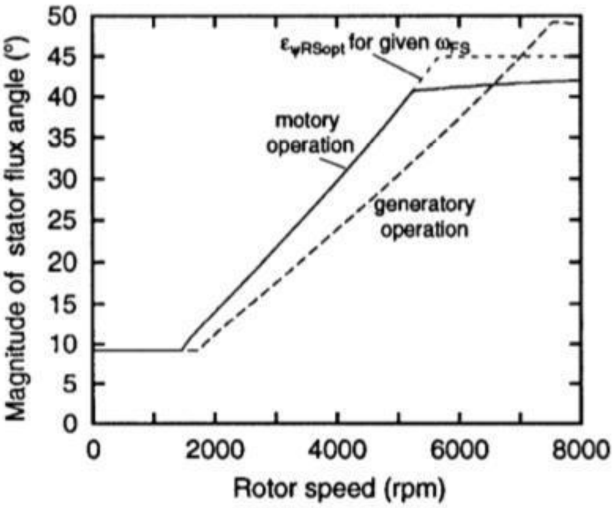
$$L_m = f(i_{Sd}, i_{Sq}) \tag{8}$$

$$u_{max}^2 = u_{Sd}^2 + u_{Sq}^2 \tag{9}$$

with

$$u_{Sd} = R_S\, i_{Sd} - K_L \omega_{RS}\, i_{Sq} - \frac{K_L R_R}{L_R} \cdot \frac{i_{Sq}^2}{i_{Sd}}, \tag{10}$$

With these equations the torque is maximized for a given rotor speed and not for a given excitation frequency as with equ. (6) And in some papers.



Optimal angle of stator flux in the rotor flux frame

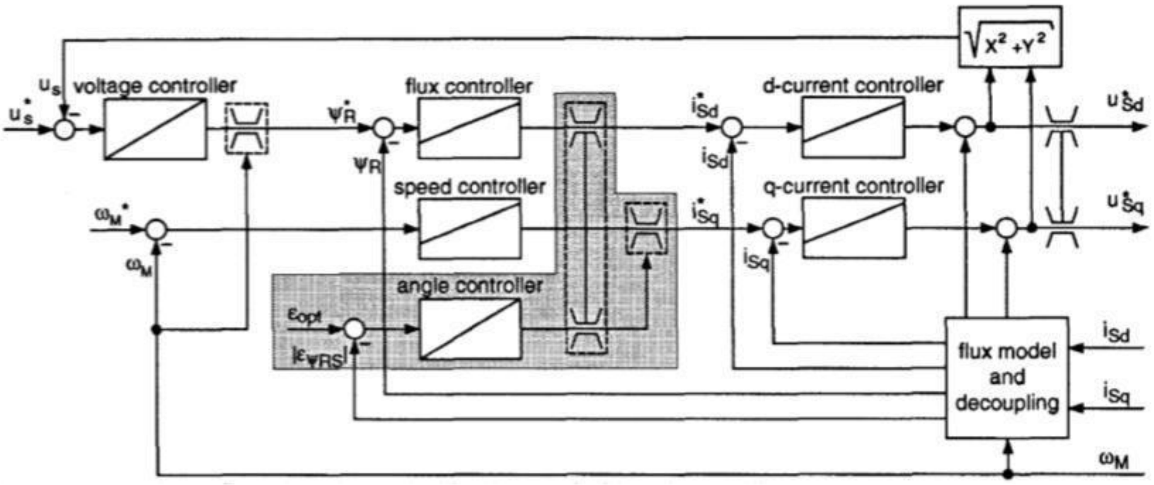
The different operation areas are characterized by different behavior

In the basic speed region EΨRSPOT is small and constant.

In the lower flux weakening region the angle is characterized by a monotonous increase with a large gradient.

In the upper flux weakening region EΨRSPOT increases monotonously as well but the gradient is very small. As proposed EΨRSPOT is just a few degrees below 45^0 and nearly the same as Ψ in this speed range. These quantity can be utilized advantageously as a criterion for the optimum operating point.

During generatory operation the upper flux weakening region is very small; the angle is negative and its magnitude runs above 45^0



Scheme of rotor flux oriented control with voltage and with angle controller

The result of the simplified optimization for the upper flux weakening region is also presented in Fig. This curve runs just below 45^{0} (exactly 45^0 if RS = 0) and the corresponding operation points are identical to the well-known pullout torque of the induction machine which characterizes the maxi- mum torque if the machine is excited with a fixed voltage and frequency. But these operation points represents not the maxi- mum torque for excitation with variable frequency and constant voltage. A larger torque can be attained for a given rotor speed if the machine runs with a smaller slip and excitation frequency and a therefore larger flux amplitude.

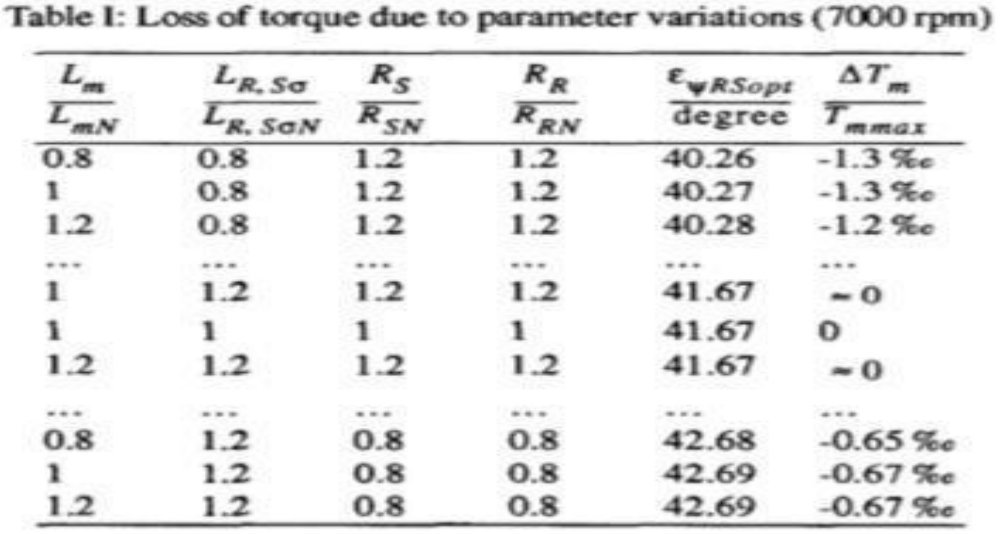


Table I: Loss of torque due to parameter variations (7000 rpm)

$\frac{L_m}{L_{mN}}$	$\frac{L_{R,S\sigma}}{L_{R,S\sigma N}}$	$\frac{R_S}{R_{SN}}$	$\frac{R_R}{R_{RN}}$	$\frac{\varepsilon_{\Psi RSopt}}{\text{degree}}$	$\frac{\Delta T_m}{T_{mmax}}$
0.8	0.8	1.2	1.2	40.26	-1.3 ‰
1	0.8	1.2	1.2	40.27	-1.3 ‰
1.2	0.8	1.2	1.2	40.28	-1.2 ‰
...	...	...	...	...	...
1	1.2	1.2	1.2	41.67	~0
1	1	1	1	41.67	0
1.2	1.2	1.2	1.2	41.67	~0
...	...	...	...	...	...
0.8	1.2	0.8	0.8	42.68	-0.65 ‰
1	1.2	0.8	0.8	42.69	-0.67 ‰
1.2	1.2	0.8	0.8	42.69	-0.67 ‰

The robustness of the stator flux angle EΨRSPOT is demonstrated with Table I. In this table the results of EΨRSPOT! for a fixed rotor speed are listed which can be obtained if variations of the electrical parameters (factor: 0.8, 1.0, 1.2) are allowed and all 81 combinations are examined. The rows are sorted to increasing EΨRSPOT.In spite of the large variations the maxi- mum and the minimum of EΨRSPOT differ only little from the correct value $41.67\ ^{0}$. For these calculations the saturation of the mutual inductance was neglected and in this case EΨRSPOT is independent of the stator voltage. The last column shows the loss of torque if the induction machine runs with EΨRSPOT calculated from the detuned parameters. An extreme robustness to parameter uncertainties can be realized.

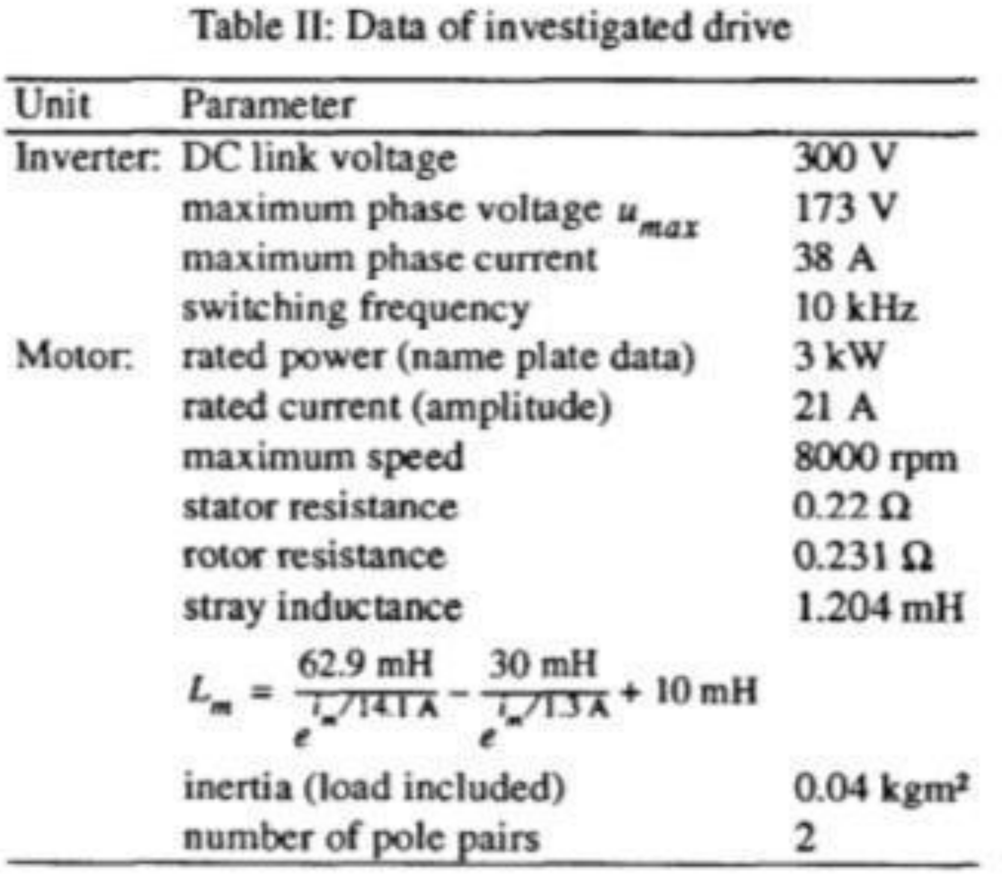


Table II: Data of investigated drive

Unit	Parameter	
Inverter:	DC link voltage	300 V
	maximum phase voltage u_{max}	173 V
	maximum phase current	38 A
	switching frequency	10 kHz
Motor:	rated power (name plate data)	3 kW
	rated current (amplitude)	21 A
	maximum speed	8000 rpm
	stator resistance	0.22 Ω
	rotor resistance	0.231 Ω
	stray inductance	1.204 mH
	$L_m = \frac{62.9\text{ mH}}{e^{i_m/14.1\text{ A}}} - \frac{30\text{ mH}}{e^{i_m/1.3\text{ A}}} + 10\text{ mH}$	
	inertia (load included)	0.04 kgm²
	number of pole pairs	2

The current reduction by means of the stator flux angle can be easily implemented in the control scheme. One solution with little expense is shown in Fig. 7. The flux model delivers additionally an estimated value of the difference to EΨRSPOT is applied to an integrator which operates as an angle controller. Its regulating quantity is the limit of the reference q-current. If (E I > EΨRSPOT) the q-current will be reduced until the regulated quantity meets its reference value EΨRSPOT.

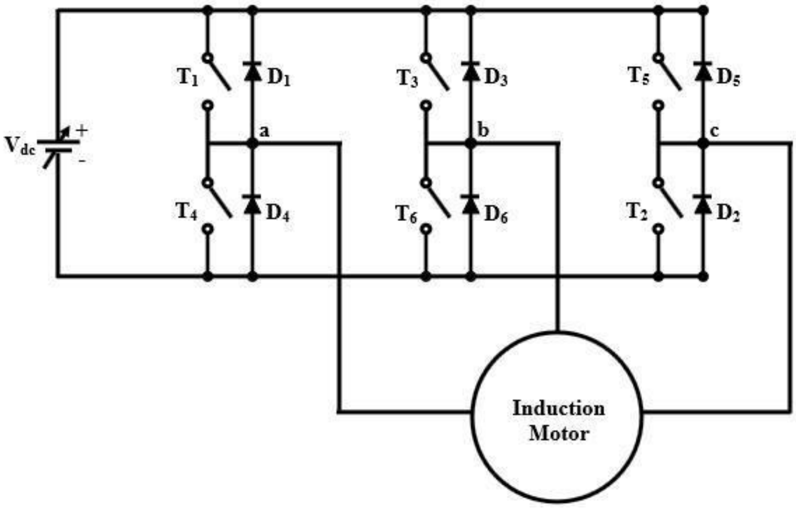
The quality of the operation point adjustment depends apparently on the quality of the flux estimation but at the relevant large rotor speeds a robust flux estimation is not difficult and uncritical. Furthermore, EΨRS coupled closely to the measurable angle Ψ in this speed range.

4.4 Voltage-source Inverter-driven Induction Motor

A three-phase variable frequency inverter supplying an induction motor is shown in Figure. The power devices are assumed to be ideal switches. There are two major types of switching schemes for the inverters, namely, **square wave switching and PWM switching.**

Square wave inverters

The gating signals and the resulting line voltages for square wave switching are shown in Figure. The phase voltages are derived from the line voltages assuming a balanced three-phase system.

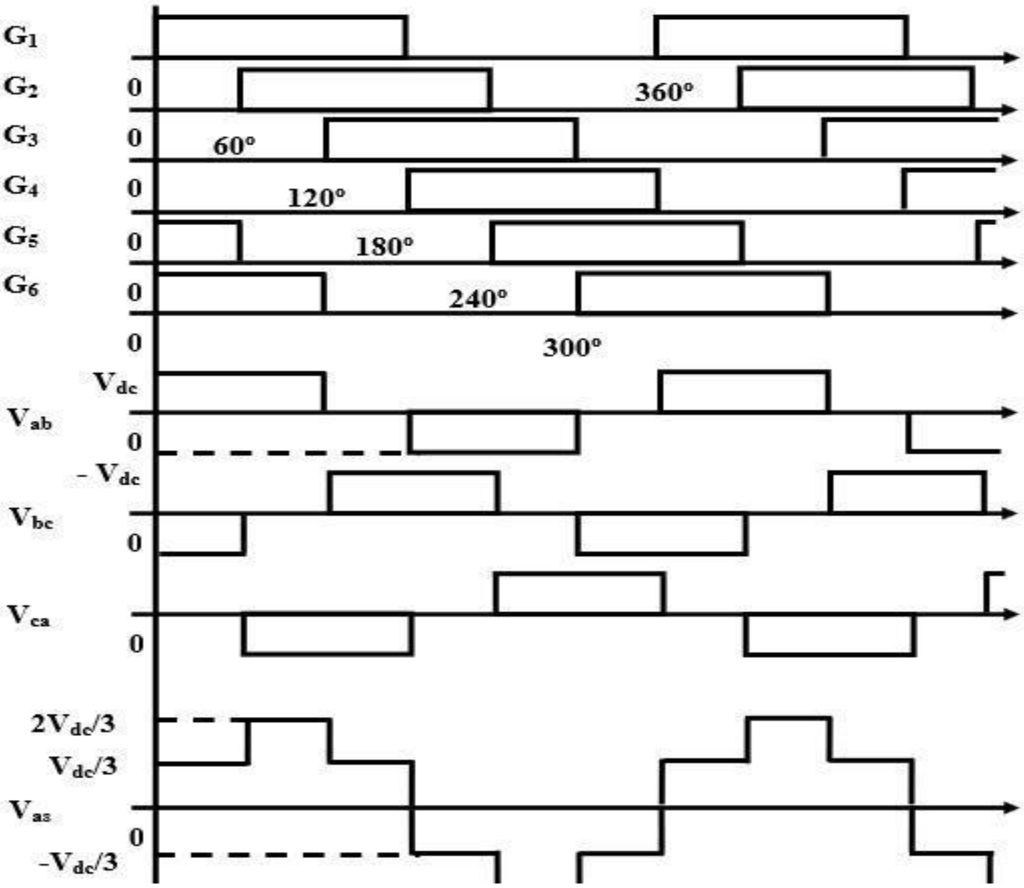


A schematic of the generic inverter-fed induction motor drive.

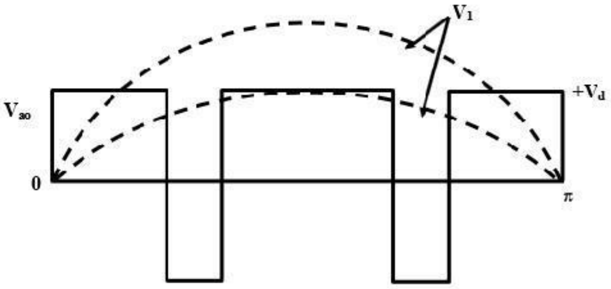
The square wave inverter control is simple and the switching frequency and consequently, switching losses are low. However, significant energies of the lower order harmonics and large distortions in current wave require bulky low-pass filters. Moreover, this scheme can only achieve frequency control. For voltage control a controlled rectifier is needed, which offsets some of the cost advantages of the simple inverter

PWM Principle

It is possible to control the output voltage and frequency of the PWM inverter simultaneously, as well as optimize the harmonics by performing multiple switching within the inverter major cycle which determines frequency. For example, the fundamental voltage for a square wave has the maximum amplitude (4Vd/π) but by intermediate switching, as shown in Fig. 34.12, the magnitude can be reduced. This determines the principle of simultaneous voltage control by PWM. Different possible strategies for PWM switching exist. They have different harmonic contents. In the following only a sinusoidal PWM is discussed.



Inverter gate (base) signals and line-and phase-voltage waveforms



PWM principle to control output voltage.

Sinusoidal PWM

Figure explains the general principle of SPWM, where an isoles triangle carrier wave of frequency fc is compared with the sinusoidal modulating wave of fundamental frequency f, and the points of intersection determine the switching points of power devices. For example, for phase-a, voltage (Va0) is obtained by switching ON Q1 and Q4 of half-bridge inverter, as shown in the figure . Assuming that f << fc, the pulse widths of va0 wave vary in a sinusoidal manner. Thus, the fundamental frequency is controlled by varying f and its amplitude is proportional to the command modulating voltage. The Fourier analysis of the va0 wave can be shown to be of the form

$V_{a0} = 0.5mV_d \sin(2\,\text{Л}ft+\pi\varphi)$+ harmonic frequency terms

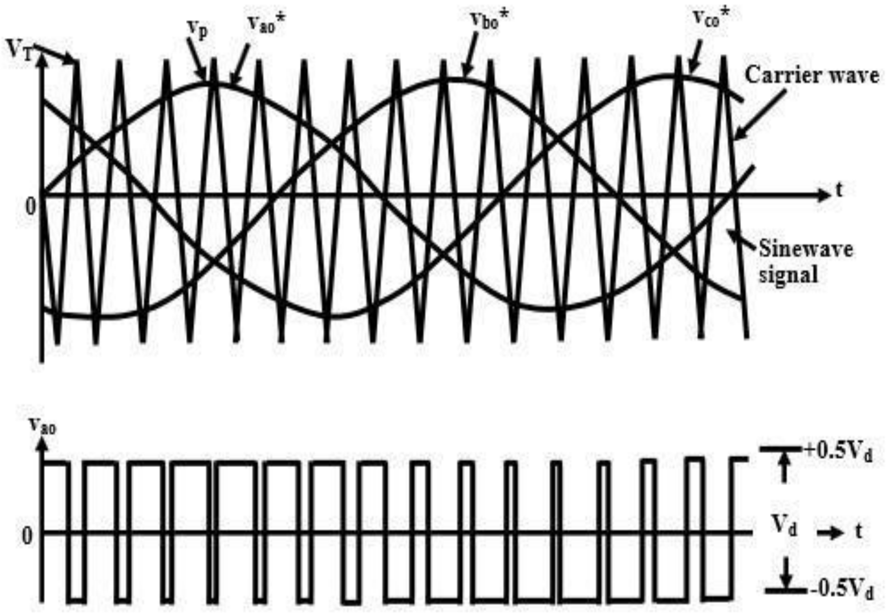
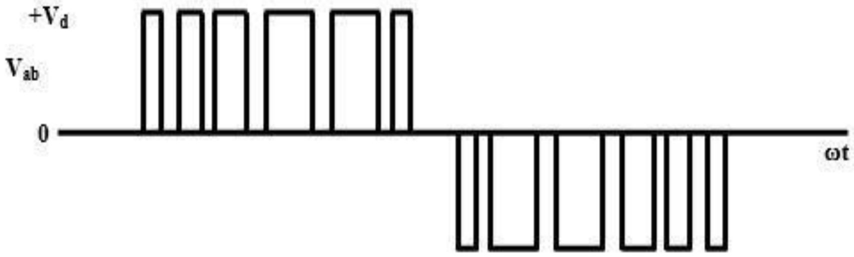


Fig. 34.13(a) Principle of sinusoidal PWM for three-phase bridge inverter.



Line voltage waves of PWM inverter

Where m = modulation index and φ = phase shift of output, depending on the position of the modulating wave. The modulation index m is defined as

$$m= V_P/V_T$$

Where Vp = peak value of the modulating wave and V_T = peak value of the carrier wave. Ideally, m can be varied between 0 and 1 to give a linear relation between the modulating and output wave. The inverter basically acts as a linear amplifier. The line voltage waveform is shown in Fig.

Current Fed Inverters

CSI classification is based on the structure of the front-end power converter, which could be either a phase-controlled thyristor rectifier or a PWM current-source rectifier.

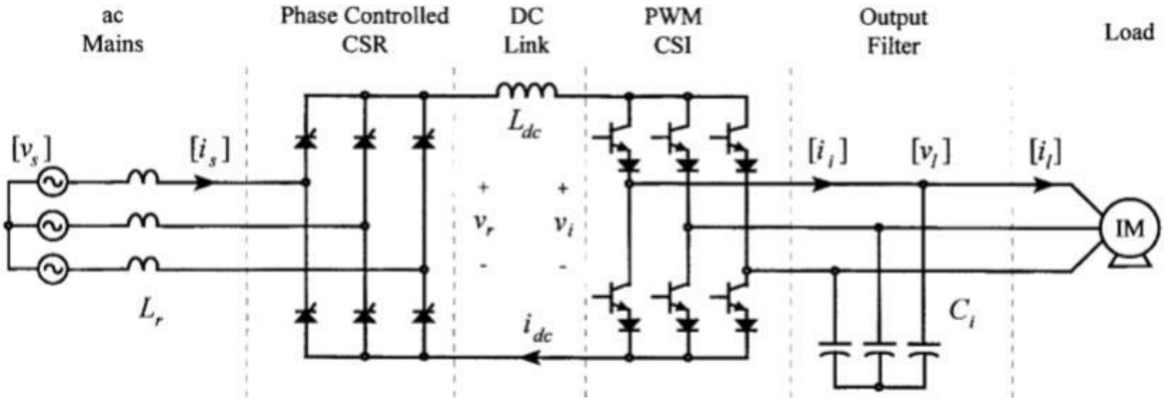
A. Phase-Controlled Front-End Rectifiers

These drives use a front-end rectifier based on thyristor-type power switches (Fig. 1), which can be operated with either variable or fixed dc-link current. The performance of the drive converter depends on this last feature.

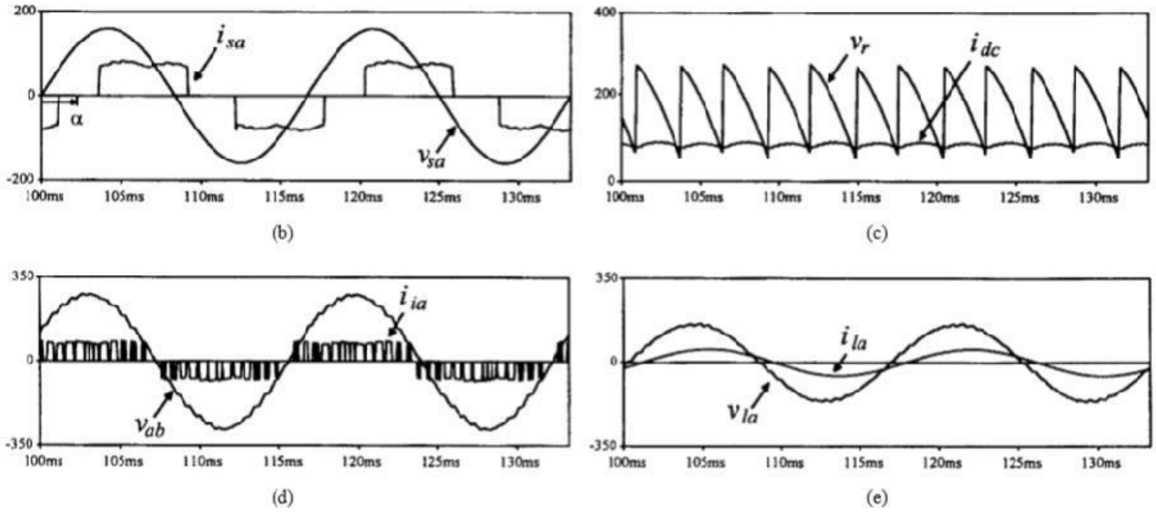
Variable DC-Link Current Scheme

The CSI is operated with a fixed pattern, which is usually optimized in terms of harmonic spectrum and switching frequency. Thus, the load voltage harmonic distortion is minimum and constant (Table I). However, the dc-link current must be adjusted through transient changes in firing angle to meet the requirements of the load. The dc voltage, on the other hand, is practically constant and independent of the load torque.

This last feature leads to a constant input current displacement factor and, thereby, a constant overall PF. Also, since the dc-link current tracks the output current, the dc-bus and switch conduction losses are kept to a minimum. Usually, the dc-link inductor is designed to have an acceptable current ripple (5%). In order to achieve this value and due to the low-order harmonics produced by the thyristor rectifier (sixth, 12th, etc.), the size of the dc inductor becomes quite bulky. This results in a slow system transient response. Also, the supply current has a high distortion factor % due to the low-order harmonics (fifth, seventh, etc.) injected by the thyristor rectifier. Fig shows typical waveforms of the converter. The rectifier phase angle is only adjusted during transient conditions occurring under load speed and torque variations.



(a)



AC drive CSI based on a phase-controlled front-end rectifier

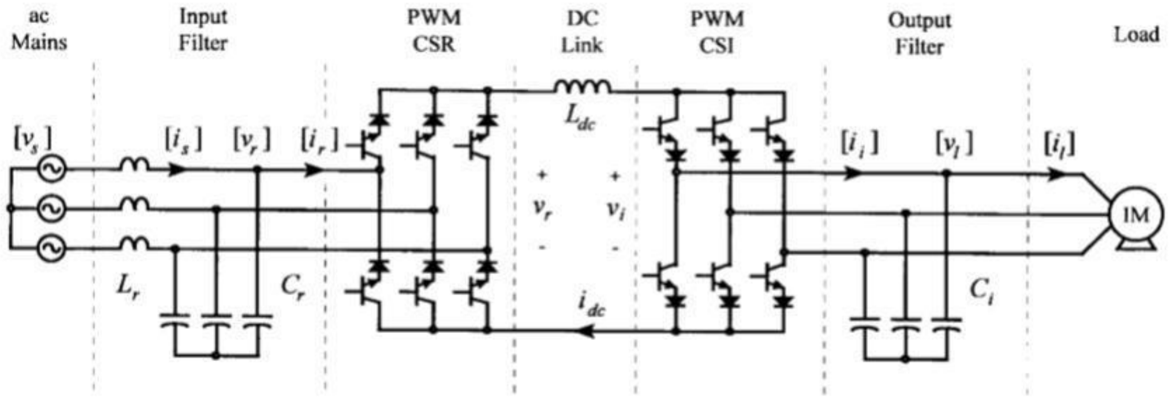
(a) Power topology. (b) Supply phase voltage and supply line current. (c) DC rectifier voltage and dc-link current. (d) CSI line current and load line voltage. (e) Load phase voltage and load line current.

Fixed DC-Link Current Scheme

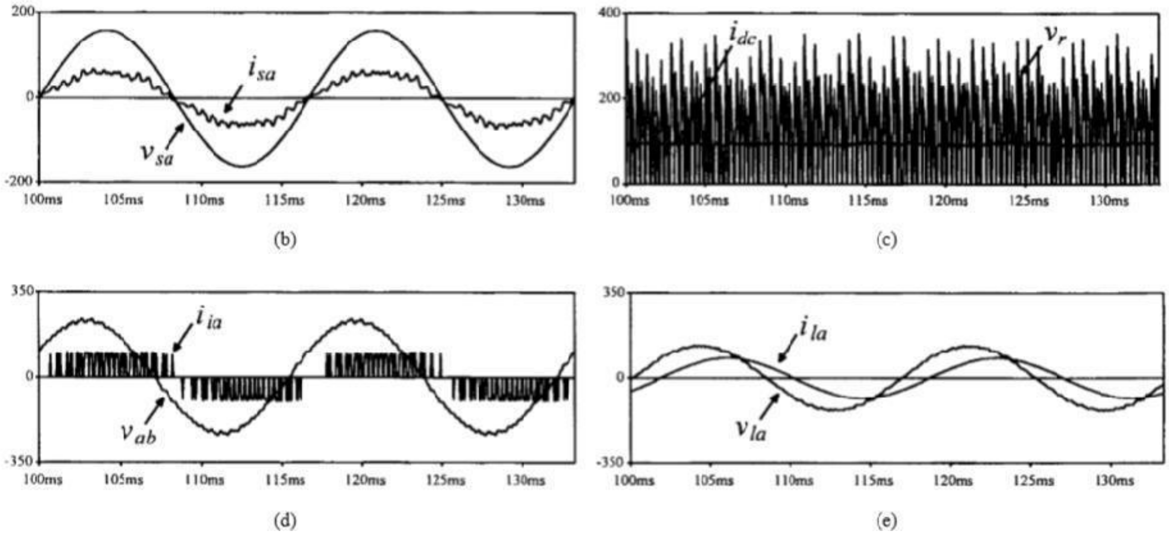
Unlike the above control scheme, the CSI is operated with a PWM pattern, which varies as a function of the CSI modulation index. Therefore, the load voltage harmonic distortion is variable and depends upon the speed and load torque (Table I). Since the dc-link current is fixed, the different load power requirements are obtained by varying the dc-link voltage. To achieve this, the input current displacement factor is continuously adjusted and, thereby, the input PF becomes variable and close to zero for light loads. Contrary to the variable dc-link current scheme, the dc -bus and switch conduction losses are always maximum, due to the fact that the dc-link current is always maximum (Table I). Although the dc-link inductor size is as big as the one used in the above scheme, the dynamic response of the load current is improved, due to the variable PWM pattern approach with time responses to modulation index changes of the order of a sampling period. This scheme also presents a high supply current harmonic distortion, due to the thyristor rectifier operation (Table I). Typical waveforms shown in Fig are also applicable in this case; however, in this mode of operation, the rectifier phase angle is continuously adjusted to maintain a constant dc-link current, regardless of the load speed and torque.

B. PWM Front-End Rectifiers

Unlike phase-controlled rectifier topologies, this topology uses a PWM rectifier. This allows a reduction in the harmonics injected into the ac supply. The rectifier is operated with a fixed dc-link current. Fig. 2 shows typical waveforms of the converter. The PWM pattern is adjusted on a continuous basis to keep a constant dc-link current. In contrast to topologies based on thyristor front-end rectifiers, the overall drive input PF is always greater than 0.95, and the total input current harmonic distortion, which depends on the sampling frequency, is typically lower than 10% (Table I) . Also, since the output inverter is PWM modulated, the system has time responses close to the sampling period. However, the dc-bus losses and switch conduction losses are maximum, since the dc-link current is always equal to its maximum value, regardless of the load speed and torque.



(a)



(b) (c)

(d) (e)

AC drive CSI based on a PWM front-end rectifier

(a) Power topology. (b) Supply phase voltage and supply line current. (c) DC rectifier voltage and dc-link current. (d) CSI line current and load line voltage. (e) Load phase voltage and load line current.

4.5 Vector Control of AC Induction Machines

Vector control is the most popular control technique of AC induction motors. In special reference frames, the expression for the electromagnetic torque of the smooth-air-gap machine is similar to the expression for the torque of the separately excited DC machine. In the case of induction machines, the control is usually performed in the reference frame (d-q) attached to the rotor flux space vector. That's why the implementation of vector control requires information on the modulus and the space angle (position) of the rotor flux space vector. The stator currents of the induction machine are separated into flux- and torque-producing components by utilizing transformation to the d-q coordinate system, whose direct axis (d) is aligned with the rotor flux space vector. That means that the q-axis component of the rotor flux space vector is always zero:

$$\Psi_{rq} = 0 \text{ and also } \frac{d}{dt}\Psi_{rq} = 0$$

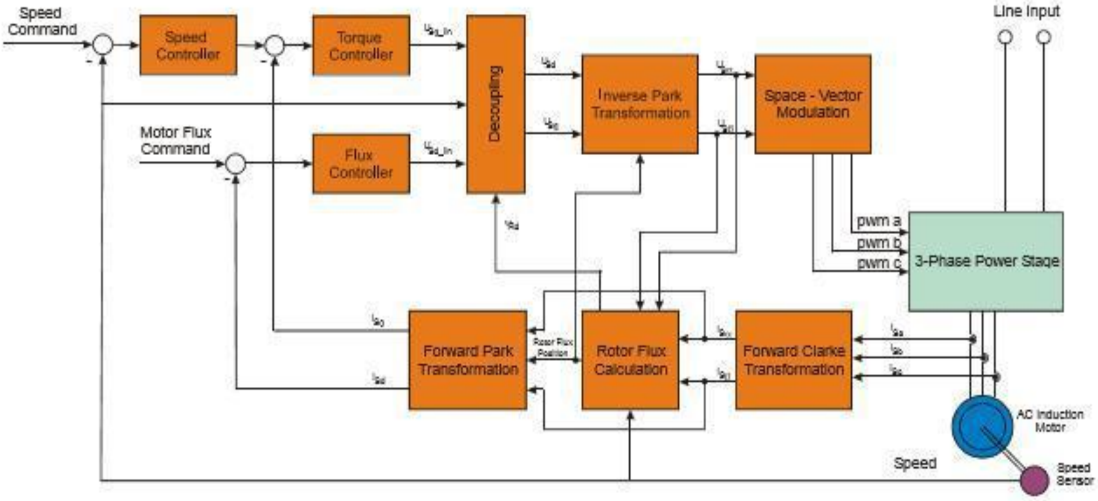
The rotor flux space vector calculation and transformation to the d-q coordinate system require the high computational power of a microcontroller. The digital signal processor is suitable for this task. The following sections describe the space vector transformations and the rotor flux space vector calculation.

Block Diagram of the Vector Control

Shows the basic structure of the vector control of the AC induction motor. To perform vector control, it is necessary to follow these steps:

- Measure the motor quantities (phase voltages and currents)
- Transform them to the 2-phase system (α,β) using a Clarke transformation
- Calculate the rotor flux space vector magnitude and position angle
- Transform stator currents to the d-q coordinate system using a Park transformation

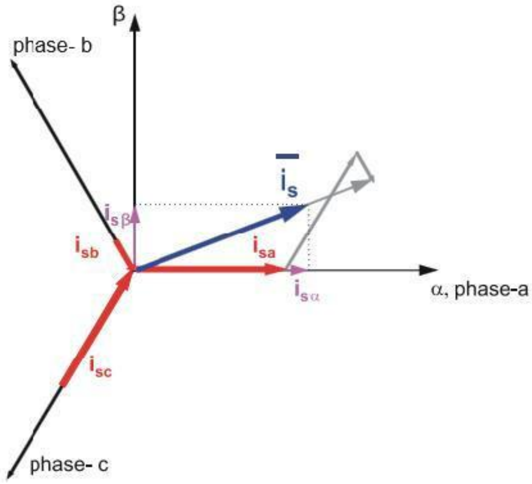
- The stator current torque and flux producing components are separately controlled
- The output stator voltage space vector is calculated using the decoupling block
- The stator voltage space vector is transformed by an inverse Park transformation back from the d-q coordinate system to the 2-phase system fixed with the stator
- Using the space vector modulation, the output 3-phase voltage is generated



Block Diagram of the AC Induction Motor Vector Control

Forward and Inverse Clarke Transformation (a,b,c to α,β and backwards)

The forward Clarke transformation converts a 3-phase system a,b,c to a 2-phase coordinate system α,β. Figure shows graphical construction of the space vector and projection of the space vector to the quadrature-phase components α,β.

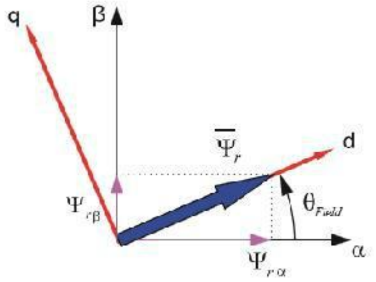


The inverse Clarke transformation goes back from a 2-phase (α,β) to a 3-phase isa, isb, isc system. For constant k=2/3, it is given by the following equations:

$$i_{sa} = i_{s\alpha}$$
$$i_{sb} = -\frac{1}{2} i_{s\alpha} + \frac{\sqrt{3}}{2} i_{s\beta}$$
$$i_{sc} = -\frac{1}{2} i_{s\alpha} - \frac{\sqrt{3}}{2} i_{s\beta}$$

Forward and Inverse Park Transformation (α,β to d-q and backwards)

The components isα and isβ, calculated with a Clarke transformation, are attached to the stator reference frame α, β. In vector control, it is necessary to have all quantities expressed in the same reference frame. The stator reference frame is not suitable for the control process. The space vector $i_{s\beta}$ is rotating at a rate equal to the angular frequency of the phase currents. The components $i_{s\alpha}$ and isβ depend on time and speed. We can transform these components from the stator reference frame to the d-q reference frame rotating at the same speed as the angular frequency of the phase currents. Then the i_{sd} and i_{sq} components do not depend on time and speed. If we consider the d-axis aligned with the rotor flux, the transformation is illustrated in Figure where θ_{field} is the rotor flux position.



Park Transformation

The inverse Park transformation from the d-q to α,β coordinate system is given by the following equations:

$$i_{s\alpha} = i_{sd} \cos\theta_{Field} - i_{sq} \sin\theta_{Field}$$
$$i_{s\beta} = i_{sd} \sin\theta_{Field} + i_{sq} \cos\theta_{Field}$$

Rotor Flux Model

Knowledge of the rotor flux space vector magnitude and position is key information for the AC induction motor vector control. With the rotor magnetic flux space vector, the rotational coordinate system (d-q) can be established. There are several methods for obtaining the rotor magnetic flux space vector. The implemented flux model utilizes monitored rotor speed and stator voltages and currents. It is calculated in the stationary reference frame (α,β) attached to the stator. The error in the calculated value of the rotor flux, influenced by the changes in temperature, is negligible for this rotor flux model.

The rotor flux space vector is obtained by solving the differential equations (EQ 4-2) and (EQ 4-3), which are resolved into the α and β components. The equations are derived from the equations of the AC induction motor model

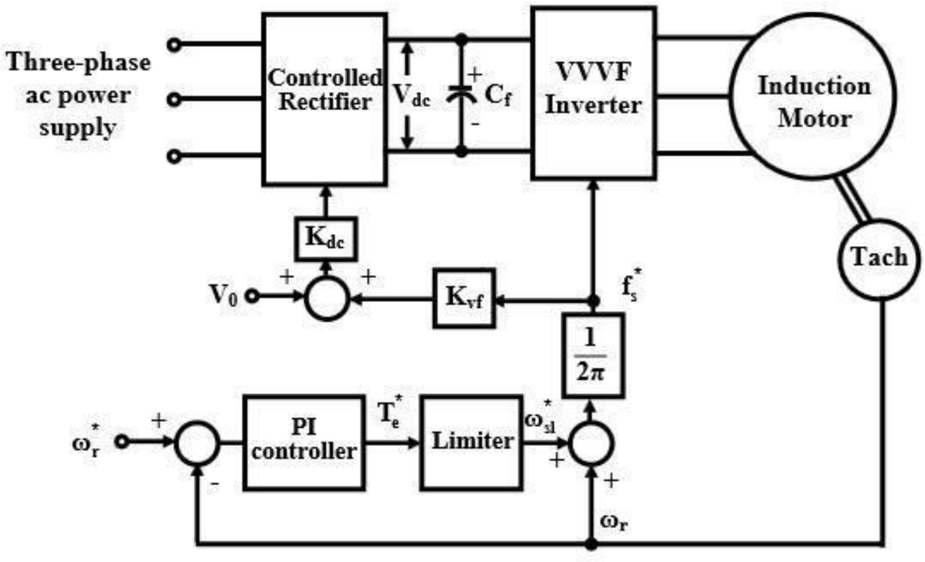
$$[(1-\sigma)T_s+T_r]\frac{d\Psi_{r\alpha}}{dt} = \frac{L_m}{R_s}u_{s\alpha}-\Psi_{r\alpha}-\omega T_r\Psi_{r\beta}-\sigma L_m T_s\frac{di_{s\alpha}}{dt}$$

$$[(1-\sigma)T_s+T_r]\frac{d\Psi_{r\beta}}{dt} = \frac{L_m}{R_s}u_{s\beta}+\omega T_r\Psi_{r\alpha}-\Psi_{r\beta}-\sigma L_m T_s\frac{di_{s\beta}}{dt}$$

where:

L_s	self-inductance of the stator	[H]
L_r	self-inductance of the rotor	[H]
L_m	magnetizing inductance	[H]
R_r	resistance of a rotor phase winding	[Ohm]
R_s	resistance of a stator phase winding	[Ohm]
ω	angular rotor speed	[rad.s^{-1}]
p_p	number of motor pole-pairs	
$T_r = \frac{L_r}{R_r}$	rotor time constant	[s]
$T_s = \frac{L_s}{R_s}$	stator time constant	[s]
$\sigma = 1-\frac{L_m^2}{L_sL_r}$	resultant leakage constant	[-]

4.6 Closed-loop control of induction motor



Closed-loop induction motor drive with constant volts/Hz control strategy

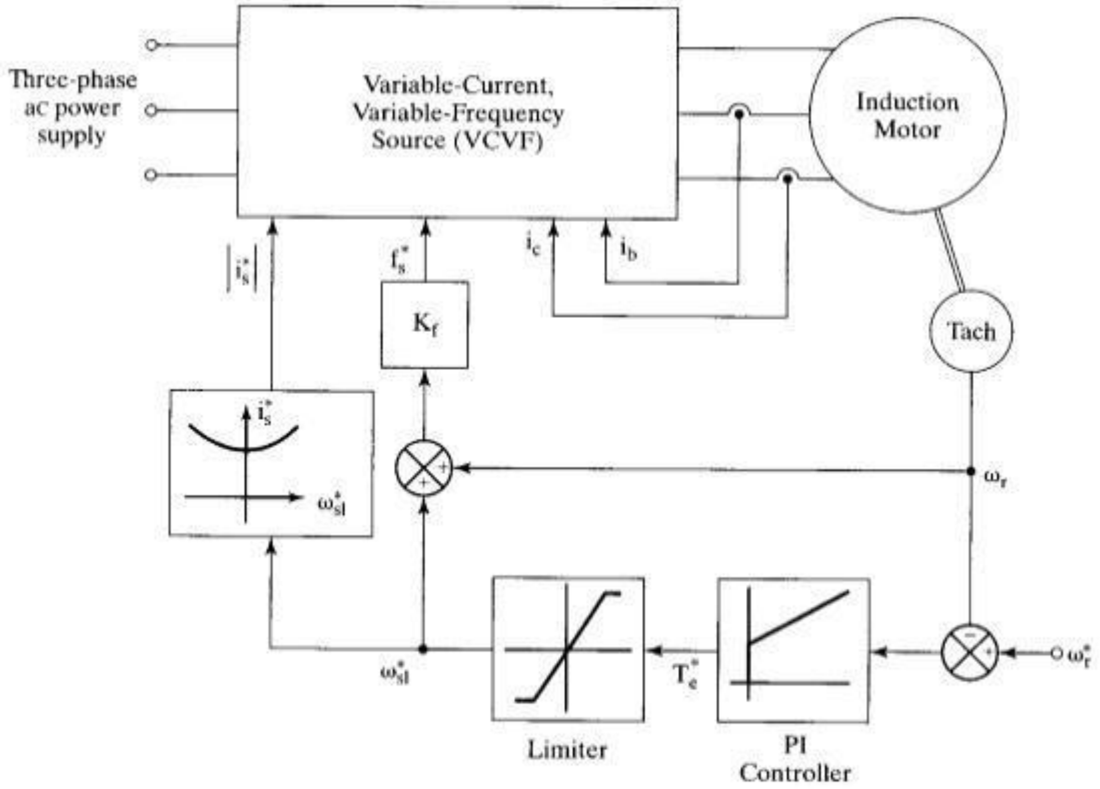
An outer speed PI control loop in the induction motor drive, shown in Figure computes the frequency and voltage set points for the inverter and the converter respectively. The limiter ensures that the slip-speed command is within the maximum allowable slip speed of the induction motor. The slip-speed command is added to electrical rotor speed to obtain the stator frequency command. Thereafter, the stator frequency command is processed in an open-loop drive. K_{dc} is the constant of proportionality between the dc load voltage and the stator frequency.

4.7 Constant air gap flux control:

1. Equivalent separately-excited dc motor in terms of its speed but not in terms of decoupling of flux and torque channel.

2. Constant air gar flux linkages

$$\lambda_m = L_m i_m = E_1/\omega_s$$

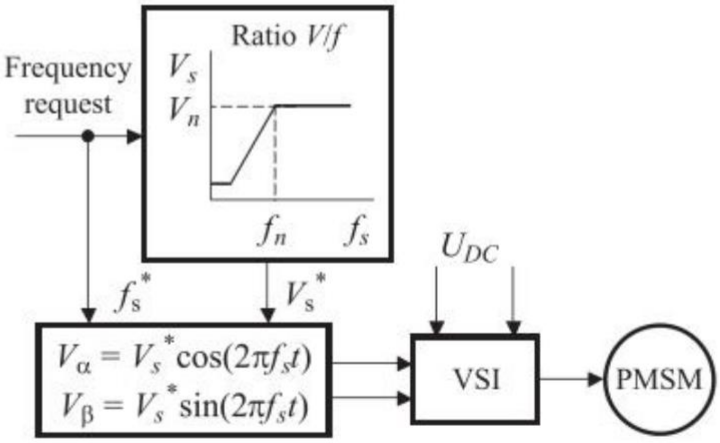


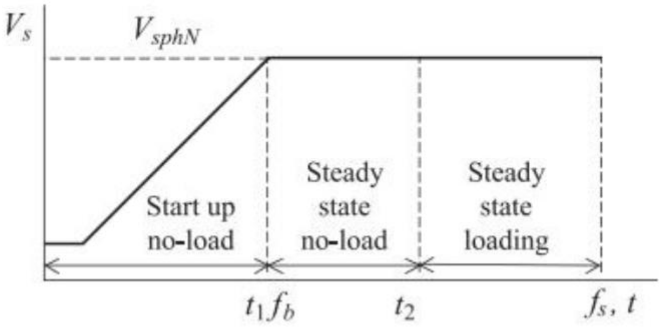
The rotor flux magnitude and position is key information for the AC induction motor control. With the rotor magnetic flux, the rotational coordinate system (d-q) can be established. There are several methods for obtaining the rotor magnetic flux. The implemented flux model utilizes monitored rotor speed and stator voltages and currents. It is calculated in the stationary reference frame (α,β) attached to the stator. The error in the calculated value of the rotor flux, influenced by the changes in temperature, is negligible for this rotor flux model

UNIT V

SYNCHRONOUS MOTOR DRIVES

5.1 V/FOFPERMANENTMAGNETS SYNCHRONOUS MOTORS





Constant volt per hertz control in an open loop is used more often in the squirrel cage IM applications. Using this technique for synchronous motors with permanent magnets offers a big advantage of sensor less control. Information about the angular speed can be estimated indirectly from the frequency of the supply voltage. The angular speed calculated from the supply voltage frequency ac- cording to (1) can be considered as the value of the rotor angular speed if the external load torque is nothing her than the break down torque.

The mechanical synchronous angular speed ωs is proportional to the frequency fs of the supply voltage

$$\omega_s = \frac{2\pi f_s}{p},$$

Where p is the number of pole pairs.

The RMS value of the induced voltage of AC motors is given as

$$E_f = \sqrt{2}\pi f_s N_s k_w \phi \, .$$

By neglecting the stator resistive voltage drop and as sum- in steady state conditions, the stator voltage is identical to the induced one and the expression of magnetic flux can be written as

$$\phi = \frac{V_{sph}}{\sqrt{2}\pi f_s N_s k_w} = c\frac{V_{sph}}{f_s} \, .$$

To maintain the stator flux constant at its nominal value in the base speed range, the voltage-to-frequency ratio is kept constant, hence the name V/f control. If the ratio is different from the nominal one, the motor will become overexcited around excited. The first case happens when the frequency value is lower than the nominal one and the voltage is kept constant or if the voltage is higher than that of the constant ratio V/f. This condition is called over excitation, which means that the magnetizing flux is higher than its nominal value.

An increase of the magnetizing flux leads to arise of the magnetizing current. In this case the hysteresis and eddy current losses are not negligible. The second case represents under excitation. The motor becomes under excited because the voltage is kept constant and the value of stator frequency is higher than the nominal one. Scalar control of the synchronous motor can also be demonstrated via the torque equation of SM, similar to that of an induction motor. The electromagnetic torque of the synchronous motor, when the stator resistance Rs is not negligible, is given

$$T_e = -\frac{m}{\omega_s}\left[\frac{V_{sph}E_f}{Z_d}\sin\left(\vartheta_L - \alpha\right) - \frac{E_f^2 R_s}{Z_d}\right]$$

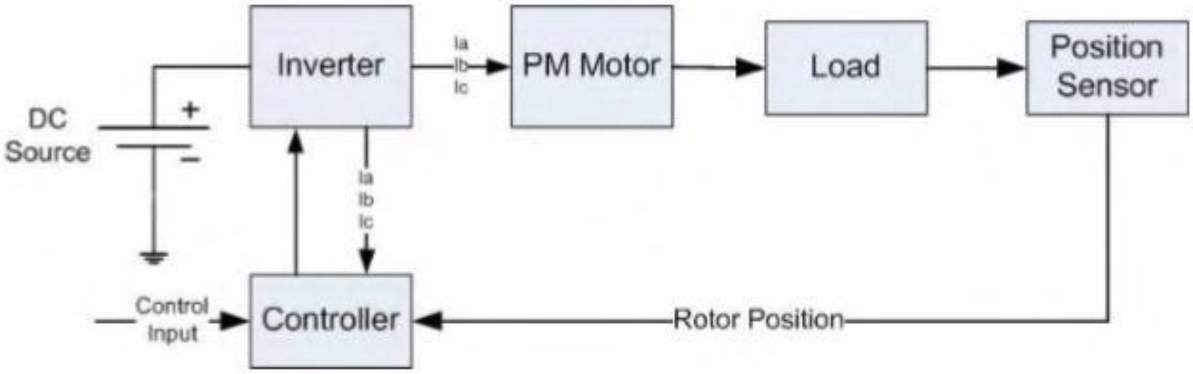
$$T_m = \frac{3p}{2\pi f_s}\frac{V_{sph}E_{PM}}{2\pi f_s L_d} = \frac{3p}{2\pi f_s}\frac{V_{sph}2\pi f_s \Psi_{PM}}{2\pi f_s L_d} \, .$$

The torque will be constant in a wide speed range up to the nominal speed if the ratio of stator voltage and frequency is kept constant

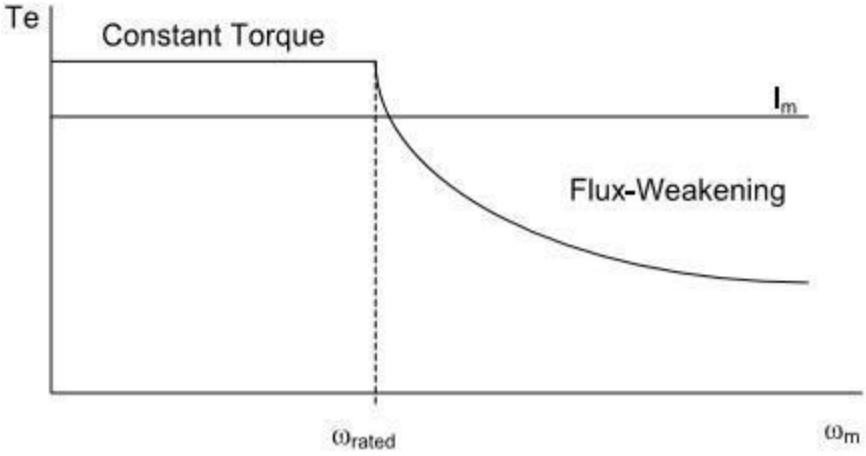
$$\frac{V_{sph}}{f_s} = \text{const.}$$

5.2 Self-Control Synchronous Motor

Control of PM motors is performed using field oriented control for the operation of synchronous motor as a dc motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor as shown in figure.



Field oriented control was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective. In order for the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter. The limit is established by the rated speed of the motor.



Steady State Torque versus Speed

Field Oriented Control of PM Motors:

The PMSM control is equivalent to that of the dc motor by a decoupling control known as field oriented control or vector control. The vector control separates the torque component of current and flux channels in the motor through its stator excitation.

The vector control of the PM synchronous motor is derived from its dynamic model. Considering the currents as inputs, the three currents are:

$$i_a = I_m \sin(\omega_r t + \alpha)$$

$$i_b = I_m \sin(\omega_r t + \alpha - \frac{2\pi}{3})$$

$$i_c = I_m \sin(\omega_r t + \alpha + \frac{2\pi}{3})$$

$$\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} \cos(\omega_r t + \alpha) \\ \cos(\omega_r t + \alpha - \frac{2\pi}{3}) \\ \cos(\omega_r t + \alpha + \frac{2\pi}{3}) \end{pmatrix} (I_m)$$

Where α is the angle between the rotor field and stator current phasor, r ω is the electrical rotor speed

The previous currents obtained are the stator currents that must be transformed to the rotor reference frame with the rotor speed r ω, using Park's transformation. The q and d axis currents are constants in the rotor reference frames since α is a constant for a given load torque. As these constants, they are similar to the armature and field currents in the separately excited dc machine. The q axis current is distinctly equivalent to the armature current of the dc machine; the d axis current is field current, but not in its entirety. It is only a partial field current; the other part is contributed by the equivalent current source representing the permanent magnet field. For this reason the q axis current is called the torque producing component of the stator current and the d axis current is called the flux producing component of the stator current.

Substituting equation above and obtain i_d and i_q in terms of I_m as follows

$$\begin{pmatrix} i_q \\ i_d \end{pmatrix} = I_m \begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix}$$

Using equations the electromagnetic torque equation is obtained as given below.

$$T_e = \frac{3}{2} \cdot \frac{P}{2} \left[\frac{1}{2}(L_d - L_q) I_m^2 \sin 2\alpha + \lambda_f I_m \sin\alpha \right]$$

Constant Torque Operation:

Constant torque control strategy is derived from field oriented control, where the maximum possible torque is desired at all times like the dc motor. This is performed by making the torque producing current i_q equal to the supply current I_m. That results in selecting the α angle to be 90 º degrees according to equation. By making the id current equal to zero the torque equation can be rewritten as:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f \cdot i_q$$

Assuming that:

$$k_t = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f$$

The torque is give by

$$T_e = k_t \cdot i_q$$

Flux-weakening:

Flux weakening is the process of reducing the flux in the d axis direction of the motor which results in an increased speed range.

The motor drive is operated with rated flux linkages up to a speed where the ratio between the induced emf and stator frequency (V/f) is maintained constant. After the base frequency, the V/f ratio is reduced due to the limit of the inverter dc voltage source which is fixed. The weakening of the field flux is required for operation above the base frequency.

This reduces the V/f ratio. This operation results in a reduction of the torque proportional to a change in the frequency and the motor operates in the constant power region.

The rotor flux of PMSM is generated by permanent magnet which cannot be directly reduced as induction motor. The principle of flux-weakening control of PMSM is to increase negative direct axis current and use armature reaction to reduce air gap flux, which equivalently reduces flux and achieves the purpose of flux-weakening control.

This method changes torque by altering the angle between the stator MMF and the rotor d axis. In the flux weakening region where $\omega_r > \omega_{rated}$ angle α is controlled by proper control of i_d and i_q for the same value of stator current. Since i_q is reduced the output torque is also reduced. The angle α can be obtained as:

$$\alpha = Tan^{-1}\left(\frac{i_q}{i_d}\right)$$

The current I_m is related to i_d and i_q by:

$$I_m = \sqrt{i_d^2 + i_q^2}$$

Flux-weakening control realization

The realization process of equivalent flux-weakening control is as follows,

1) Measuring rotor position and speed ωr from a sensor which is set in motor rotation axis.

2) The motor at the flux weakening region with a speed loop, Te* is obtained from the PI controller.

3) Calculate Iq*

$$i_q = \frac{T_e^*}{\left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_f})$$

4) Calculate Id* using equation:

$$i_d^* = \frac{\lambda_d - \lambda_f}{L_d}$$

5) Calculate α using equation

$$\alpha = Tan^{-1}\left(\frac{i_q}{i_d}\right)$$

6) Then the current controller makes uses of the reference signals to control the inverter for the desired output currents.

7) The load torque is adjust to the maximum available torque for the reference speed

$$T_L = T_{e(rated)} \frac{\omega_{rated}}{\omega_r}$$

5.3 Power Factor Correction Of Permanent Magnet Synchronous Motor Drive With Field Oriented Control Using Space Vector Modulation

Field oriented control demonstrates that, a synchronous motor could be controlled like a separately excited dc motor by the orientation of the stator mmf or current vector in relation to the rotor flux to achieve a desired objective. The aim of the FOC method is to control the magnetic field and torque by controlling the d and q components of the stator currents or relatively fluxe. With the information of the stator currents and the rotor angle a FOC technique can control the motor torque and the flux in a very effective way.

The main advantages of this technique are the fast response and reduced torque ripple. The implementation of this technique will be carried out using two current regulators, one for the direct-axis component and another for the quadrature -axis component, and one speed regulator. There are three PI regulators in the control system. One is for the mechanical system (speed) and two others for the electrical system (d and q currents). At first, the reference speed is compared with the measured speed and the error signal is fed to the speed PI controller.

This regulator compares the actual and reference speed and outputs a torque command. Once is obtained the torque command, it can be turned into the quadrature-axis current reference, $I_{q,ref}$. There is a PI controller to regulate the d component of the stator current. The reference value, $I_{d,ref}$, is zero since there is no flux weakening operation. The d component error of the current is used as an input for the PI regulator. Moreover, there is another PI controller to regulate the q component of the current. The reference value is compared with the measured and then fed to the PI regulator. The performance of the FOC block diagram can be summarized in the following steps

The performance of the FOC block diagram can be summarized in the following steps:

1. The stator currents are measured as well as the rotor angle.
2. The stator currents are converted into a two-axis reference frame with the Clark Transformation.
3. The α,β currents are converted into a rotor reference frame using Park Transformation
4. With the speed regulator, a quadrature-axis current reference is obtained. The d-current controls the air gap flux, the q-current control the torque production.
5. The current error signals are used in controllers to generate reference voltages for the inverter.
6. The voltage references are turned back into abc domain.
7. With these values are computed the PWM signals required for driving the inverter.

SPACE VECTOR MODULATION

The basis of SVPWM is different from that of sine pulse width modulation (SPWM). SPWM aims to achieve symmetrical 3-phase sine voltage waveforms of adjustable voltage and frequency, while SVPWM takes the inverter and motor as a whole, using the eight fundamental voltage vectors to realize variable frequency of voltage and speed adjustment. SVPWM aims to generate a voltage vector that is close to the reference circle through the various switching modes of inverter. Fig is the typical diagram of a three-phase voltage source inverter model. For the on- off state of the three-phase inverter circuit, every phase can be considered as a switch S. Here, $S_A(t)$, $S_B(t)$ and $S_C(t)$ are used as the switching functions for the three phases, respectively.

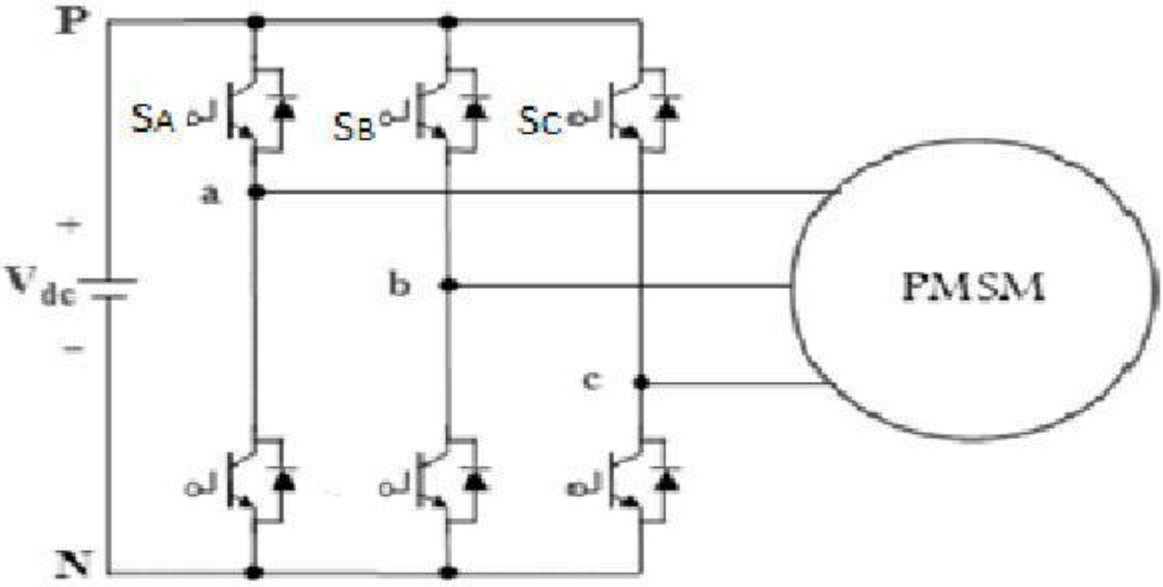
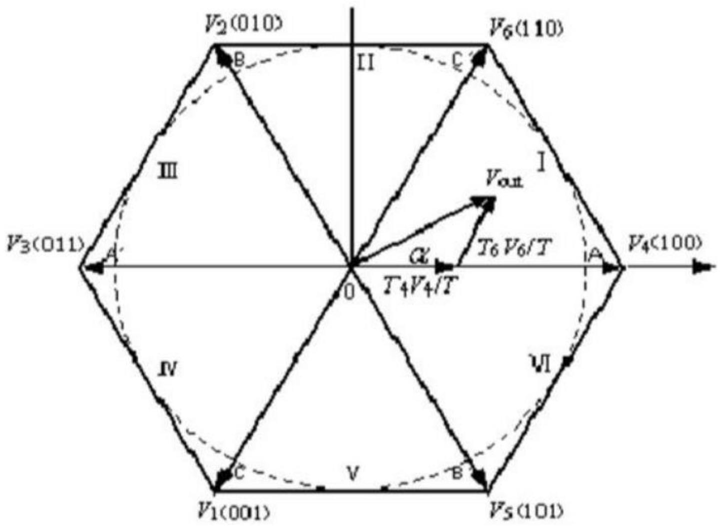


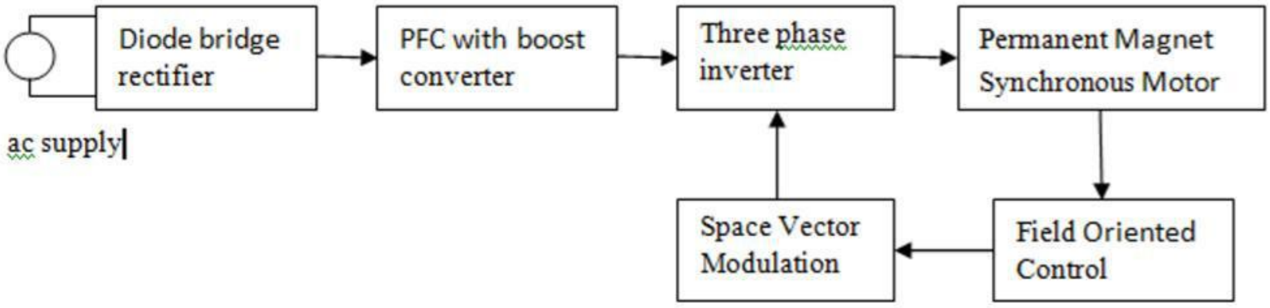
Diagram of a three phase inverter

The space vector of output voltage of inverter can be expressed as

$$V(S_A, S_{B,} S_C) = \frac{2 * V_{dc}(S_A + \alpha S_B + \alpha^2 S_C)}{3}$$



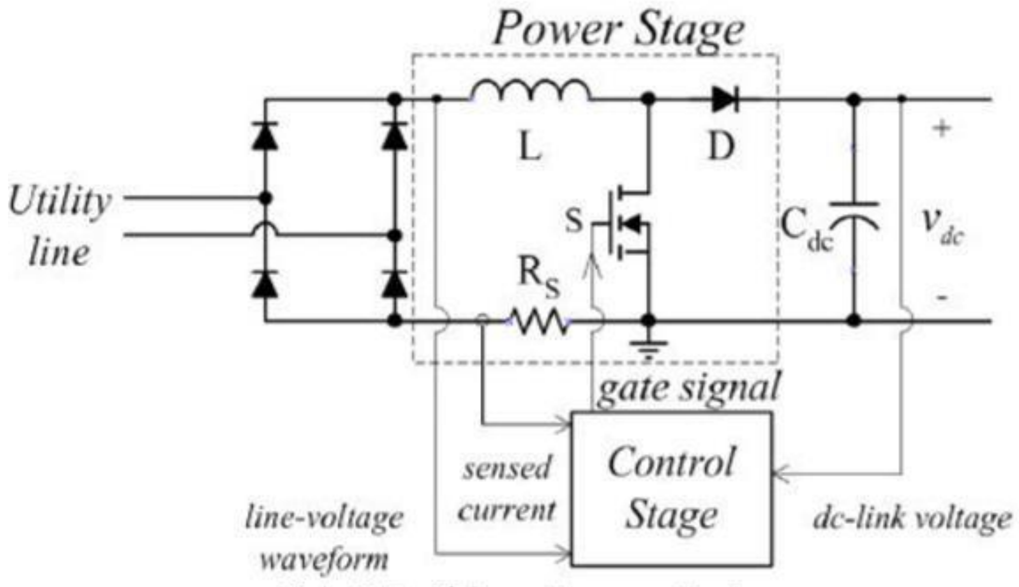
PMSM Drive with Active Power Factor Correction (Apfc):



PMSM drive with PFC

The above figure shows the block diagram of PMSM drive with Active power Factor Correction. The APFC consists of an energy stored element, switching device and control module. It is commonly installed between the power rectifier and the dc link bus. The main purpose of APFC is to make the input of the power supply look like a pure resistor. In other words, it is to make the input current waveform in phase with the input voltage waveform so that there is no phase displacement between them. The operation of APFC is basically based on a controller that can output the signal to a switching device to control the energy being stored or released in the reactive elements. In such a way, the input current waveform can be adjusted. The magnitude and phase of the input current waveforms by proper control can follow that of the input voltage waveform. Consequently, the power factor improvement can be achieved and further, the voltage stability can be obtained as well. The dc link voltage for the inverter is obtained from PFC block. The stator currents and rotor position of PMSM are given to the FOC, which controls the flux and torque components.

The current error signals are used in controllers to generate reference voltages V_{α} and V_{β}, which are the inputs of SVM. Space Vector modulation gives signals required for driving the inverter. By using inverter three phase supply is given to the PMSM



PFC with Boost Converter Circuit

The above Figure shows the circuit of power factor correction circuit with boost converter. An uncontrolled diode rectifier with a boost converter is used to convert the single phase AC voltage into a constant DC link voltage, which is fed to the three phase inverter supplying a PMSM.

The boost converter is the widely used topology for achieving power factor correction. This converter draws nearly unity power factor current from the AC mains and eliminates a harmonic current which regulates the DC link voltage even under fluctuating voltage conditions of AC mains.

This circuit uses a diode bridge rectifier, an inductor which is connected in series with the supply, a switch MOSFET and an output capacitor. The bulk energy storage capacitor sits on the output side of the converter rather than just after the diode rectifier bridge. The average inductor current which charges the bulk capacitor is proportional to the utility line voltage.

For proper operation, the output voltage must be higher than the peak line voltage and current drawn from the line must be proportional to the line voltage. In circuit operation, it is assumed that the inductance of boost inductor is large so that it can be represented by constant current source and that the output ripple voltage is negligible so that the voltage across the output filter capacitor can be represented by constant voltage source.

5.4 DESIGN EQUATIONS OF BOOST POWER FACTOR CORRECTION CIRCUIT

The AC input voltage given to the power factor correction circuit is 100V and input frequency is 50Hz. The selection of boost converter components is based on the following equations Maximum input power, Maximum input power,

$$P_{in(\max)} = \frac{P_{o(\max)}}{\eta_{\min}}$$

Maximum rms input current,

$$I_{in(rms)\max} = \frac{P_{in(\max)}}{V_{in(rms)\max}}$$

Maximum peak input current,

$$I_{in(pk)\max} = I_{in(rms)\max}$$

Average input current,

$$I_{in(avg)\max} = \frac{2 * I_{in(pk)\max}}{\prod}$$

Boost capacitor,

$$C_{in} = K_{\Delta} I_{L} \frac{I_{in(rms)\max}}{2 * \prod * f_{sw} * r * V_{in(rms)\max}}$$

Switching frequency, fsw= 100KHz

Minimum input peak voltage,

$$V_{in(pk)\min} = \sqrt{2} V_{in(pk)\min}$$

Peak boost transistor duty cycle

$$D_{pk} = 1 - \frac{V_{in(pk)}}{V_{o}}$$

Inductor ripple current

$$\Delta I_{L} = 0.2 * I_{in(pk)\max}$$

ΔI_L is based on the assumption of 20% ripple current

Peak inductor current,

$$I_{L(pk)\max} = I_{in(pk)\max} + \frac{\Delta I_{L}}{2}$$

Inductance,

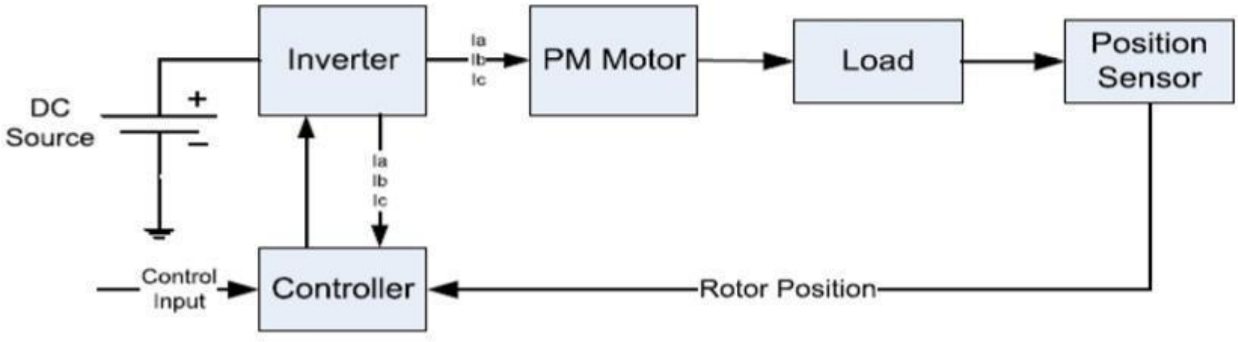
$$L = \frac{V_{in(pk)\min} * D_{pk}}{f_{sw} * \Delta I_{L}}$$

Output Capacitor

$$C_{out} = \frac{I_{out(\max)}}{f_{sw} * \Delta V}$$

5.5 Permanent Magnet Synchronous Motor Black Diagram Of Closed Loop Control

The basic block-diagram of PMSM drive system shown in figure in this figure basic four part divided in this circuit. All part discuss in briefly in this below section. The below figure shown it is one type of closed-loop block diagram.

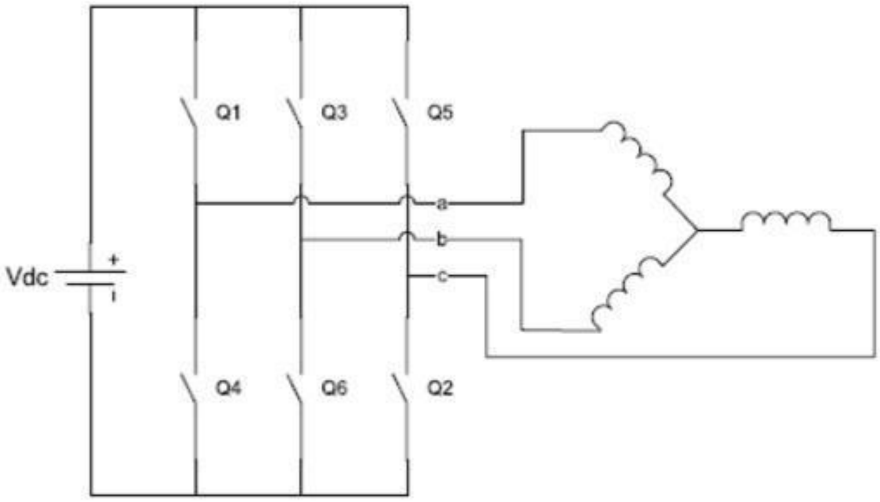


There are four basic component

1. Voltage Source Inverter
2. Pm Synchronous Motor
3. Current Controller
4. Position Sensor

Voltage Source Inverter

Voltage Source Inverters are devices that convert a DC voltage to AC voltage of variable frequency and magnitude. They are very commonly used in adjustable speed drives and are characterized by a well-defined switched voltage wave form in the terminals. The ac voltage frequency can be variable or constant depends on the application. Three phase inverters consist of six power switches connected as shown in figure to dc voltage source. An inverter switches must be carefully selected based on the requirements of operation, ratings and the application.



Voltage Source Inverter

PM Synchronous Motor

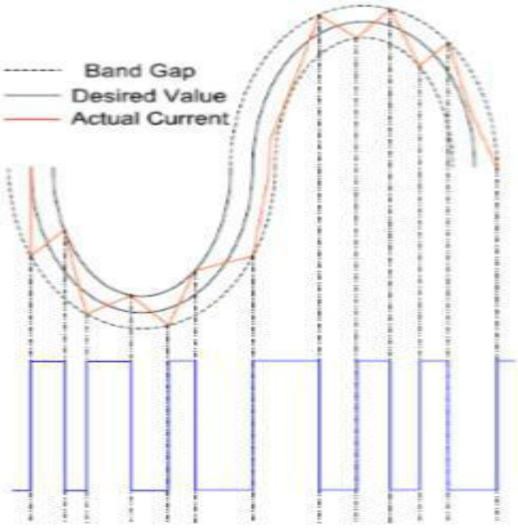
A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. The properties of the permanent magnet material will affect directly the performance of the motor and proper knowledge is required for the selection of the materials and for understanding PM motors. Permanent magnet (PM) synchronous motors are widely used in low and mid power applications such as computer peripheral equipment’s, robotics, adjustable speed drives and electric vehicles.

HYSTERESIS Current Controller

Current regulators for AC drives are complex because an AC current regulator must control both the amplitude and phase of the stator current. The AC drive current regulator forms the inner loop of the overall motion controller. As such, it must have the widest bandwidth in the system and must, by necessity, have zero or nearly zero steady-state error both current source inverters (CSI) and voltage source inverters (VSI) can be operated in controlled current modes. The current source inverter is a "natural" current supply and can readily be adapted to controlled current operation.

The voltage source inverter requires more complexity in the current regulator but offers much higher bandwidth and elimination of current harmonics as compared to the CSI and is almost exclusively used for motion control applications. Hysteresis current controller can also be implemented to control the inverter currents. The controller will generate the reference currents with the inverter within a range which is fixed by the width of the band gap. In this controller the desired current of a given phase is summed with the negative of the measured current. The error is fed to a comparator having a hysteresis band.

When the error crosses the lower limit of the hysteresis band, the upper switch of the inverter leg is turned on but when the current attempts to become less than the upper reference band, the bottom switch is turned on. The hysteresis band with the actual current and the resulting gate signals. This controller does not have a specific switching frequency and changes continuously but it is related with the band width shown in figure.



Hysteresis Current Controller

Position Sensor

Operation of permanent magnet synchronous motors requires position sensors in the rotor shaft when operated without damper winding. The need of knowing the rotor position requires the development of devices for position measurement. There are four main devices for the measurement of position, the potentiometer, linear variable differential transformer, optical encoder and resolvers. The ones most commonly used for motors are encoders and revolvers. Depending on the application and performance desired by the motor a position sensor with the required accuracy can be selected.

5.6 VECTOR CONTROL TECHNIQUE

The PMSM control is equivalent to that of the dc motor by a decoupling control known as field oriented control or vector control. The vector control separates the torque component of current and flux channels in the motor through its stator excitation. The vector control strategy is somewhat similar to that of the induction motor vector control, except for the following:

1. The slip frequency is zero because the machine always runs at synchronous speed.

2. The magnetizing current I_{ds} =0 because the rotor flux is supplied by the PM.

3. The unit vector generated from an absolute position sensor because, the unlike slipping poles of an induction motor, the poles are fixed on the rotor.

Two Marks Question Bank

UNIT – I

1. What is meant by electrical drives?

Systems employed for motion control are called drives and they employ any of the prime movers such as diesel or petrol engines, gas or steam turbines, hydraulic motors and electric motors for supplying mathematical energy for motion control. Drives employing electric motion are called electric drives.

2. What are the requirements of an electric drive? Stable operation should be assured.

The drive should have good transient response

3. Specify the functions of power modulator.

a. Modulates flow of power form the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load.

b. During transient operations, such as starting, braking and speed reversal, it restricts source and motor currents within permissible values; excessive current drawn from source may overload it or may cause a voltage dip.

4. Mention the different types of drives.

1) Group drive 2) Individual drive

3) Multimotor drive

5. List the different types of electrical drives.

1) dc drives 2) ac drives

6. What are the advantages of electric drives?

They have flexible control characteristics. the steady state and dynamic characteristics of electrical drives can be shaped to satisfy load requirements.

1) Drives can be provided with automatic fault detection systems, programmable logic controllers and computers can be employed to automatically ctrl the drive operations in a desired sequence.
2) They are available in which range of torque, speed and power.
3) It can operate in all the four quadrants of speed-torque plane. Electric braking gives smooth deceleration and increases life of the equipment compared to other forms of braking.
4) Control gear required for speed control, starting and braking is usually simple and easy to operate.

7. What are the functions performed by electric drives?

Various functions performed by electric drives include the following.

a. Driving fans, ventilators, compressors and pumps etc.

b. Lifting goods by hoists and cranes

c. Imparting motion to conveyors in factories, mines and warehouses and

d. Running excavators and escalators, electric locomotives, trains, cars, trolley buses, lifts and drums winders etc.

8. What are the disadvantages of electric drives? The disadvantages of electric drives are

a. Electric drives system is tied only up to the electrified area.

b. The condition arising under the short circuits, leakage from conductors and breakdown of overhead conductor may lead to fatal accidents.
c. Failure in supply for a few minutes may paralyses the whole system.

9. What are the advantages of group drive over individual drive?

The advantages of group drive over individual drive are

a. Initial cost: Initial cost of group drive is less as compared to that of the individual drive.
b. Sequence of operation: Group drive system is useful because all the operations are stopped simultaneously.
c. Space requirement: Less space is required in group drive as compared to individual drive.
d. Low maintenance cost: It requires little maintenance as compared to individual drive.

10. What the group drive is not used extensively.

Although the initial cost of group drive is less but yet this system is not used extensively because of following disadvantages.

a. Power factor: Group drive has low power factor
b. Efficiency: Group drive system when used and if all the machines are not working together the main motor shall work at very much reduced load.
c. Reliability: In group drive if the main motor fails whole industry will come to stand still.
d. Flexibility: Such arrangement is not possible in group drive i.e., this arrangement is not suitable for the place where flexibility is the prime factor.
e. Speed: Group drive does not provide constant speed.
f. Types of machines: Group drive is not suitable fro driving heavy machines such as cranes, lifts and hoists etc.

11. Write short notes on individual electric drives.

In individual drive, each individual machine is driven by a separate motor. This motor also imparts motion to various other parts of the machine. Examples of such machines are single spindle drilling machines (Universal motor is used) and lathes. In a lathe, the motor rotates the spindle, moves the feed and also with the help of gears, transmits motion to lubricating and cooling pumps. A three phase squirrel cage induction motor is used as the drive. In many such applications the electric motor forms an integral part of the machine.

12. Mention the different factors for the selection of electric drives?

1) Steady state operation requirements.
2) Transient operation requirements.
3) Requirements related to the source.
4) Capital and running cost, maintenance needs life.
5) Space and weight restriction.
6) Environment and location.
7) Reliability.

13. Mention the parts of electrical drives.

1) Electrical motors and load.
2) Power modulator
3) Sources

4) Control unit
5) Sensing unit

14. Mention the applications of electrical drives

- Paper mills
- Electric traction Cement mills
- Steel mills

15. Mention the types of enclosures

Screen projected type
Drip proof type
Totally enclosed type

16. Mention the different types of classes of duty

Continuous duty, Discontinuous duty, Short time duty, intermittent duty.

17. What is meant by regenerative braking?

Regenerative braking occurs when the motor speed exceeds the synchronous speed. In this case the IM runs as the induction m\c is converting the mechanical power into electrical power which is delivered back to the electrical system. This method of braking is known as regenerative braking.

18. What is meant by dynamic braking?

Dynamic braking of electric motors occurs when the energy stored in the rotating mass is dissipated in an electrical resistance. This requires a motor to operate as a gen. to convert the stored energy into electrical.

19. What is meant by plugging?

It is one method of braking of IM. When phase sequence of supply of the motor running at the speed is reversed by interchanging connections of any two phases of stator with respect to supply terminals, operation shifts from motoring to plugging region.

20. What is critical speed?

It is the speed that separates continuous conduction from discontinuous conduction mode.

21. Which braking is suitable for reversing the motor?

Plugging is suitable for reversing the motor.

22. Define equivalent current method

The motor selected should have a current rating more than or equal to the current. It is also necessary to check the overload of the motor. This method of determining the power rating of the motor is known as equivalent current method.

23. Define cooling time constant

It is defined as the ratio between C and A. Cooling time constant is denoted as Tau.

Tau = C/A

Where C=amount of heat required to raise the temp of the motor body by 1 degree Celsius
A=amount of heat dissipated by the motor per unit time per degree Celsius.

24. What are the methods of operation of electric drives? Steady state

Acceleration including starting
Deceleration including starting

25. Define four quadrant operations.

The motor operates in two mode: motoring and braking. In motoring, it converts electrical energy into mechanical energy which supports its motion. In braking, it works as a generator, converting mathematical energy into electrical energy and thus opposes the motion. Motor can provide motoring and braking operations for both forward and reverse directions.

26. What is meant by mechanical characteristics?

The curve is drawn between speed and torque. This characteristic is called mechanical characteristics.

27. Mention the types of braking

Regenerative braking Dynamic braking
Plugging

28. What are the advantage and disadvantages of D.C. drives? The advantages of D.C. drives are,

a. Adjustable speed
b. Good speed regulation
c. Frequent starting, braking and reversing.

The disadvantage of D.C. drives is the presence of a mechanical commutator which limits the maximum power rating and the speed.

29. Give some applications of D.C. drives.

The applications of D.C. drives are,

a. Rolling mills b. Paper mills e. Machine tools f. Traction c. Mine winders d. Hoists g. Printing presses h. Excavators
i. Textile mils j. Cranes

30. Why the variable speed applications are dominated by D.C. drives?

The variable speed applications are dominated by D.C. drives because of lower cost, reliability and simple control.

UNIT – II

TWO MARKS

1. What is the use of flywheel? Where it is used?

It is used for load equalization. It is mounted on the motor shaft in compound motor.

2. What are the advantages of series motor?

The advantages of series motors are,

a. High starting torque
b. Heavy torque overloads.

3. Define and mention different types of braking in a dc motor?

In breaking the motor works as a generator developing a negative torque which opposes the motion. Types are regenerative braking, dynamic or rheostat braking and plugging or reverse voltage braking.

4. How the D.C. motor is affected at the time of starting?

A D.C. motor is started with full supply voltage across its terminals, a very high current will flow, which may damage the motor due to heavy sparking at commuter and heating of the winding. Therefore, it is necessary top limit the current to a safe value during starting.

5. List the drawbacks of armature resistance control?

In armature resistance control speed is varied by wasting power in external resistors that are connected in series with the armature. since it is an inefficient method of speed control it was used in intermittent load applications where the duration of low speed operations forms only a small proportion of total running time.

6. **What is static Ward-Leonard drive?**

   Controlled rectifiers are used to get variable d.c. voltage from an a.c. source of fixed voltage controlled rectifier fed dc drives are also known as static Ward-Leonard drive.

7. **What is aline commutated inverter?**

   Full converter with firing angle delay greater than 90 deg. is called line commutated inverter. such an operation is used in regenerative braking mode of a dc motor in which case a back emf is greater than applied voltage.

8. **Mention the methods of armature voltage controlled dc motor? When the supplied voltage is ac,**

   Ward-Leonard schemes
   Transformer with taps and un controlled rectifier bridge
   Static Ward-Leonard scheme or controlled rectifiers
   when the supply is dc:
   Chopper control

9. **How is the stator winding changed during constant torque and constant horsepower operations?**

   For constant torque operation, the change of stator winding is made form series - star to parallel - star, while for constant horsepower operation the change is made from series-delta to parallel-star. Regenerative braking takes place during changeover from higher to lower speeds.

10. **Define positive and negative motor torque.**

    Positive motor torque is defined as the torque which produces acceleration or the positive rate of change of speed in forward direction. Positive load torque is negative if it produces deceleration.

11. **Write the expression for average o/p voltage of full converter fed dc drives?**

    Vm=(2Vm/pi)cospi.........continuous conduction
    Vm=[Vm(cos alpha-cos beta)+(pi+alpha+beta)]/pi] discontinuous conduction

12. **What are the disadvantages of conventional Ward-Leonard schemes?** Higher initial cost due to use of two additional m\cs. Heavy weight and size.
    Needs more floor space and proper foundation. Required frequent maintenance

13. **Mention the drawbacks of rectifier fed dc drives?**

    Distortion of supply. Low power factor.
    Ripple in motor current

14. **What are the advantages in operating choppers at high frequency?**

    The operation at a high frequency improves motor performance by reducing current ripple and eliminating discontinuous conduction.

15. **Why self commutated devices are preferred over thyristors for chopper circuits?**

    Self commutated devices such as power MOSFETs power transistors, IGBTs, GTOs and IGCTs are preferred over thyristors for building choppers because they can be commutated by a low power control signal and don't need commutation circuit.

16. State the advantages of dc chopper drives?

DC chopper device has the advantages of high efficiency, flexibility in control, light weight, small size, quick response and regeneration down to very low speed.

17. What are the advantages of closed loop c of dc drives?

Closed loop control system has the adv. of improved accuracy, fast dynamic response and reduced effects of disturbance and system non-linearities.

18. What are the types of control strategies in dc chopper?

- Time ratio control.
- Current limit control.

19. What are the adv. of using PI controller in closed loop ctrl. of dc drive? Stabilize the drive

- Adjust the damping ratio at the desired value
- Makes the steady state speed error close to zero by integral action and filters out noise again due to the integral action.

20. What are the different methods of braking applied to the induction motor?

Regenerative braking Plugging, Dynamic braking.

21. What are the different methods of speed control of IM?

Stator voltage control, Supply frequency control, Rotor resistance control, Slip power recovery control.

22. What is meant by stator voltage control.?

The speed of the IM can be changed by changing the stator voltage. Because the torque is proportional to the square of the voltage.

23. Mention the application of stator voltage control.

This method is suitable for applications where torque demand reduced with speed, which points towards its suitability for fan and pump drives.

24. Mention the applications of ac drives.

AC drives are used in a no. of applications such as fans, blowers, mill run-out tables, cranes, conveyors, traction etc.

25. What are the three regions in the speed-torque characteristics in the IM? Motoring region ($0<=s<=1$)
Generating region($s<0$)
Plugging region ($1<=s<=2$) where s is the slip.

26. What are the advantages of stator voltage control method?

- The control circuitry is simple
- Compact size
- Quick response time
- There is considerable savings in energy and thus it is economical method as compared to other methods of speed ctrl.

27. What is meant by soft start?

The ac voltage controllers show a stepless control of supply voltage from zero to rated voltage they are used for soft start for motors.

28. List the adv of squirrel cage IM?

- Cheaper
- light in weight
- Rugged in construction
- More efficient
- Require less maintenance
- It can be operated in dirty and explosive environment

29. Define slip

The difference between the synchronous speed (Ns)and actual speed(N)of the rotor is known as slip speed. the % of slip is gn by,
%slip s=[(Ns-N)/Ns]x 100

30. Define base speed.

The synchronous speed corresponding to the rated freq is called the base speed.

UNIT – III

TWO MARKS

1. What is meant by frequency control of IM?

The speed of IM can be controlled by changing the supply freq because the speed is directly proportional to supply frequency. This method of speed ctrl is called freq control.

2. What is meant by V/F control l?

When the freq is reduced the i/p voltage must be reduced proportionally so as to maintain constant flux otherwise the core will get saturated resulting in excessive iron loss and magnetizing current. This type of IM behavior is similar to the working of dc series motor.

3. What are the advantages of V/F control?

- Smooth speed ctrl
- Small i/p current and improved power factor at low freq. start
- Higher starting torque for low case resistance

3. What is meant by stator current control?

The 3 phase IM speed can be controlled by stator current control. The stator current can be varied by using current source inverter.

5. What are the 3 modes of region in the adjustable-freq IM drives characteristics?

- Constant torque region
- Constant power region
- High speed series motoring region

6. What are the two modes of operation in the motor?

The two modes of operation in the motor are, motoring and braking. In motoring, it converts electrical energy to mechanical energy, which supports its motion. In braking, it works as a generator converting mechanical energy to electrical energy and thus opposes the motion.

7. How will you select the motor rating for a specific application?

When operating for a specific application motor rating should be carefully chosen that the insulation temperature never exceed the prescribed limit. Otherwise either it will lead to its immediate thermal breakdown causing short circuit and damage to winding, or it will lead to deterioration of its quality resulting into thermal breakdown in near future.

8. What is braking? Mention its types.

The motor works as a generator developing a negative torque which opposes the motion is called barking.

It is of three types. They are,

a. Regenerative braking.
b. Dynamic or rheostat braking.
c. Plugging or reverse voltage braking.

9. What are the three types of speed control?

The three types of speed control as,

a. Armature voltage control
b. Field flux control
c. Armature resistance control.

10. What are the advantages of armature voltage control?

The advantages of armature voltage control are,

a. High efficiency
b. Good transient response
c. Good speed regulation.

11. What are the methods involved in armature voltage control? When the supply in A.C.

a. Ward-Leonard schemes
b. Transformer with taps and an uncontrolled rectifier bridge.
c. Static ward Leonard scheme or controlled rectifiers when the supply in D.C.
d. Chopper control.

12. Give some drawbacks and uses of Ward-Leonard drive.

a. High initial cost
b. Low efficiency

The Ward-Leonard drive is used in rolling mills, mine winders, paper mills, elevators, machine tools etc.

13. Give some advantages of Ward-Leonard drive.

The advantages of Ward-Leonard drive are,

a. Inherent regenerative barking capability
b. Power factor improvement.

14. What is the use of controlled rectifiers?

Controlled rectifiers are used to get variable D.C. Voltage form an A.C. Source of fixed voltage.

15. What is known as half-controlled rectifier and fully controlled rectifier?

The rectifiers provide control of D.C. voltage in either direction and therefore, allow motor control in quadrants I and IV. They are known as fully-controlled rectifiers.

The rectifiers allow D.C. Voltage control only in one direction and motor control in quadrant I only. They are known as half-controlled rectifiers.

16. What is called continuous and discontinuous conduction?

A D.C. motor is fed from a phase controlled converter the current in the armature may flow in discrete pulses in called continuous conduction.

A D.C. motor is fed from a phase controlled converter the current in the armature may flow continuously with an average value superimposed on by a ripple is called discontinuous conduction.

17. What are the three intervals present in discontinuous conduction mode of single phase half and fully controlled rectifier?

The three intervals present in half controlled rectifier
are, a. Duty interval
b. Free, wheeling interval
c. Zero current intervals.

The two intervals present in fully controlled rectifier
are a. Duty interval
b. Zero current intervals.

18. What is called inversion?

Rectifier takes power from D.C. terminals and transfers it to A.C. mains is called inversion.

19. What are the limitations of series motor? Why series motor is not used in traction applications now a days?

1. The field of series cannot be easily controlled. If field control is not employed, the series motor must be designed with its base speed equal to the highest desired speed of the drive.
2. Further, there are a number of problems with regenerative braking of a series motor. Because of the limitations of series motors, separately excited motors are now preferred even for traction applications.

20. What are the advantages of induction motors over D.C. motors?

The main drawback of D.C. motors is the presence of commutate and brushes, which require frequent maintenance and make them unsuitable for explosive and dirty environments. On the other hand, induction motors, particularly squirrel-cage are rugged, cheaper, lighter, smaller, more efficient, require lower maintenance and can operate in dirty and explosive environments.

21. Give the applications of induction motors drives.

Although variable speed induction motor drives are generally expensive than D.C. drives, they are used in a number of applications such as fans, blowers, mill run-out tables, cranes, conveyors, traction etc., because of the advantages of induction motors. Other applications involved are underground and underwater installations, and explosive and dirty environments.

22. How is the speed controlled in induction motor?

The induction motor speed can be controlled by supplying the stator a variable voltage, variable frequency supply using static frequency converters. Speed control is also possible by feeding the slip power to the supply system using converters in the rotor circuit, basically one distinguishes two different methods of speed control.

a. Speed control by varying the slip frequency when the stator is fed from a constant voltage, constant frequency mains.

b. Speed control of the motor using a variable frequency variable voltage motor operating a constant rotor frequency.

23. How is the speed control by variation of slip frequency obtained?

Speed control by variation of slip frequency is obtained by the following ways.

a. Stator voltage control using a three-phase voltage controller.
b. Rotor resistance control using a chopper controlled resistance in the rotor circuit.
c. Using a converter cascade in the rotor circuit to recover slip energy.
d. Using a cyclconverter in the rotor circuit.

24. Mention the effects of variable voltage supply in a cage induction motor.

When a cage induction motor is fed from a variable voltage for speed control the following observations may be made.

a.The torque curve beyond the maximum torque point has a negative shape. A stable operating point in this region is not possible for constant torque load.

b.The voltage controlled must be capable of withstanding high starting currents. The range of speed control is rather limited.
c.The motor power factor is poor.

25. Classify the type of loads driven by the motor.

The type of load driven by the motor influences the current drawn and losses of the motor as the slip various. The normally occurring loads are

a. Constant torque loads.
b. Torque varying proportional to speed.
c. Torque varying preoperational to the square of the speed.

26. What are the disadvantages of constant torque loads?

The constant torque loads are not favored due to increase in the losses linearly with slip and becoming maximum at s= 1.0. This is obvious form the variation of flux as the voltage is varied for speed control. To maintain constant torque the motor draws heavy current resulting in poor torque/ampere, poor efficiency ad poor power factor at low speeds.

27. In which cases, torque versus speed method is suitable.

Torque versus speed method is suitable only for the following cases.

a. For short time operations where the duration of speed controls ids defined.
b. For speed control of blowers or pumps having parabolic or cubic variations of torque with speed. This is not suitable for constant torque loads due to increases and heating.

28. How is the speed of a squirrel cage induction motor controlled?

The speed of a squirrel cage induction motor can be controlled very effectively by varying the stator frequency. Further the operation of the motor is economical and efficient, if it operates at very small slips. The speed of the motor is therefore, varied by varying the supply frequency and maintaining the rotor frequency at the rated value or a value corresponding to the required torque on the linear portion of the torque-speed curve.

29. Why the control of a three-phase indication motor is more difficult than D.C. motors.

The control of a three-phase induction motor, particularly when the dynamic performance involved is more difficult than D.C. motors. This is due to a. Relatively large internal resistance of the converter causes voltage fluctuations following load fluctuations because the capacitor cannot be ideally large.

b. In a D.C. motor there is a decoupling between the flux producing magnetizing current and torque producing armature current. They can be independently controlled. This is not the case with induction motors.

c. An induction motor is very poorly damped compared to a D.C. motor.

30. Where is the V/f control used?

The V/f control would be sufficient in some applications requiring variable torque, such as centrifugal pumps, compressors and fans. In these, the torque varies as the square of the speed. Therefore at small speeds the required torque is also small and V/f control would be sufficient to drive these leads with no compensation required for resistance drop. This is true also for the case of the liquid being pumped with minimal solids.

UNIT – IV

TWO MARKS

1. What are the components of the applied voltage to the induction motor?

The applied voltage to the induction motor has two components at low frequencies. They are a. Proportional to stator frequency.

b.To compensate for the resistance drop in the stator.

The second component deepens on the load on the motor and hence on rotor frequency.

2. What is indirect flux control?

The method of maintaining the flux constant by providing a voltage boost proportional to slip frequency is a kind of indirect flux control. This method of flux control is not desirable if very good dynamic behaviour is required.

3. What is voltage source inverter?

Voltage source inverter is a kind of D.C. link converter, which is a two stage conversion device.

4. What is the purpose of inductance and capacitance in the D.C. link circuit?

The inductance in the D.C. link circuit provides smoothing whereas the capacitance maintains the constancy of link voltage. The link voltage is a controlled quality.

5. What are the disadvantages of square wave inverter in induction motor drive?

Square wave inverters have commutation problems at very low frequencies, as the D.C. link voltage available at these frequencies cannot charge the commutating capacitors sufficiently enough to commutate the thrusters. Those puts a limit on the lower frequency of operation. To extend the frequency towards zero, special charging circuits must be used.

6. What is slip controlled drive?

When the slip is used as a controlled quantity to maintain the flux constant in the motor the drive is called slip enrolled drive. By making the slip negative (i.e., decreasing the output frequency of the inverter) The machine may be made to operate as a generator and the energy of the rotating parts fed back to the mains by an additional line side converter or dissipated in a resistance for dynamic barking. By keeping the slip frequency constant, braking at constant torque and current can be achieved. Thus braking is also fast.

7. What are the effects of harmonics in VSI fed induction motor drive?

The motor receives square wave voltages. These voltage has harmonic components. The harmonics of the stator current cause additional losses and heating. These harmonics are also responsible for torque pulsations. The reaction of the fifth and seventh harmonics with the fundamental gives rise to the seventh harmonic pulsations in the torque developed. For a given induction motor fed from a square wave inverter the harmonic content in the current tends to remain constant independent of input frequency, with the rang of operating frequencies of the inverter.

8. What is a current source inverter?

In a D.C. link converter, if the D.C. link current is controlled, the inverter is called a current source inverter, The current in the D.C. link is kept constant by a high inductance and he capacitance of the filter is dispensed with . A current source inverter is suitable for loads which present a low impedance to harmonic currents and have unity p.f.

9. Explain about the commutation of the current source inverter.

The commutation of the inverter is load dependent. The load parameters form a part of the commutation circuit. A matching is therefore required between the inverter and the motor. Multimotor operation is not possible. The inverter must necessarily be a force commutated one as the induction motor cannot provide the reactive power for the inverter. The motor voltage is almost sinusoidal with superimposed spikes.

10. Give the features from which a slip controlled drive is developed.

The stator current of an induction motor operating on a variable frequency, variable voltage supply is independent of stator frequency if the air gap flux is maintained constant. However, it is a function of the rotor frequency. The torque developed is also a function of rotor frequency. The torque developed is also a function of rotor frequency only. Using these features a slip controlled drive can be developed employing a current source inverter to feed an induction motor.

11. How is the braking action produced in plugging?

In plugging, the barking torque is produced by interchange any two supply terminals, so that the direction of rotation of the rotating magnetic field is reversed with respect to the rotation of the motor. The electromagnetic torque developed provides the braking action and brings the rotor to a quick stop.

12. Where is rotor resistance control used?

Where the motors drive loads with intermittent type duty, such as cranes, ore or coal unloaders, skip hoists, mine hoists, lifts, etc. slip-ring induction motors with speed control by variation of resistance in the rotor circuit are frequently used. This method of speed control is employed for a motor generator set with a flywheel (Ilgner set) used as an automatic slip regulator under shock loading conditions.

13. What are the advantages and disadvantages of rotor resistance control?

Advantage of rotor resistance control is that motor torque capability remains unaltered even at low speeds. Only other method which has this advantage is variable frequency control. However, cost of rotor resistance control is very low compared to variable frequency control.

Major disadvantage is low efficiency due to additional losses in resistors connected in the rotor circuit.

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16. How is the resistance in the output terminals of a chopper varied?

The resistance connected across the output terminals of a chopper can be varied form O to R by varying the time ratio of the chopper. When the chopper is always OFF, the supply is always connected to the resistance R. The time ratio in this case is zero and the effective resistance connected in R. Similarly when the chopper is always ON, the resistance is short circuited. The time ratio in the case is unity and the effective resistance connected is 0. Hence by varying the time ratio from 0 to 1, the value of resistance can be varied from R to O.

17. What is the function of inductance L and resistance R in the chopper resistance circuit?

A smoothing inductance L is used in the circuit to maintain the current at a constant value. Any short circuit in the chopper does not become effective due to L.

The value of R connected across the chopper is effective for all phases and its value can be related to the resistance to be connected in each phase if the conventional method has been used. The speed control range is limited by the resistance.

18. What are the disadvantages and advantages of chopper controlled resistance in the rotor circuit method?

The method is very inefficient because of losses in the resistance. It is suitable for intermittent loads such as elevators. At low speeds, in particular the motor has very poor efficiency. The rotor current is non-sinusoidal. They harmonics of the rotor current produce torque pulsations. These have a frequency which is six times the slip frequency.

Because of the increased rotor resistance, the power factor is better.

19. How is the range of speed control increased?

The range of speed control can be increased if a combination of stator voltage control and rotor resistance control is employed. Instead of using a high resistance rotor, a slip ring rotor with external rotor resistance can be used when stator voltage control is used for controlling the speed.

20. Why the static scherbius drive has a poor power factor?

Drive input power is difference between motor input power and the power fed back. Reactive input power is the sum of motor and inverter reactive power. Therefore, drive has a poor power factor throughout the range of its options.

21. How is super synchronous speed achieved?

Super synchronous speed can be achieved if the power is fed to the rotor from A.C. mains. This can be made possible by replacing the converter cascade by a cycloconverter. A cycloconverter allows power flow in either direction making the static sherbets drive operate at both sub and supper synchronous speeds.

22. Give the features of static scherbius drive

The torque pulsations and other reactions are minimal. The performance of the drive improves with respect to additional losses and torque pulsations. A smooth transition is possible from sub to super synchronous speeds without any commutation problems. Speed reversal is not possible. A step up transformer may be interposed between the lines and the converter, to reduce the voltage rating of the converter.

23. Where is Kramer electrical drive system used?

Some continuous rolling mills, large air blowers, mine ventilators, centrifugal pumps and any other mechanisms including pumps drives of hydraulic dredgers require speed adjustment in the range from 15 to 30% below or above normal. If the induction motor is of comparatively big size (100 to 200 KW) it becomes uneconomical to adjust speed by mean's pf external resistances due to copper losses as slip power is wasted as heat in the retort circuit resistance. In these case , the Kramer electrical drive system is used , where slip power recovery takes places.

24. What is the use of sub synchronous converter cascades?

Sub synchronous converter cascades have been used, till now, in applications requiring one quadrant operation. These can be employed for drives where at least one electrical barking

is required. A four quadrant operation can also be made possible in these cascades, using suitable switching.

25. How is the speed control obtained in static Kramer drive?

For speed control below synchronous speed, the slip power is pumped back to the supply, where as for the case of speed above synchronous speed, additional slip power is injected into the rotor circuit.

26. What is static Kramer drive?

Instead of wasting the slip power in the rotor circuit resistance, it can be converted to 60 Hz A.C. and pumped back to the line. The slip power controlled drive that permits only a sub synchronous range of speed control through a converter cascade is know as static Kramer drive.

27. What is the use and functions of step down transformer is static Kramer drive?

For a restricted speed range closer to synchronous speed, the system power factor can be further improved by using a step -down transformer.
The step-down transformer has essentially two functions: besides improving the line power factor, it also helps to reduce the converter power ratings.

28. What are the advantages of static Kramer drive?

The static Kramer drive has been very popular in large power pump and fan-type drives, where the range of speed control is limited near, but below the synchronous speed. The drive system is very efficient and the converted power rating is low because t has to handle only the slip power, In fact, the power rating becomes lower with a more restricted range of speed control. The additional advantages are that the drive system has D.C. machine like characteristics and the control is very simple.

29. What are the causes of harmonic currents in static Kramer drive?

The rectification of slip power causes harmonic currents in the rotor, and these harmonics are reflected to the stator by the transformer action of the machine. The harmonic currents are also injected into the A.C. line by the inverter. As a result, the machine losses are increased and some amount of harmonic torque is produced. Each harmonic current in the rotor will create a reading magnetic filed and its direction of rotation will depend on the order pf the harmonic.

UNIT – V

TWO MARKS

1. Give the four modes of operation of a Scherbius drive The four modes of operation of static Scherbius drive are,

Sub synchronous motoring.
Sub synchronous regeneration

Super synchronous motoring

Super synchronous regeneration

2. Give the use of synchronous motors.

Synchronous motors were mainly used in constant speed applications. The development of semiconductor variable frequency sources, such as inverters and cycloconverters, has allowed their use in draft fane, main line traction, servo drives, etc.

3. How are the stator and rotor of the synchronous motor supplied?

The stator of the synchronous motor is supplied from a thyristor power converter capable of providing a variable frequency supply. The rotor, depending upon the situation, may be constructed with slip rings, where it conforms to a conventional rotor. It is supplied with D.C. through slip rings. Sometimes rotor may also be free from sliding contacts (slip rings), in which case the rotor is fed from a rectifier rotating with rotor.

4. What is the difference between an induction motor and synchronous motor?

An induction motor operates at lagging power factor and hence the converter supplying the same must invariable is a force commutated one. A synchronous motor, on the other hand, can be operated at any power factor by controlling the field current.

5. List out the commonly used synchronous motors. Commonly used synchronous motors are,

a. Wound field synchronous motors.
b. Permanent magnet synchronous motors
c. Synchronous reluctance synchronous motors.
d. Hysterias motors.

6. Mention the main difference between the wound field and permanent magnet motors.

When a wound filed motor is started as an induction motor, D.C. field is kept off. In case of a permanent magnet motor, the field cannot be 'turned off'.

7. Give the advantages and applications of PMSM. The advantages of PMSM are,

a. High efficiency b. High power factor
c. Low sensitivity to supply voltage variations.

The application of PMSM is that it is preferred of industrial applications with large duty cycle such as pumps, fans and compressors.

8. Give the uses of a hysteresis synchronous motor.

Small hysteresis motors are extensively used in tape recorders, office equipment and fans. Because of the low starting current, it finds application in high inertia application such as gyrocompasses and small centrifuges.

9. Mention the two modes employed in variable frequency control

Variable frequency control may employ and of the two modes.

a. True synchronous mode b. Self-controlled mode

10. Define load commutation

Commutation of thyristors by induced voltages pf load is known as load commutation.

11. List out the advantages of load commutation over forced commutation.

Load commutation has a number of advantages over forced commutation

It does not require commutation circuits

Frequency of operation can be higher

It can operate at power levels beyond the capability of forced commutation.

12. Give some application of load commutated inverter fed synchronous motor drive.

Some prominent applications of load commutated inverter fed synchronous motor drive are high speed and high power drives for compressors, blowers, conveyers, steel rolling mills, main-line traction and aircraft test facilities.

13. How the machine operation is performed in self-controlled mode?

For machine operation in the self -controlled mode, rotating filed speed should be the same as rotor speed. This condition is relaised by making frequency of voltage induced in the armature. Firning pulses are therefore generated either by comparison of motor terminal voltages or by rotor position sensors.

14. What is meant by margin angle of commutation?

The difference between the lead angle of firing and the overlap angle is called the margin angle of commutation. If this angle of the thyristor, commutation failure occurs. Safe commutation is assured if this angle has a minimum value equal to the turn off angle f the thyristor.

15. What are the disadvantages of VSI fed synchronous motor drive?

VSI synchronous motor drives might impose fewer problems both on machine as well as on the system design. A normal VSI with 180° conduction of thyristors required forced commutation and load commutation is not possible.

16. How is PNM inverter supplied in VSI fed synchronous motor?

When a PWM inverter is used, two cases may arise the inverter may be fed from a constant D.C. source in which case regeneration is straight forward. The D.C. supply to the inverter may be obtained form a diode rectifier. In this case an additional phase controlled converter is required on the line side.

17. What is D.C. link converter and cycloconverter?

D.C. link converter is a two stage conversion device which provides a variable voltage, variable frequency supply.

Cycloconverter is a single stage conversion device which provides a Variable voltage, variable frequency supply.

18. What are the disadvantages of cycloconverter?

A cycloconverter requires large number of thyristors and ts control circuitry is complex. Converter grade thyristors are sufficient but the cost of the converter is high.

19. What are the applications of cycloconverter?

A cycloconverter drive is attractive for law speed operation and is frequently employed in large, low speed reversing mils requiring rapid acceleration and deceleration. Typical applications are large gearless drives, e.g. drives for reversing mills, mine heists, etc.

20. Give the application of CSI fed synchronous motor.

Application of this type of drive is in gas turbine starting pumped hydroturbine starting, pump and blower drives, etc.

21. What are the disadvantages of machine commutation?

The disadvantages of machine commutation are,

a.Limitation on the speed range. b. The machine size is large

c. Due to overexciting it is underutilized.

22. What is the use of an auxiliary motor?

Sometimes when the power is small an auxiliary motor can be used to run up the synchronous motor to the desired speed.

23. What are the advantages of brushless D.C. motor?

The brushless D.C. motor is in fact an inverter-fed self controlled permanent synchronous motor drive. The advantages of brushless D.C. motor are low cost, simplicity reliability and good performance.

24. When can the synchronous motor be load commutated?

When the synchronous motor operates at a leading power factor thyristors of load side converter can be commutated by the motor induced voltages same way as the thyristors of a line commutated converter are commutated by line voltages.

25. What are the characteristics of self controlled mode operated synchronous motor?

a) It operates at like dc motor also commutator less motor.
b) These machines have better stability behavior.
c) Do not have oscillatory behavior.

26. What are the characteristics of true synchronus mode operated synchronous motor? The motor behaves like conventional synchronous motor i.e) hunting oscillations exists.
The change in frequency is slow enough for rotor to truck the changes.
Multi motor operation is possible here.

27. What is meant by sub synchronous speed operation?

The sub synchronous speed operation means the SRIM speed can be controlled below the synchronous speed. i.e) the slip power is fed back to the supply.

28. What is meant by super synchronous speed operation?

The super synchronous speed operation means the SRIM speed can be controlled above the synchronous speed. i.e) the supply is fed back to the rotor side.

29. What are the two types of static scherbius system?

a) DC link static scherbius system b) Cyclo converter scherbius system