UNIT – I
CONTROL OF DC MOTORS THROUGH PHASE CONTROLLED RECTIFIERS

Introduction of 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.

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.

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 Electric Drive.

- ✓ Paper mills
- ✓ Cement Mills
- ✓ Textile mills
- ✓ Sugar Mills

- ✓ Steel Mills
- ✓ Electric Traction
- ✓ Petrochemical Industries
- ✓ Electrical Vehicles

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

The basic circuit for a single-phase separately excited dc motor drive is shown in Fig. 1.1.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.

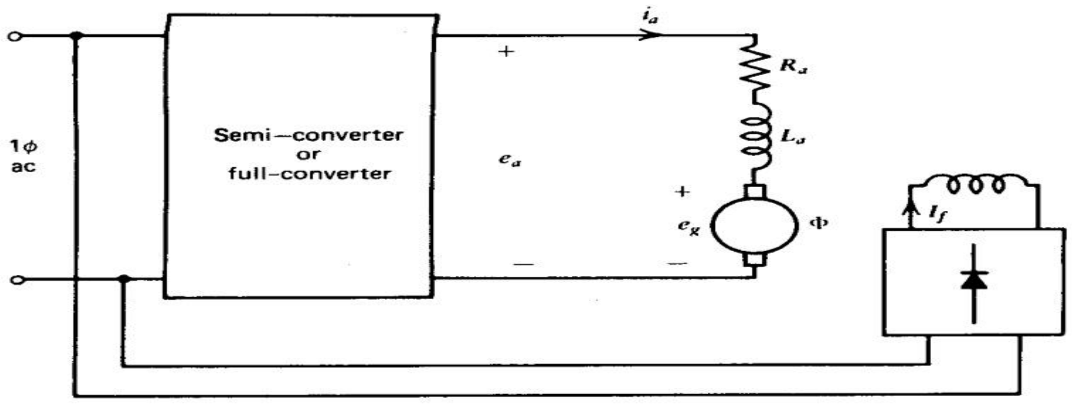


Fig. 1.1
Single-phase full-wave drives are used for low and medium-horsepower applications as indicated in fig1.1.Such drives have poor speed regulation on open-loop firing angle control. However, with armature voltage or tachometer feedback, good regulation can be achieved.

Basic Equation I

The armature circuit of the de motor is represented by its back voltage eg, armature resistance Ra, and armature inductance La as shown inFig.1.1.
Back voltage:

$$e_g = K_a \Phi n$$

Average Back Voltage

$$E_g = K_a \Phi N$$

Developed torque:

$$t = K_a \Phi i_a$$

Average developed torque:

$$T = K_a \Phi I_a$$

The armature circuit voltage equation is

$$e_a = R_a i_a + L_a \frac{di_a}{dt} + e_g$$

Interms of average values,

$$E_a = R_a I_a + E_g$$

(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 e_a and current t, change with time. This is unlike the M-G set drive in which both e_a 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

Continuous Armature Current

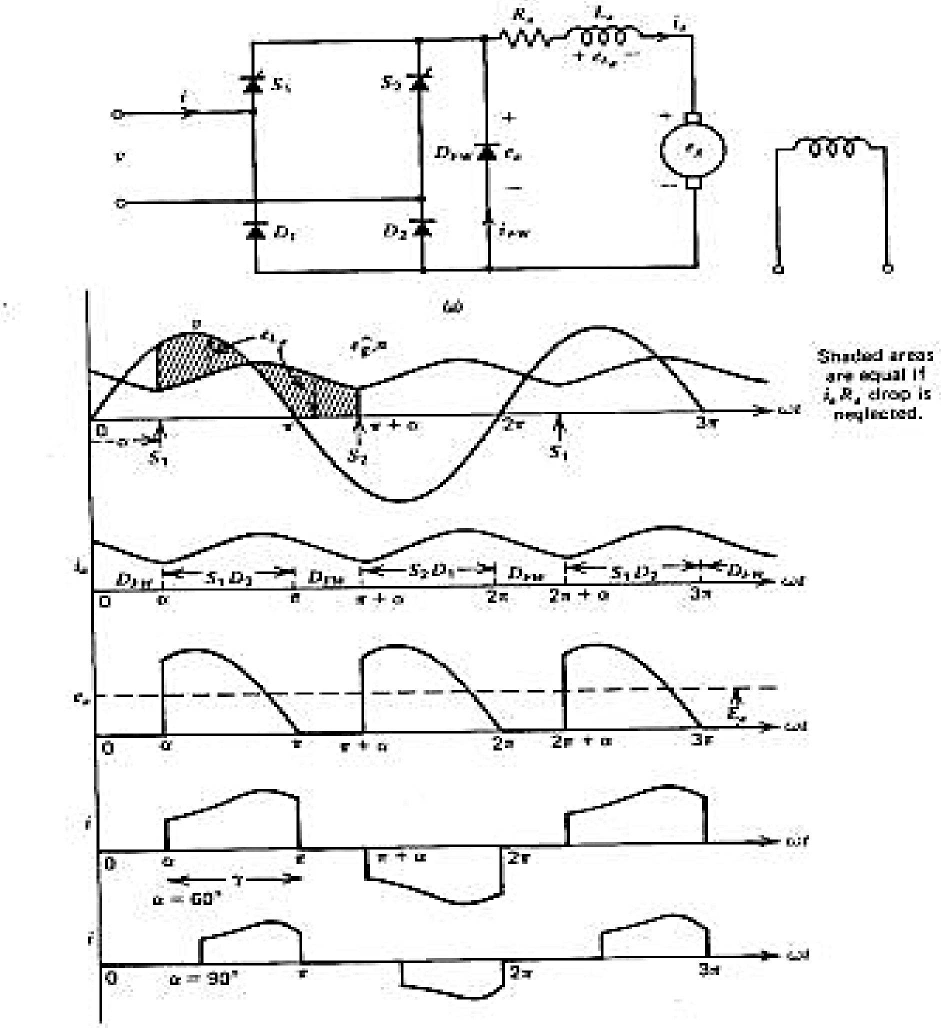
Let us assume that the armature current is continuous over the whole range of operation. Typical voltage and current waveforms are shown in Figs.1.2 and 1.3 for semi-converter and full-converter systems, respectively. The thyristors are symmetrically triggered. In the semi-converter systemshowninFig.1.2, thyristor Sl is triggered at an angle a and S2atan anglea+7T with respect to the supply voltage v. In the full-converter system shown in Fig.1.3, thyristors S, and S3 are simultaneously triggered at a, thyristors S2andS4aretriggeredat7T +a.

In Fig. 1.2, 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.

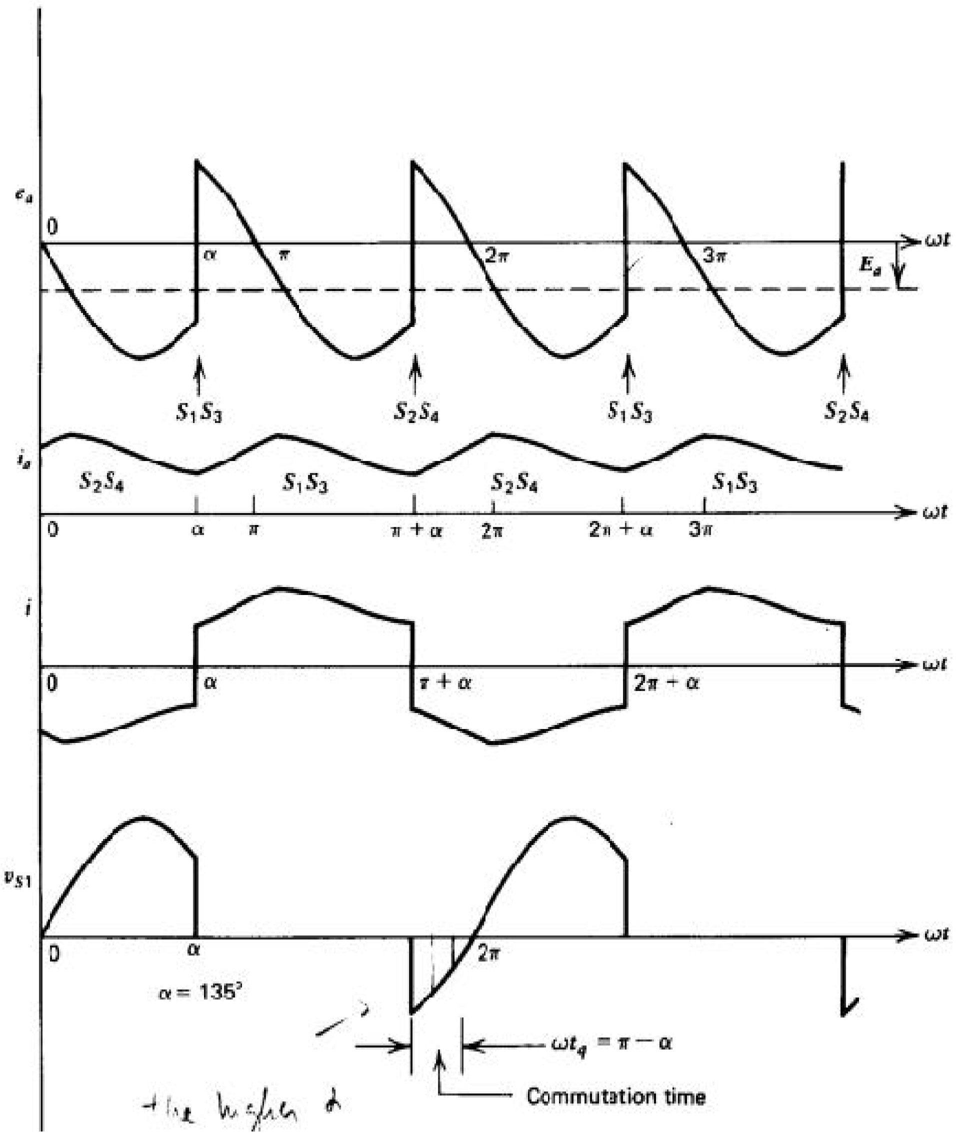
In Fig.1.3, the motor is always connected to the input supply through the thyristors. Thyristors Sl and S3conduct during the interval a<wt <(7T +a) and connect the motor to



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 positive, 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.1.3b 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.



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:

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

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 voltages 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

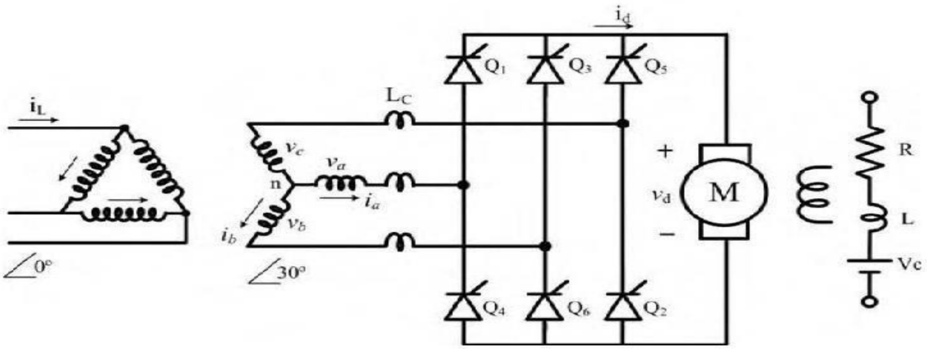
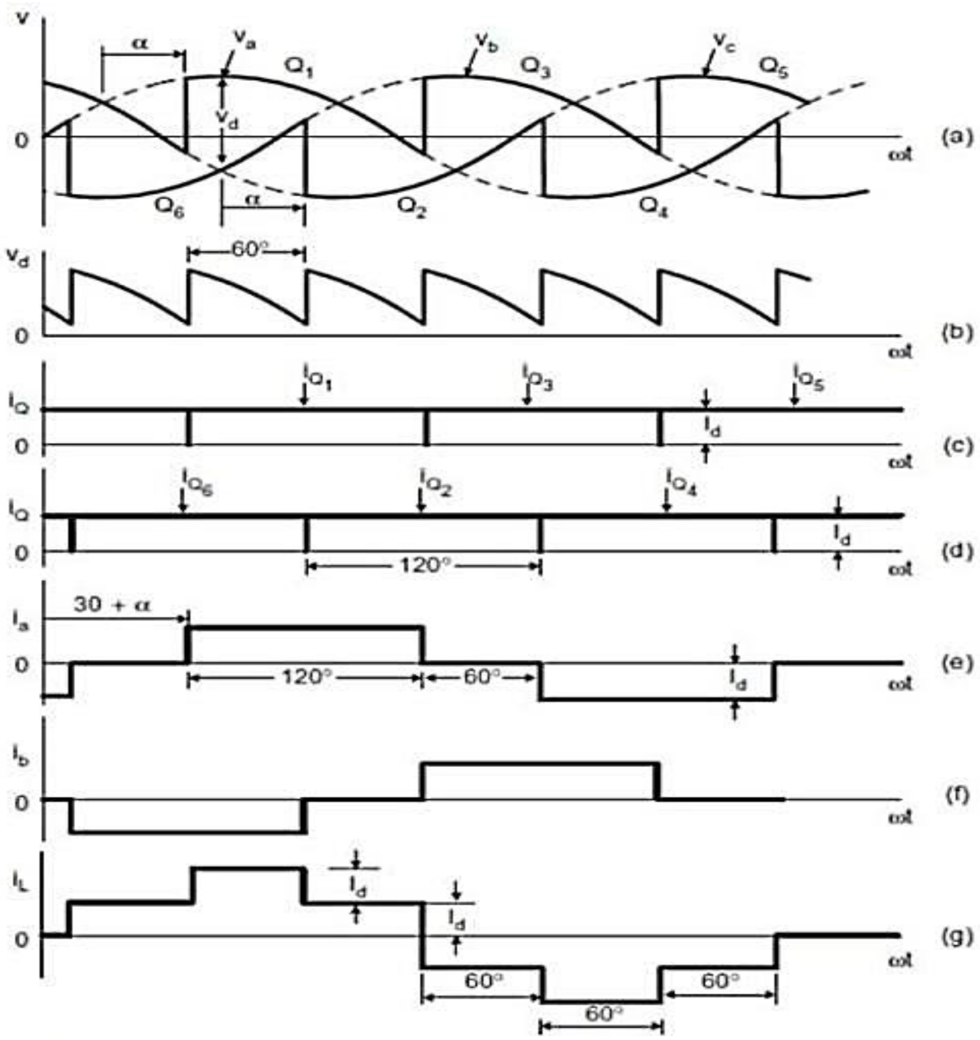


Figure 2.13



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

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.

The average motor armature voltage is given by

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

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

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

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

$$\omega_m = \frac{V_a - I_a R_a}{K_a \phi}$$

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

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

UNIT-II

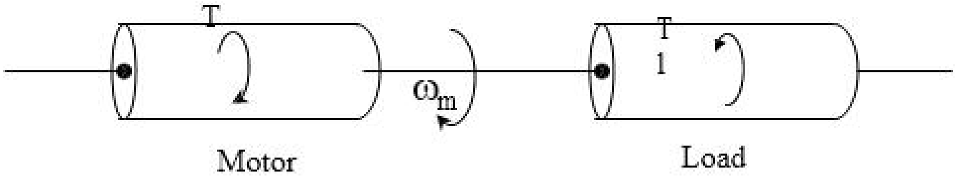
FOUR QUADRANT OPERATION OF DC DRIVES THROUGH DUAL CONVERTER

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

T_l = Instantaneous value of load torque, referred to the motor shaft N-m

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

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

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

Industrial robots. For drives with constant inertia

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

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

Equation (2) shows that torque developed by motor

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)

- ✓ Torque due to force of gravity
- ✓ Torque due tension
- ✓ Torque due to compression and torsionetc

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 T_l can be further divided in to following components

- ✓ Friction Torque (T_F):

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

- ✓ Windage Torque (T_W)

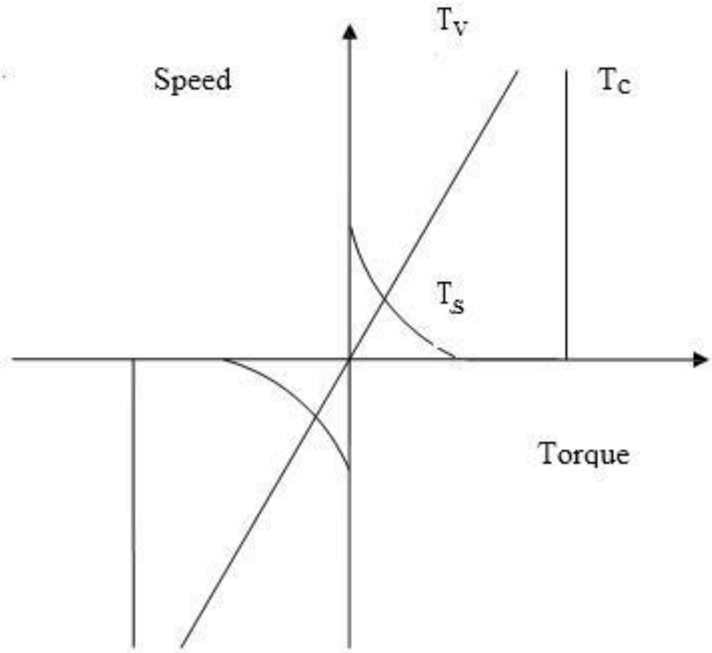
When motor runs, wind generates a torque opposing the motion. This is known as windage torque.

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

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

From the above discussions, for finitespeed

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

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 fourcategories.

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)

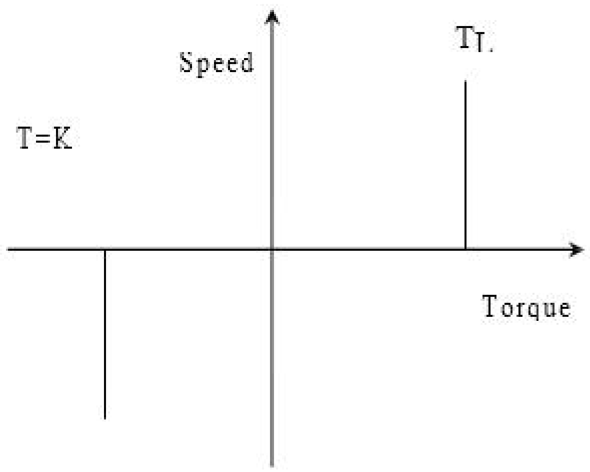
Constant Torque characteristics:

Most of the working machines that have mechanical nature of work like shaping, cutting, grinding or shearing, require co n s t an t 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

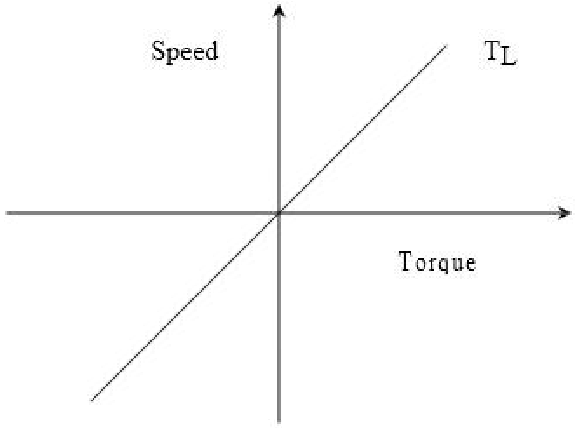


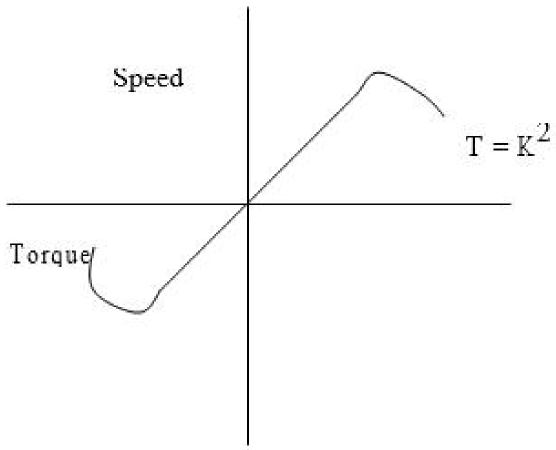
Torque proportional to square of the speed:

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

Examples:

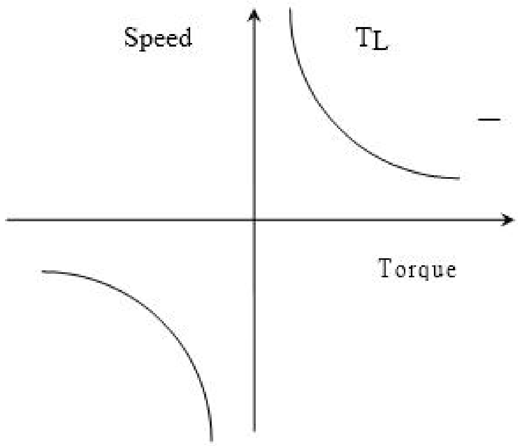
- ✓ Fans rotary pumps,
- ✓ Compressors
- ✓ Ship propellers





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



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.

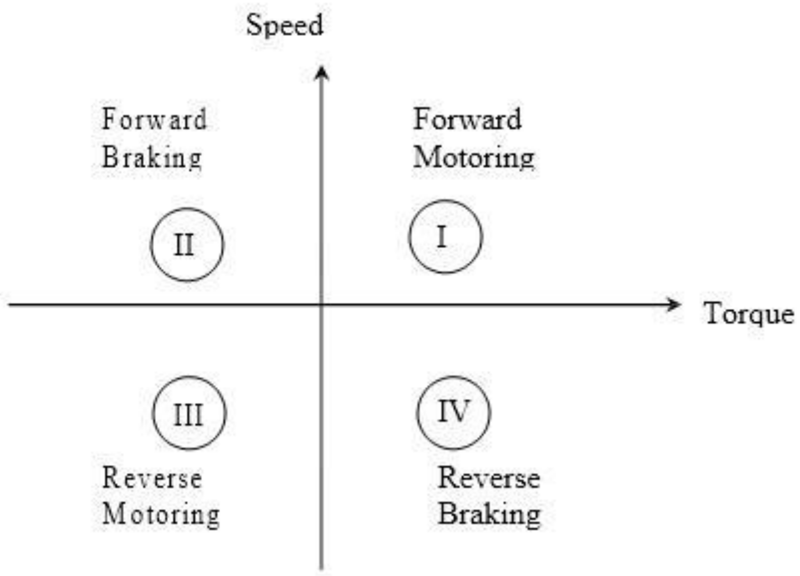
Similarly when working at point B and increase in speed will make motor torque greater than the load torque, which will move the operating point away from point B

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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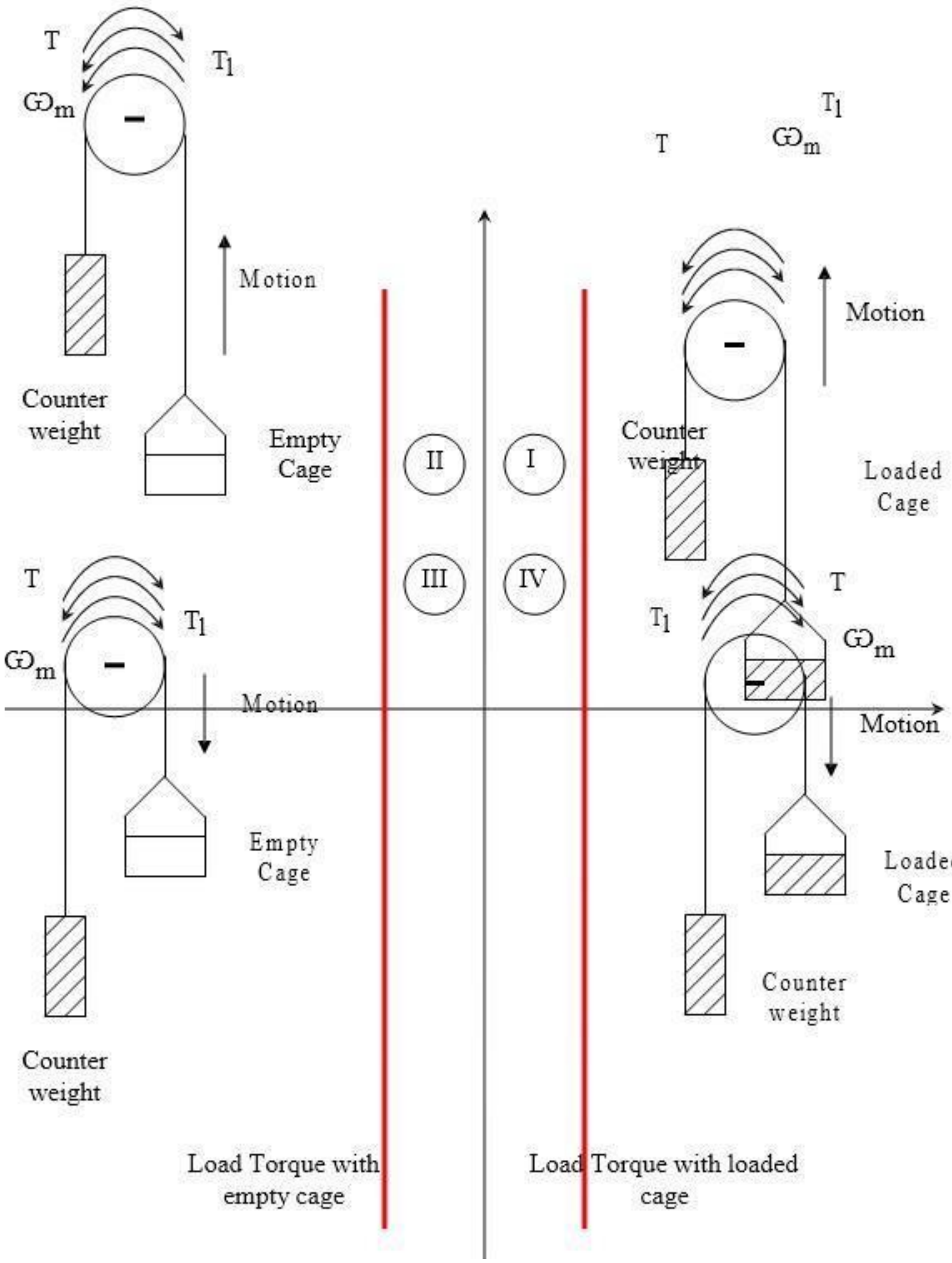

T
T_l
ωm
Motion
Counter weight
Empty Cage
II
I
III
IV
T
ωm
Motion
Counter weight
Loaded Cage
T
T_l
ωm
Motion
Empty Cage
Counter weight
T_l
T
ωm
Motion
Loaded Cage
Counter weight
Load Torque with empty cage
Load Torque with loaded cage

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.

Braking and its classification.

The term braking comes from the term brake. We know that brake is an equipment to reduce the speed of any moving or rotating equipment, like vehicles, locomotives. The process of applying brakes can be termed as braking. Now coming to the term or question what is braking. First of all we can classify the term braking in two parts i) mechanical braking and the ii) electrical braking. Mechanical braking is left out here because as it is an electrical engineering site, we should only focus on electrical braking here. In mechanical braking the speed of the machine is reduced solely by mechanical process but electrical braking is far more interesting than that because the whole process is depended on the flux and torque directions. We will further see through the various types of braking but the main idea behind each type of barking is the reversal of the direction of the flux. So, we can understand that when it is asked that what is braking? We can say that it is the process of reducing speed of any rotating machine. The application of braking is seen at almost every possible area, be it inside the motor used in factories, industrial areas or be it in locomotives or vehicles. Everywhere the use of mechanical and electrical brakes is inevitable.

Types of Braking

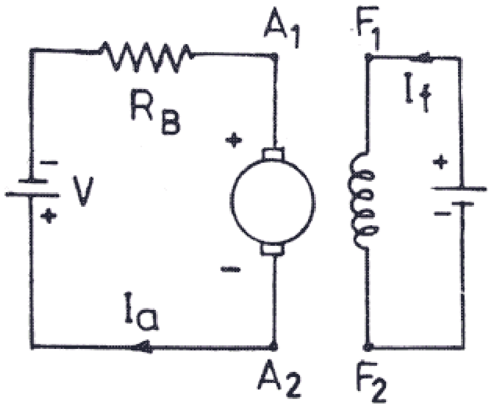
Brakes are used to reduce or cease the speed of motors. We know that there are various types of motors available (DC motors, induction motors, synchronous motors, single phase motors etc.) and the specialty and properties of these motors are different from each other, hence this braking methods also differs from each other. But we can divide braking in to three parts mainly, which are applicable for almost every type of motors.

i) Regenerative Braking

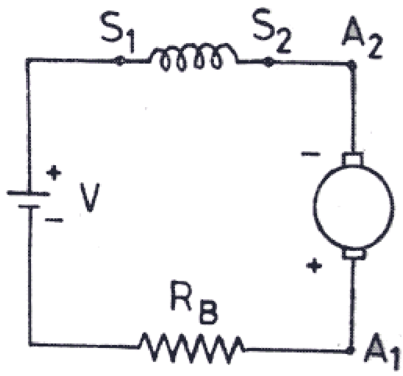
ii) Plugging type braking

iii) Dynamic braking.

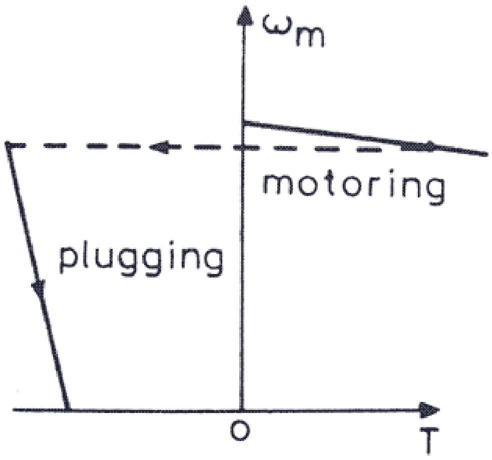
Regenerative Braking



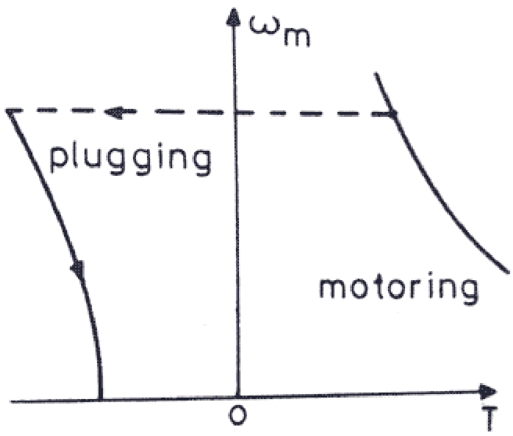
Separately excited



Series



Separately excited



Series

Regenerative braking takes place whenever the speed of the motor exceeds the synchronous speed. This baking method is called regenerative braking because here the motor works as generator and supply itself is given power from the load, i.e. motors. The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed, only then the motor will act as a generator and the direction of current flow through the circuit and direction of the torque reverses and braking takes place.

The only disadvantage of this type of braking is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically, but regenerative braking can be done at sub synchronous speed if the variable frequency source is available.

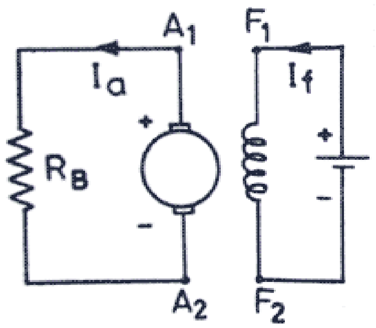
Plugging Type Braking

Another type of braking is Plugging type braking. In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases. During plugging external resistance is also introduced into the circuit to limit the flowing current. The main disadvantage of this method is that here power is wasted.

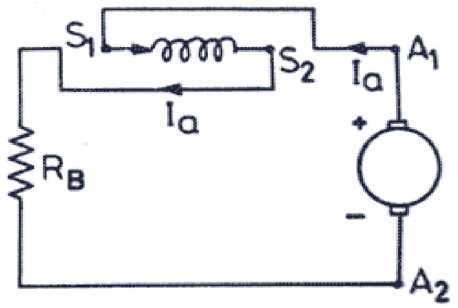
Dynamic Braking

Another method of reversing the direction of torque and braking the motor is dynamic braking. In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance. When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self –excited generator. When the motor works as a generator the flow of the current and torque reverses. During braking to maintain the steady torque sectional resistances are cut out one by one.

Basics of Regenerative Braking



Separately excited motor



Series motor

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.

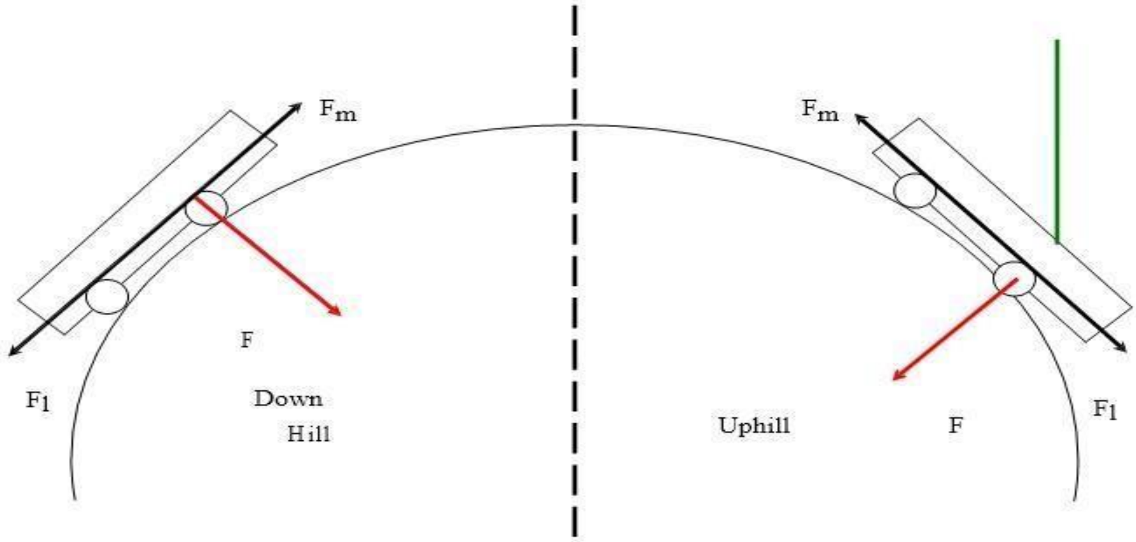
Mechanical energy is converted into electrical energy, part of which is returned to the supply and rest of the energy is last as heat in the winding and bearings of electrical machines pass smoothly from motoring region to generating region, when over driven bythe load.

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.

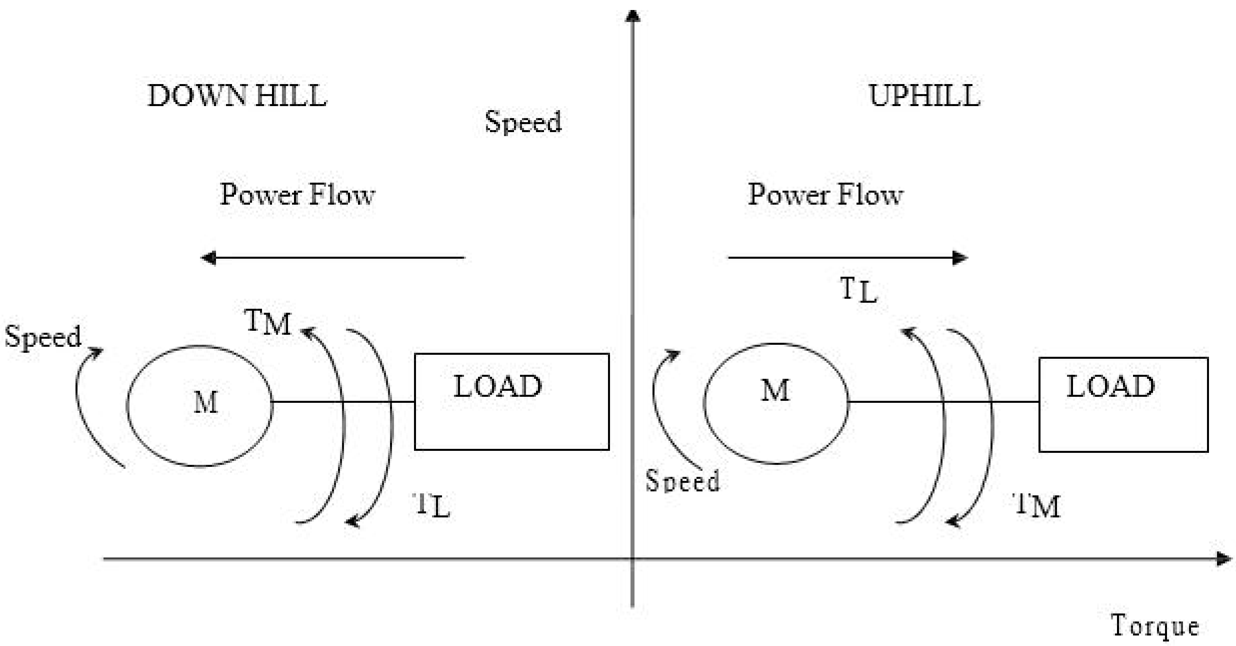
One is perpendicular to the load surface (F) and another one is parallel to the road surface Fl. The parallel force pulls the motor towards bottom of the hill.

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.



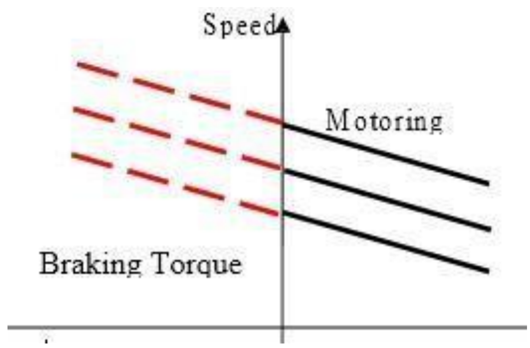
Now we consider that the same bus is traveling in downhill, the gravitational force doesn't change its direction but the load torque pushes the motor towards the bottom of the hill. The motor produces a torque in the reverse direction because the direction of the motor torque is always opposite to the 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 for DC motor:

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

$E > V$ and I_a should be negative



Modes of Operation:

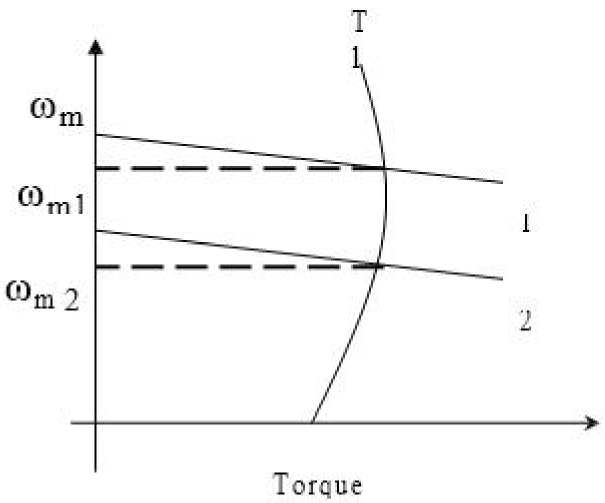
An electrical drive operates in three modes

- ✓ 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 $\omega_{m\ 1}$.

Speed is changed to $\omega_{m\ 2}$ 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.

Four Quadrant Operation of a Converters.

Separately-excited dc shunt motor can be operated in either direction in either of the two modes, the two modes being the motoring mode and the regenerating mode. It can be seen that the motor can operate in any of the four quadrants and the armature of the dc motor in a fast four-quadrant drive is usually supplied power through a dual converter. The dual converter can be operated with either circulating current or without circulating current. If both the converters conduct at the same time, there would be circulating current and the level of circulating current is restricted by provision of an inductor. It is possible to operate only one converter at any instant, but switching from one converter to the other would be carried out after a small delay. This page describes the operation of a dual converter operating without circulating current.

As shown in Fig. 1, the motor is operated such that it can deliver maximum torque below its base speed and maximum power above its base speed. To control the speed below its base speed, the voltage applied to the armature of motor is varied with the field voltage held at its nominal value. To control the speed above its base speed, the armature is supplied with its rated voltage and the field is weakened. It means that an additional single-phase controlled rectifier circuit is needed for field control. Closed-loop control in the field-weakening mode tends to be difficult because of the relatively large time constant of the field.

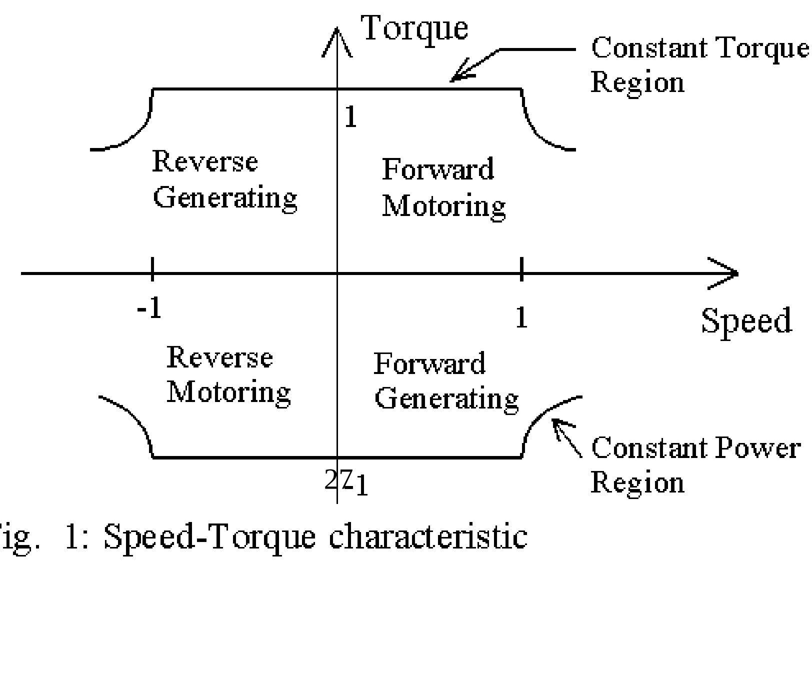


Fig. 1: Speed-Torque characteristic

The power circuit of the dual-converter dc drive is shown in Fig. 2.

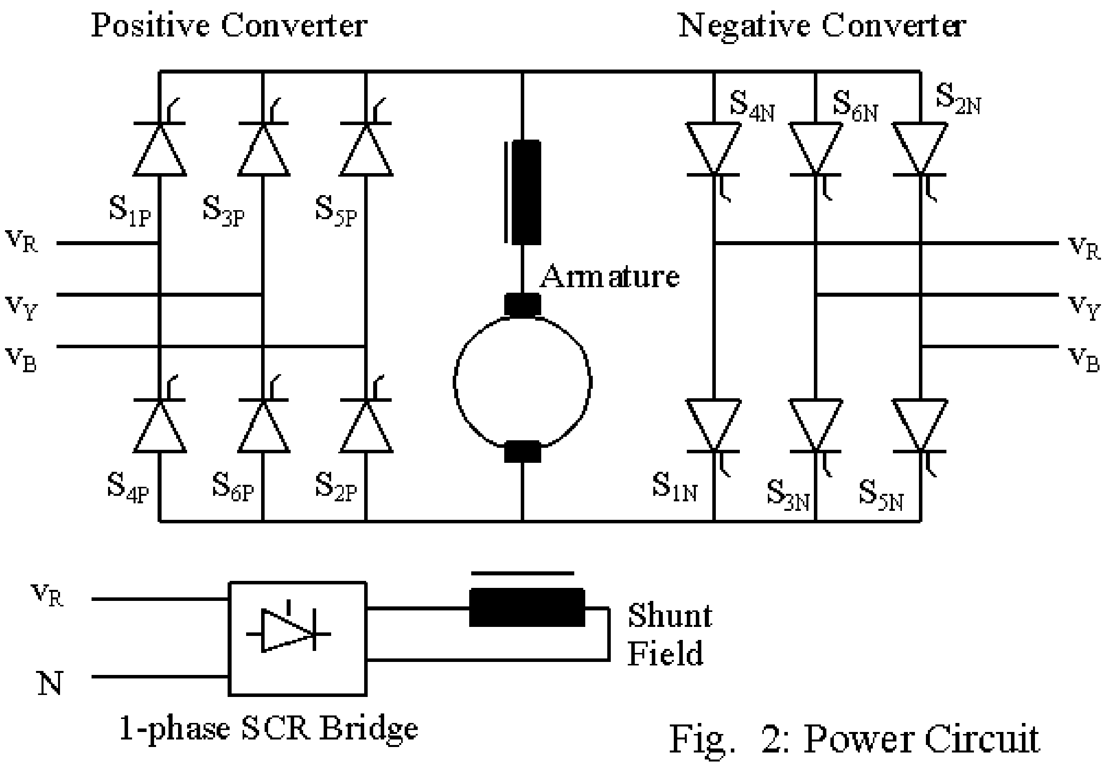


Fig. 2: Power Circuit

Each converter has six SCRs. The converter that conducts for forward motoring is called the positive converter and the other converter is called the negative converter. The names given are arbitrary. Instead of naming the converters as positive and negative converter, the names could have been the forward and reverse converter. The field is also connected to a controlled-bridge in order to bring about field weakening.

The circuit shown above can be re-drawn as shown in Fig. 3. Usually an inductor is inserted in each line as shown in Fig. 3 and this inductor reduces the impact of notches on line voltages that occur during commutation overlap.

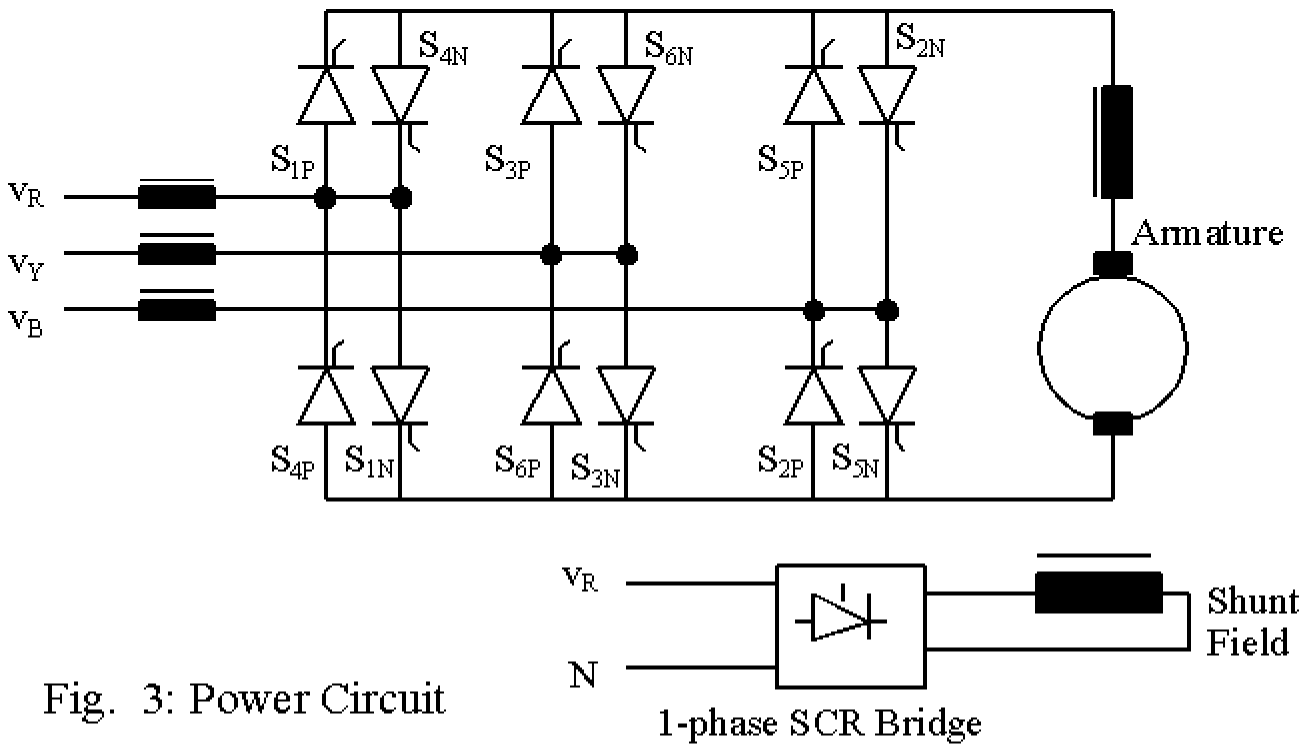


Fig. 3: Power Circuit

CIRCUIT OPERATION

The operation of the circuit in the circulating-current free mode is not very much different from that described in the previous pages. In order to drive the motor in the forward direction, the positive converter is controlled. To control the motor in the reverse direction, the negative converter is controlled. When the motor is to be changed fast from a high value to a low value in the forward direction, the conduction has to switch from the positive converter to the negative converter. Then the direction of current flow changes in the motor and it regenerates, feeding power back to the source. When the speed is to be reduced in the reverse direction, the conduction has to switch from the negative converter to the positive converter. The conduction has to switch from one converter to the other when the direction of motor rotation is to change.

At the instant when the switch from one converter to the other is to occur, it would be preferable to ensure that the average output voltage of either converter is the same. Let the firing angle of the positive converter be a_P, and the firing angle of the negative converter be

a_N . If the peak line voltage be U, then equation (1) should apply. Equation (1) leads to equation (2). Then the sum of firing angles of the two converters is p, as shown in equation (3).

$$\frac{3U}{\pi} \times \mathrm{Cos}\ (\alpha_P) = -\ \frac{3U}{\pi} \times \mathrm{Cos}\ (\alpha_N) \quad (1)$$

$$\mathrm{Cos}\ (\alpha_P) = \mathrm{Cos}\ (\pi - \alpha_N) \quad (2)$$

$$\alpha_P + \alpha_N = \pi \quad (3)$$

In a dual-converter, the firing angles for the converter are changed according to equation (3). But it needs to be emphasized that only one converter operates at any instant.

When the speed of the motor is to be increased above its base speed, the voltage applied to the armature is kept at its nominal value and the phase-angle of the single phase bridge is varied such that the field current is set to a value below its nominal value. If the nominal speed of the motor is 1500 rpm, then the maximum speed at which it can run cannot exceed a certain value, say 2000 rpm. Above this speed, the rotational stresses can affect the commutator and the motor can get damaged.

UNIT-III

CONTROL OF DC MOTORS BY CHOPPERS

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 T_{on} 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 T_{on} is kept constant or
(ii) off-time T_{off} is kept constant. This method of controlling duty ratio is also called Frequency- modulation scheme.

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

Chopper fed DC drives

- Supply is DC (maybe from rectified-filtered AC, or some other DC sources).
- DC-DC converters (coppers) are used.
- suitable for applications requiring position control or fast response, for example in servo applications, robotics, etc.
- Normally operate at high frequency

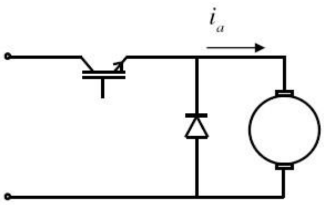
– the average output voltage response is significantly faster
– the armature current ripple is relatively less than the controlled rectifier

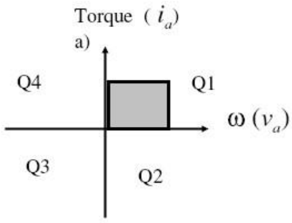
- In terms of quadrant of operations, 3 possible configurations are possible:

– single quadrant,
– two–quadrant and four–quadrant

Single-quadrant drive

- Unidirectional speed. Braking not required.





For $0 < t < T$,
The armature voltage at steady state :

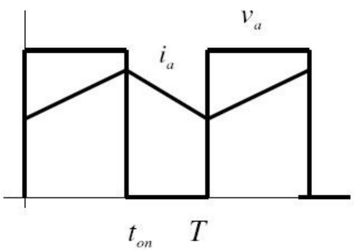
$$V_a = \frac{1}{T}\int_0^{t_{on}} V dt = \frac{t_{on}}{T} = DV$$

Armature (DC) current is :

$$I_a = \frac{V_a - E_g}{R_a};$$

and speed can be approximated as :

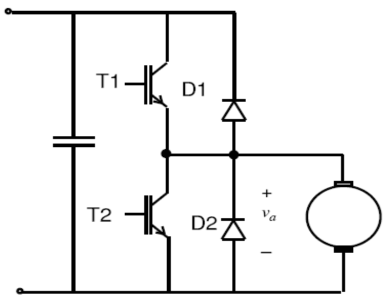
$$\omega = \frac{V_a}{K_v I_f}$$

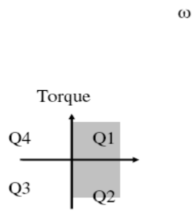


2 Quadrant DC drives

- FORWARD MOTORING (T1 and D2 operate)
  - T1 on: The supply is connected to motor terminal.
  - T1 off: The armature current freewheels through D2.
  - V*a* (hence speed) is determined by the duty ratio.

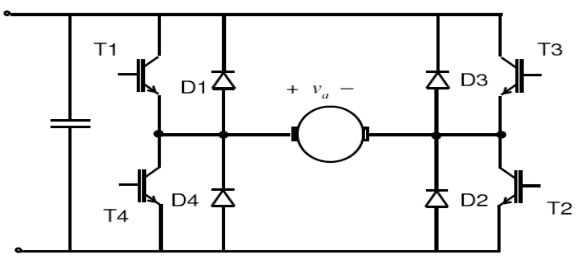
- REGENERATION (T2 and D1 operate)
  - T2 on: motor acts as a generator
  - T2 off:, the motor acting as a generator returns energy to the supply through D2.

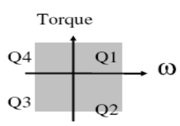




4 Quadrant DC drives

- A full-bridge DC-DC converter is used.





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

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

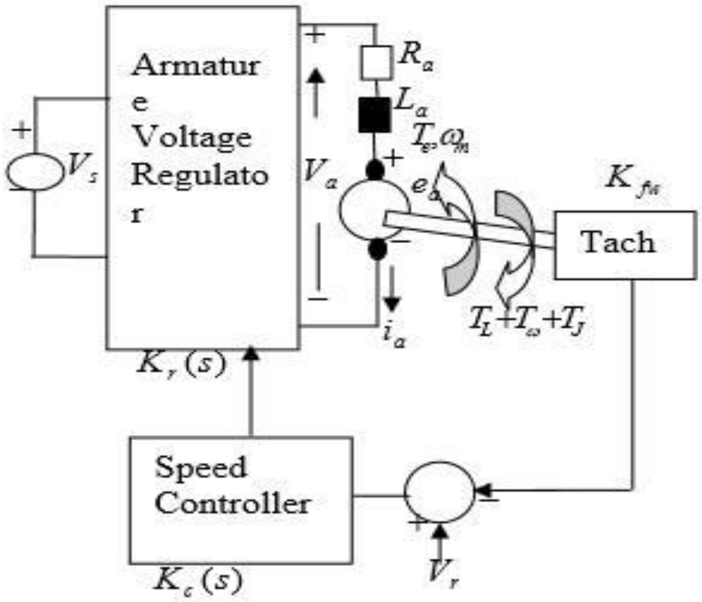
$$\frac{W(s)}{V_f(s)} = \frac{W(s)}{T_m(s)}\frac{T_m(s)}{V_f(s)} = \frac{(K_{mf}/L_f J)}{(s+c/J)(s+R_f/L_f)} \qquad \text{(2}^{nd}\text{ order system)} \qquad (1.6)$$

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

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

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

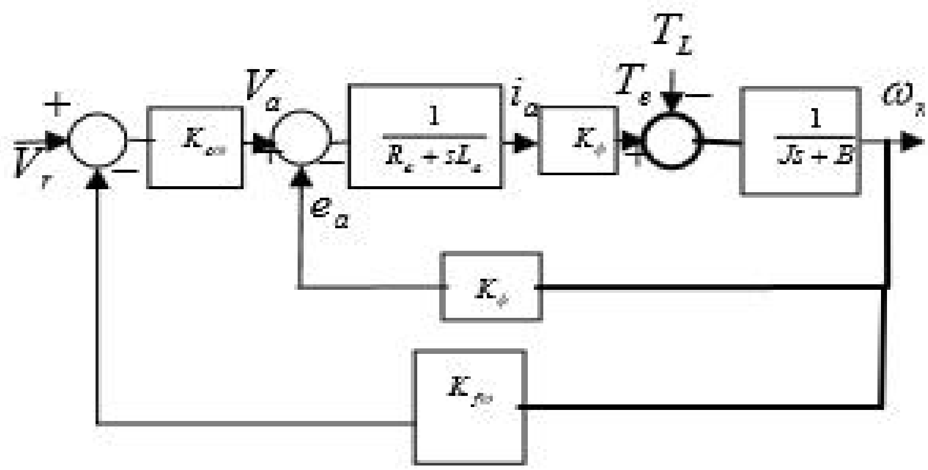
Loop Speed Control Where, $K_{f\omega}$ is

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,

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

Where,

$$D_o(s) = s^2 J L_a + (R_a J + B L_a)s + R_a B + K_\phi^2 + K_\phi K_{f\omega}(s) K_{c\omega}(s) \quad \textbf{(24)}$$

$$D_o(s) = J L_a[s^2 + (\frac{R_a J + B L_a}{J L_a})s + \frac{R_a B + K_\phi^2 + K_\phi K_{f\omega}(s) K_{c\omega}(s)}{J L_a} \quad \textbf{(25)}$$

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

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

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

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

Last Equation is a second order system

The Natural Frequency of Oscillation, ω_n is,

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

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

$$\varepsilon = \frac{R_a J + BL_a}{2\omega_n J L_a}$$

This is lower than in the open loop case

due to the increase in ω_n Speed

Regulation (SR) is also derived as

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

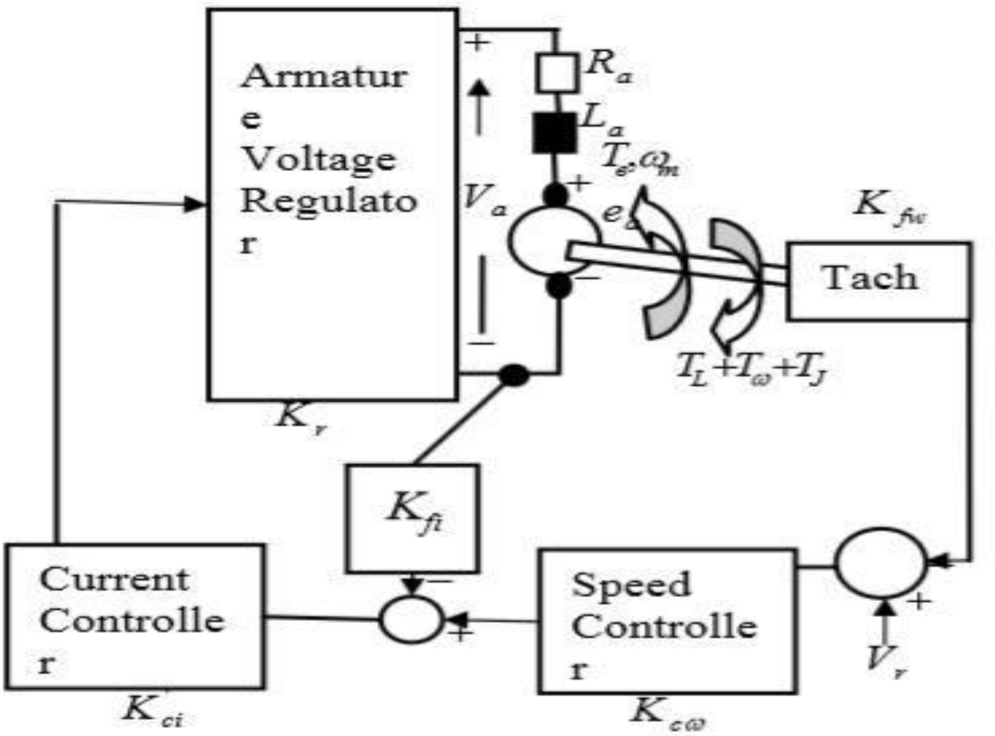
SR is also lower than in the open loop case due to the factor K_ϕ ,$K_{f\omega}$, $K_{c\omega p}$. This is an indication of a better drive performance.

Inner Current Loop Control

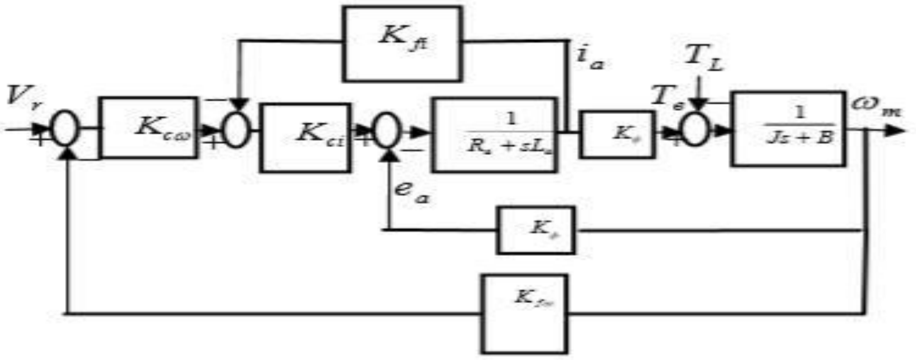
Improvement in speed control can be obtained with Inner Current Loop Control method, whereby armature current is fed back to the input. A closed loop speed control scheme with inner current control is shown in Figure.
Designating $\mathbf{K^1_{ci}+K_r=K_{ci}}$ the block diagram representation of the control

configuration is shown in Figure. The dynamic equation is,

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

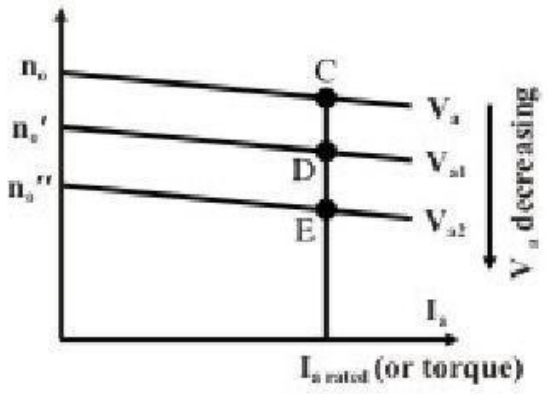


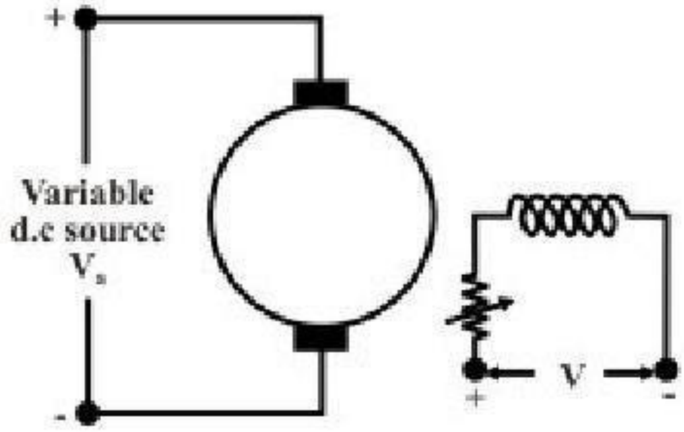
Schematic Diagram of the Inner Current Loop Control.



Block Diagram of the Inner Current Loop Control

Speed control by armature voltage variation





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.

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 a negative 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;

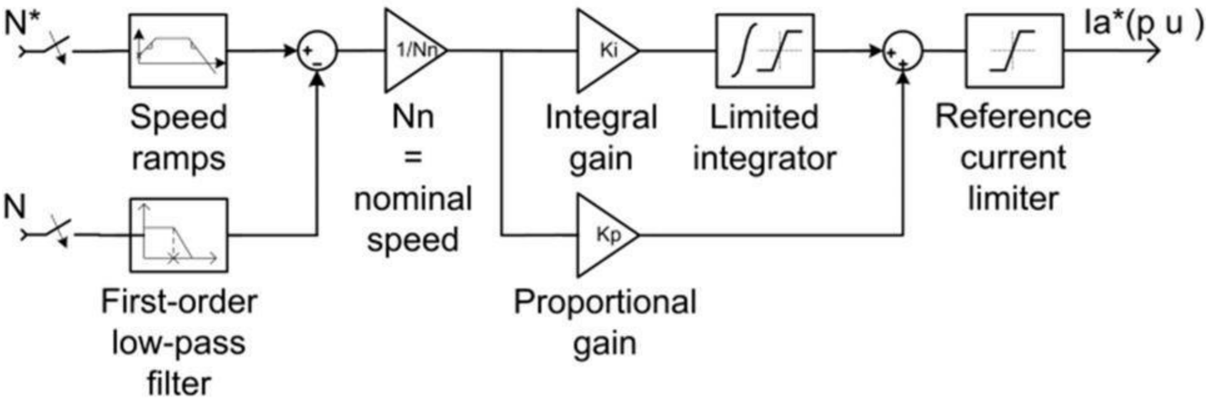
2) constant-current-constant-power(CCCP)control;and

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

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.

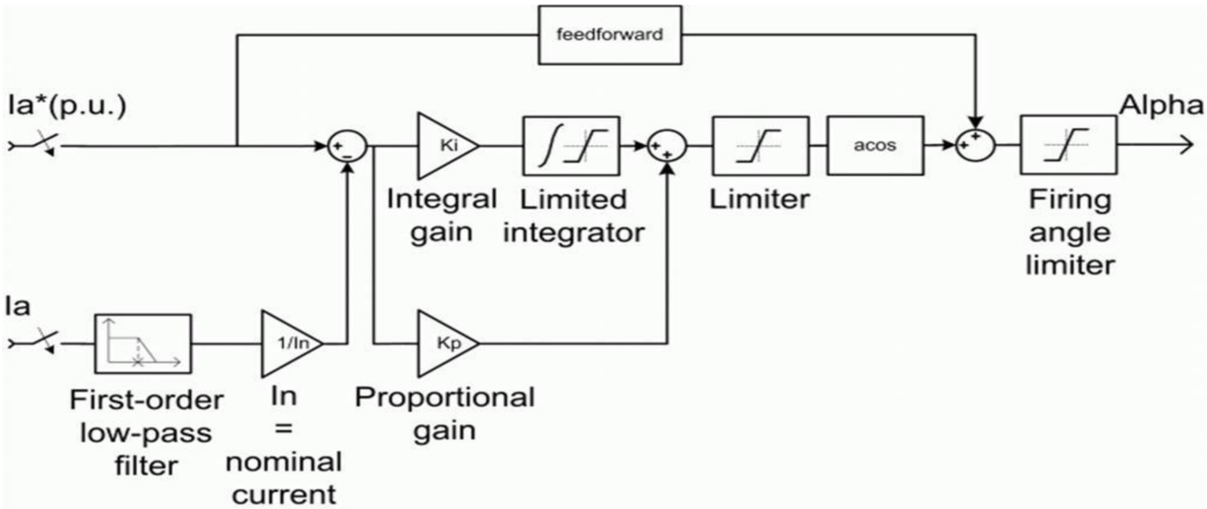


Current Controller

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

CONTROL OF INDUCTION MOTORS

CONTROL OF INDUCTION MOTORS.

A three phase induction motor is basically a constant speed motor so it's somewhat difficult to control its speed. The speed control of induction motor is done at the cost of decrease in efficiency and low electrical power factor. Before discussing the methods to control the speed of three phase induction motor one should know the basic formulas of speed and torque of three phase induction motor as the methods of speed control depends upon these formulas.

Synchronous speed

$$N_s = \frac{120f}{P}$$

Where f = frequency and P is the number of poles The speed of induction motor is given by,

$$N = N_s(1-s)$$

Where N is the speed of rotor of induction motor, N_s is the synchronous speed, S is the slip. The torque produced by three phase induction motor is given by,

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

When rotor is at sand still slip, s is one. So the equation of torque is,

$$T = \frac{3}{2\pi N_s} X \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Where E_2 is the rotor emf N_s is the synchronous speed R_2 is the rotor resistance X_2 is the rotor inductive reactance

The Speed of Induction Motor is changed from Both Stator and Rotor Side

The speed control of three phase induction motor from stator side are further classified as :

1. V / f control or frequency control.
2. Changing the number of stator poles.
3. Controlling supply voltage.
4. Adding rheostat in the stator circuit.

The speed controls of three phase induction motor from rotor side are further classified as:

1. Adding external resistance on rotor side.
2. Cascade control method.
3. Injecting slip frequency emf into rotor side.

Speed Control from Stator Side

1. V / f control or frequency control - Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

$$N_s = \frac{120f}{P}$$

   In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E \ or \ V = 4.44\phi K.T.f \ or \ \phi = \frac{V}{4.44KTf}$$

   Where K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, its important to maintain flux , φ constant and it is only possible if we change voltage . i.e if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/ f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/ f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

2. Controlling supply voltage: The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

   In low slip region $(sX)^2$ is very very small as compared to R_2 . So, it can be neglected. So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

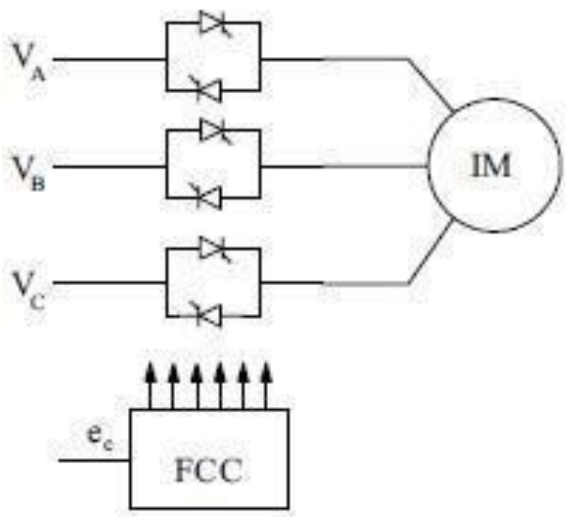
Since rotor resistance, R_2 is constant so the equation of torque further reduces to

$$T \propto sE_2^2$$

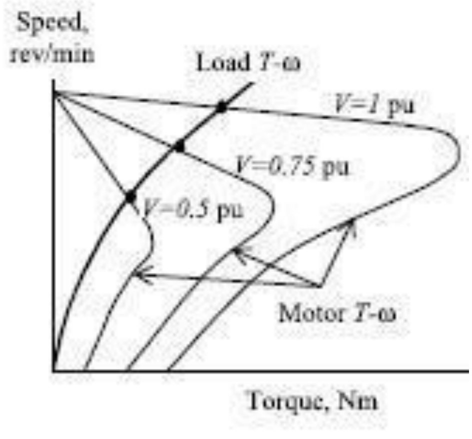
We know that rotor induced emf $E_2 \propto V$. So, $T \propto sV^2$. From the equation above it is clear that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increases the motor will run at reduced speed . This method of speed control is rarely used because small change in speed requires large reduction in voltage, and hence the current drawn by motor increases, which cause over heating of induction motor.

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.



(a)



(b)

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.

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

Ψs=Ѵs/Ꞓs

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.

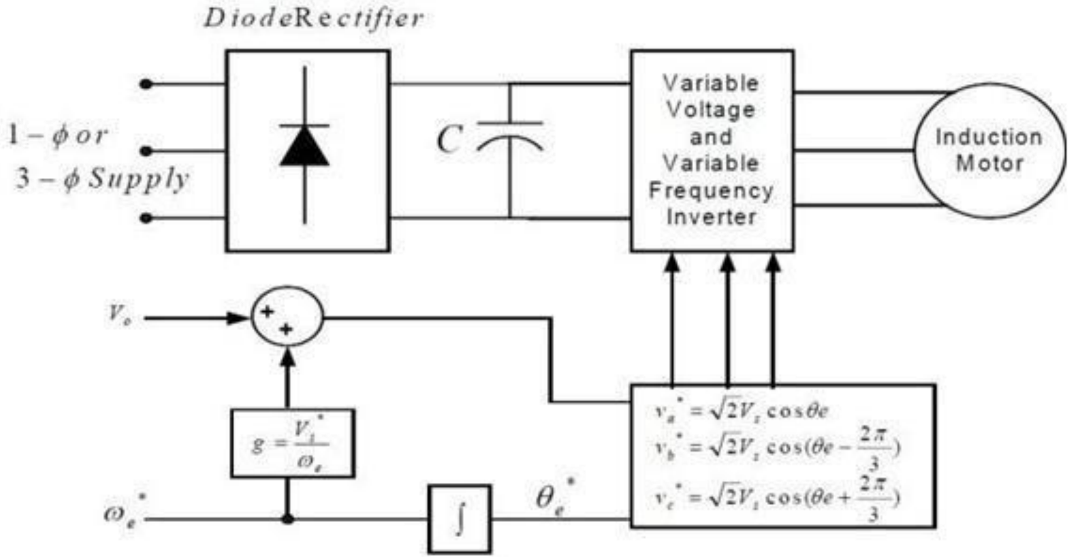
The PWM converter is merged with the inverter block. Some problems encountered in the operation of this open loop drive are the following:

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

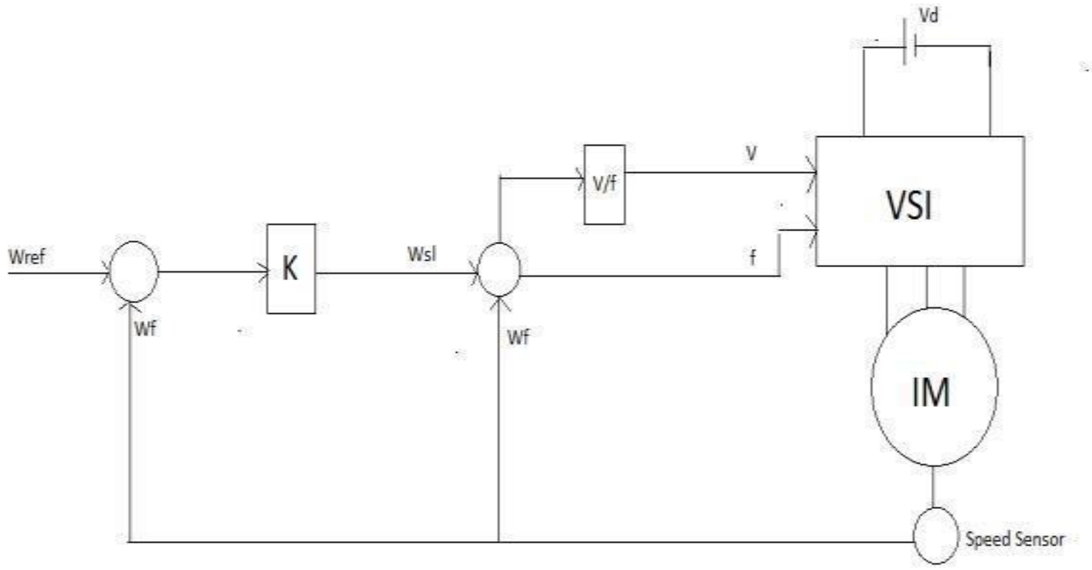
These problems are to be suppress by having an outer loop in the induction motor drive, in which the actual rotor speed is compared with its commanded value, and the error is processed through a controller usually a PI controller and a limiter is used to obtain the slip-speed command



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

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

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

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

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

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

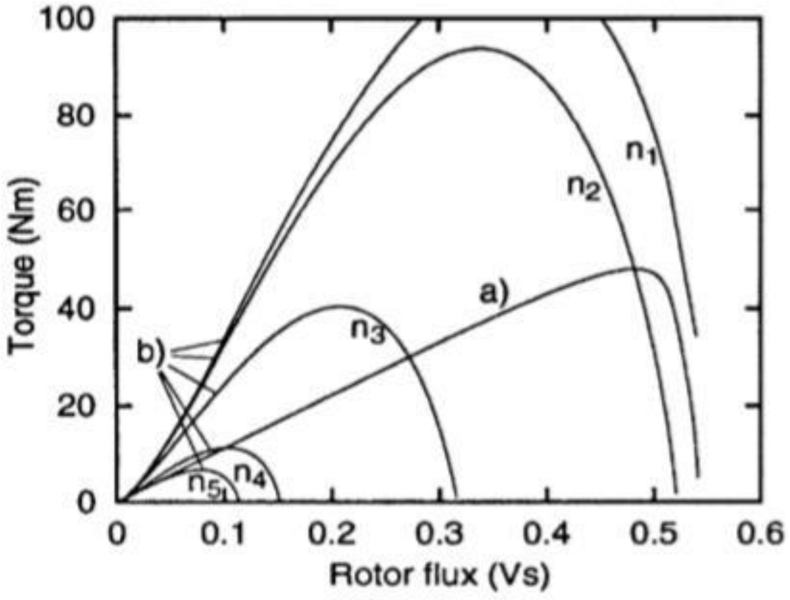
$$\omega_{FS} = \omega_{FR} + p\omega_m \quad (3)$$

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

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

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

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.

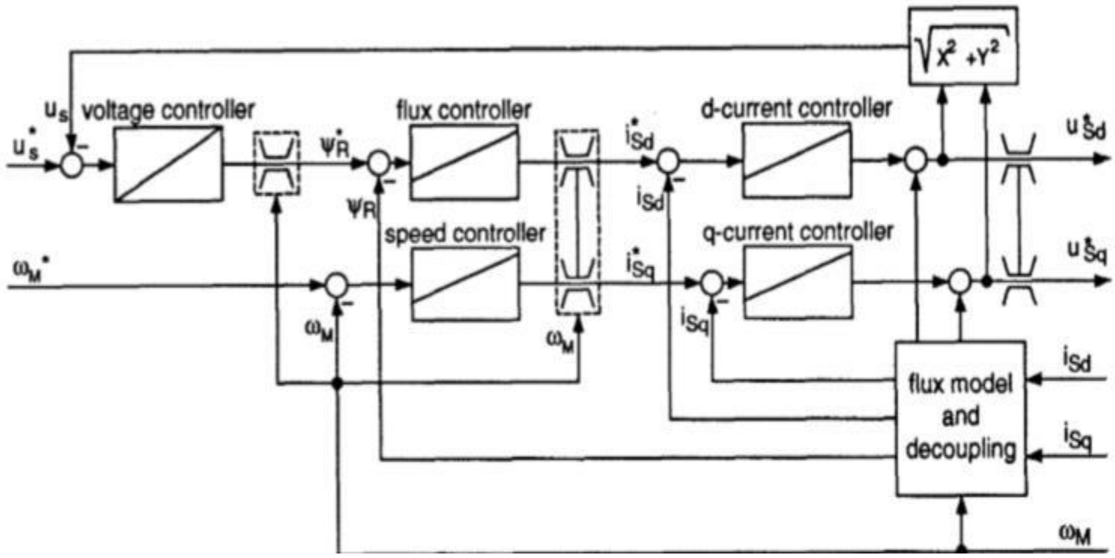
Upper flux weakening region: At high speeds the maxi- mum torque is fixed by the maxima of the voltage limitation curves only. The machine has to run only with maximum voltage but the current has to be reduced.

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



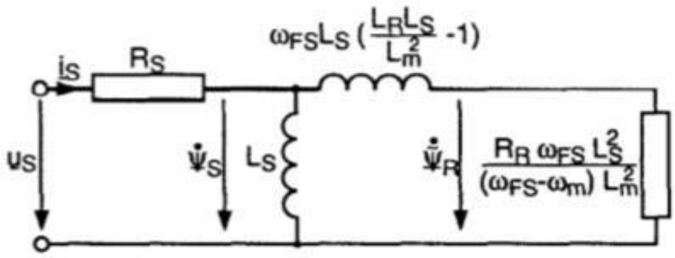
Scheme of rotor flux oriented control with voltage controller

CURRENT REDUCTION IN THE UPPER FLUX WEAKENING REGION

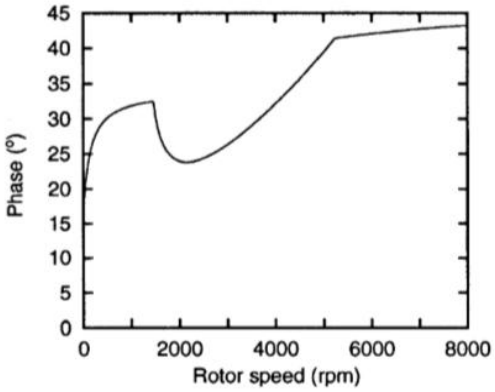
The function Iq max (n) depends on the electrical parameters as well as the DC link voltage. If the uncertainties of the electrical parameters and the variations of ud are taken into account the optimum operating point can be missed. This problem can be solved, if there is a second condition that describes 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 us and Is is nearly 450 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.



$\varphi = 45°$. 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:

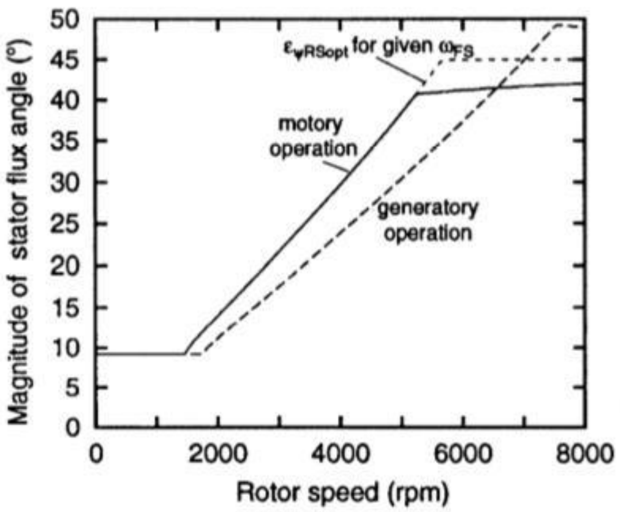
$$L_m = f(i_{Sd}, i_{Sq}) \tag{8}$$

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

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.



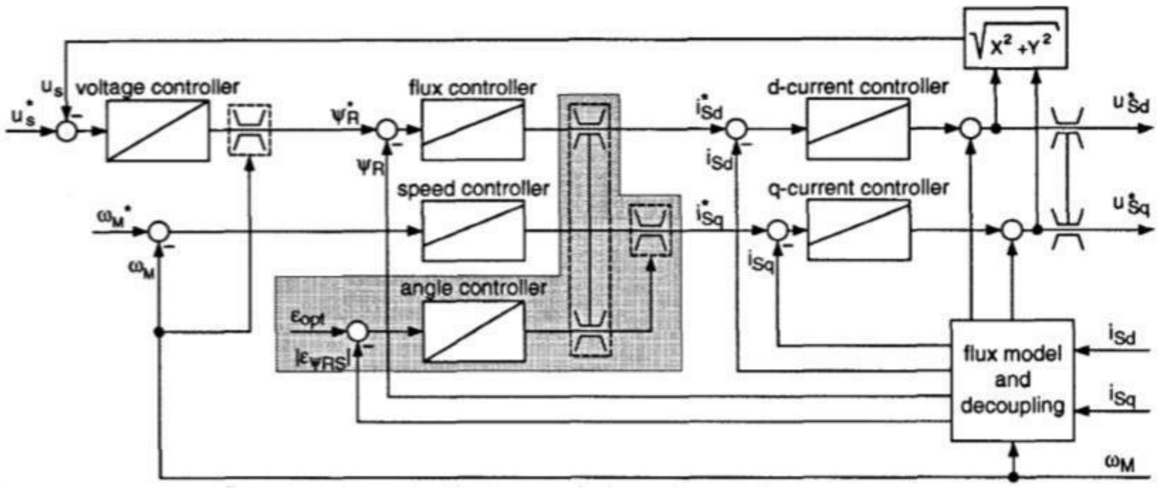
Optimal angle of stator flux in the rotor flux frame The different operation areas are characterized by different behavior

In the basic speed region $E\Psi$ 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 $E_{\Psi RSPOT}$ increases monotonously as well but the gradient is very small. As proposed $E_{\Psi RSPOT}$ is just a few degrees below 450 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



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 450 (exactly 450 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.

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 41.670. 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.

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 $E_{\Psi RSPOT}$ 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 > $E_{\Psi RSPOT}$) the q-current will be reduced until the regulated quantity meets its reference value $E_{\Psi RSPOT}$.

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, $E_{\Psi RS}$ coupled closely to the measurable angle Ψ in this speed range.

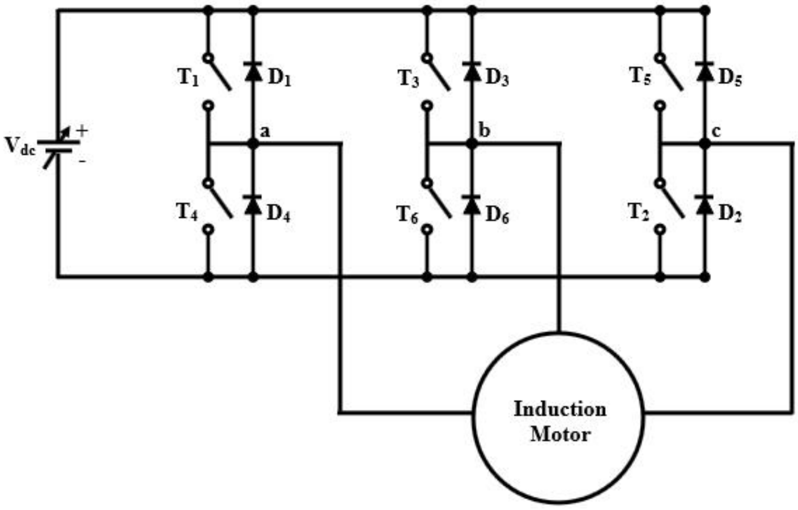
Voltage-source Inverter-driven Induction Motor

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.

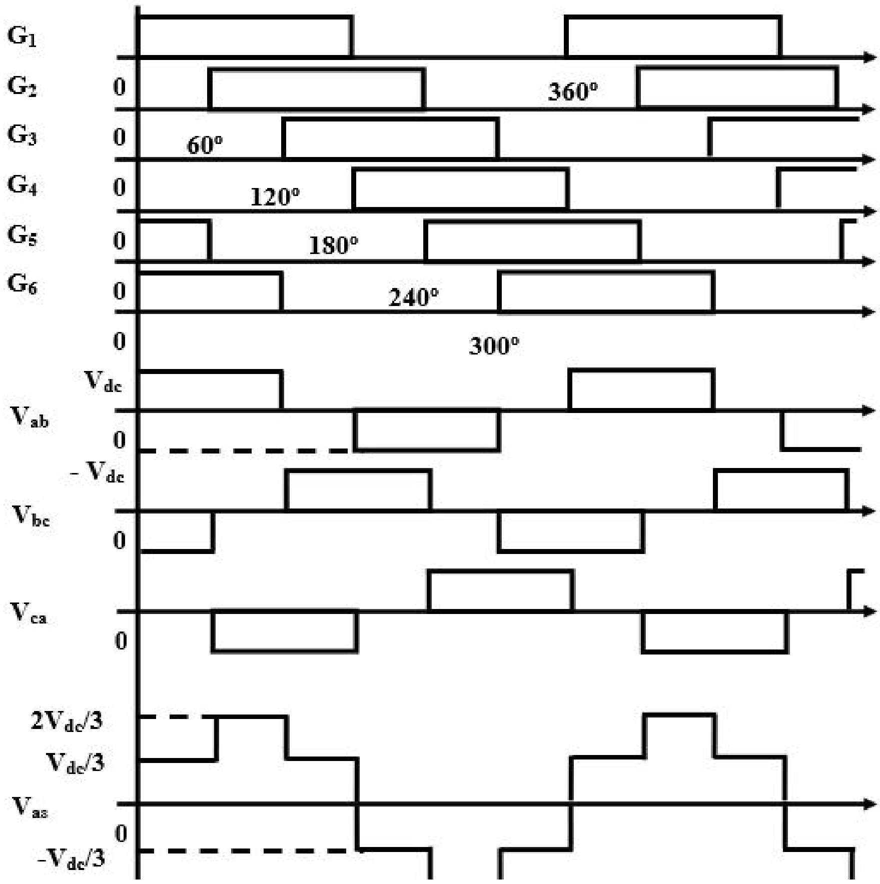


A schematic of the generic inverter-fed induction motor drive.

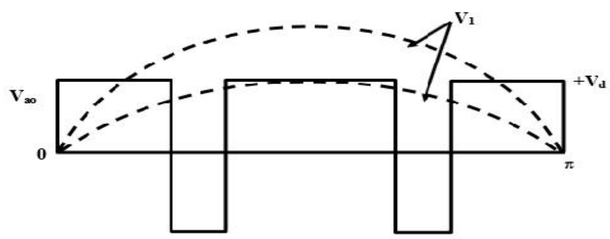
The square wave inverter control is simple and the switching frequency and consequently, switching losses are low. However, significant energies of the lower order harmonics and large distortions in current wave require bulky low-pass filters. Moreover, this scheme can only achieve frequency control. 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 ($4Vd/\pi$) 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 isosceles 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

$V_{a0} = 0.5mV_d \sin(2 Лft+\pi\varphi)$+ harmonic frequency terms

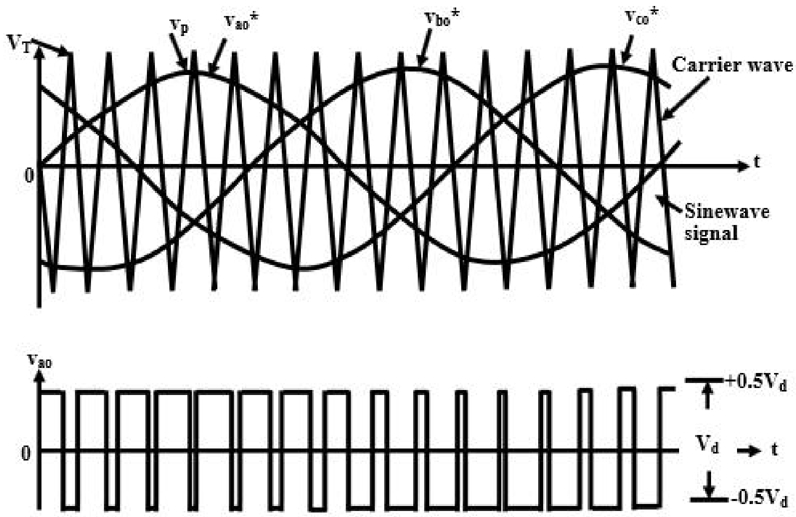
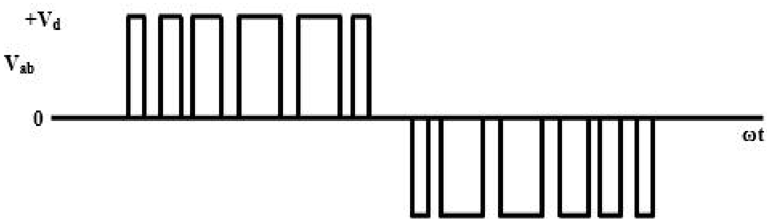


Fig. 34.13(a) Principle of sinusoidal PWM for three-phase bridge inverter.



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.

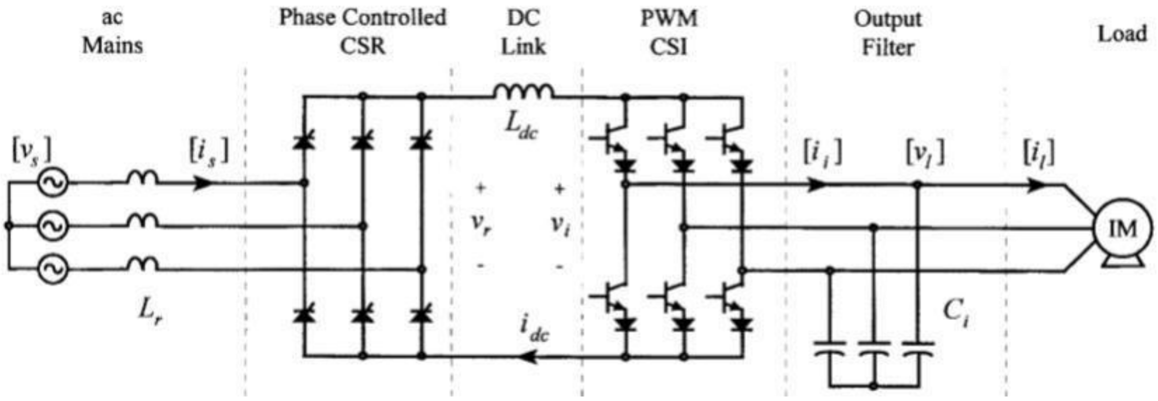
A. Phase-Controlled Front-End Rectifiers

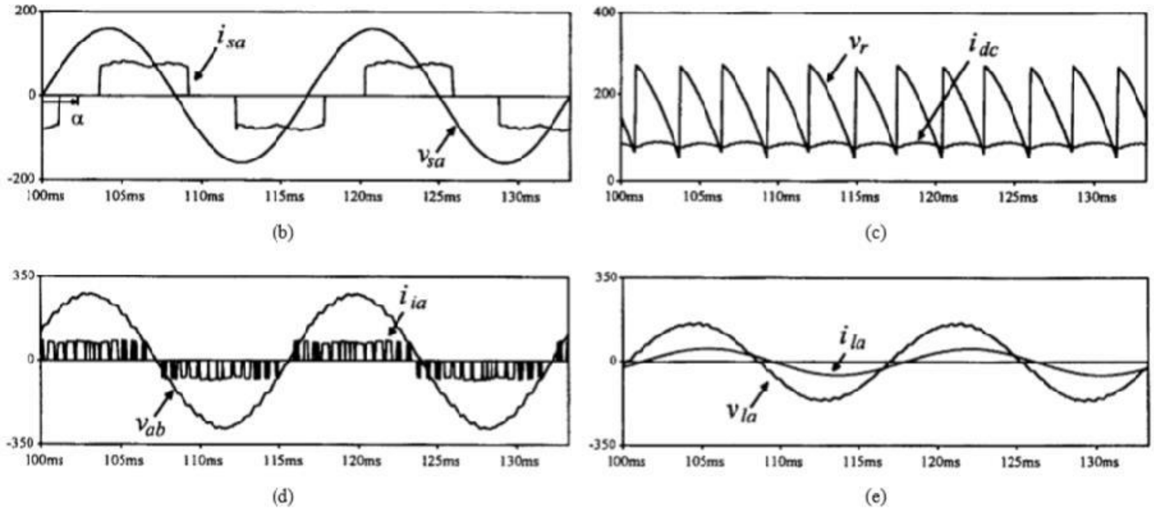
These drives use a front-end rectifier based on thyristor-type power switches (Fig. 1), which can be operated with either variable or fixed dc-link current. The performance of the drive converter depends on this last feature.

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.





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

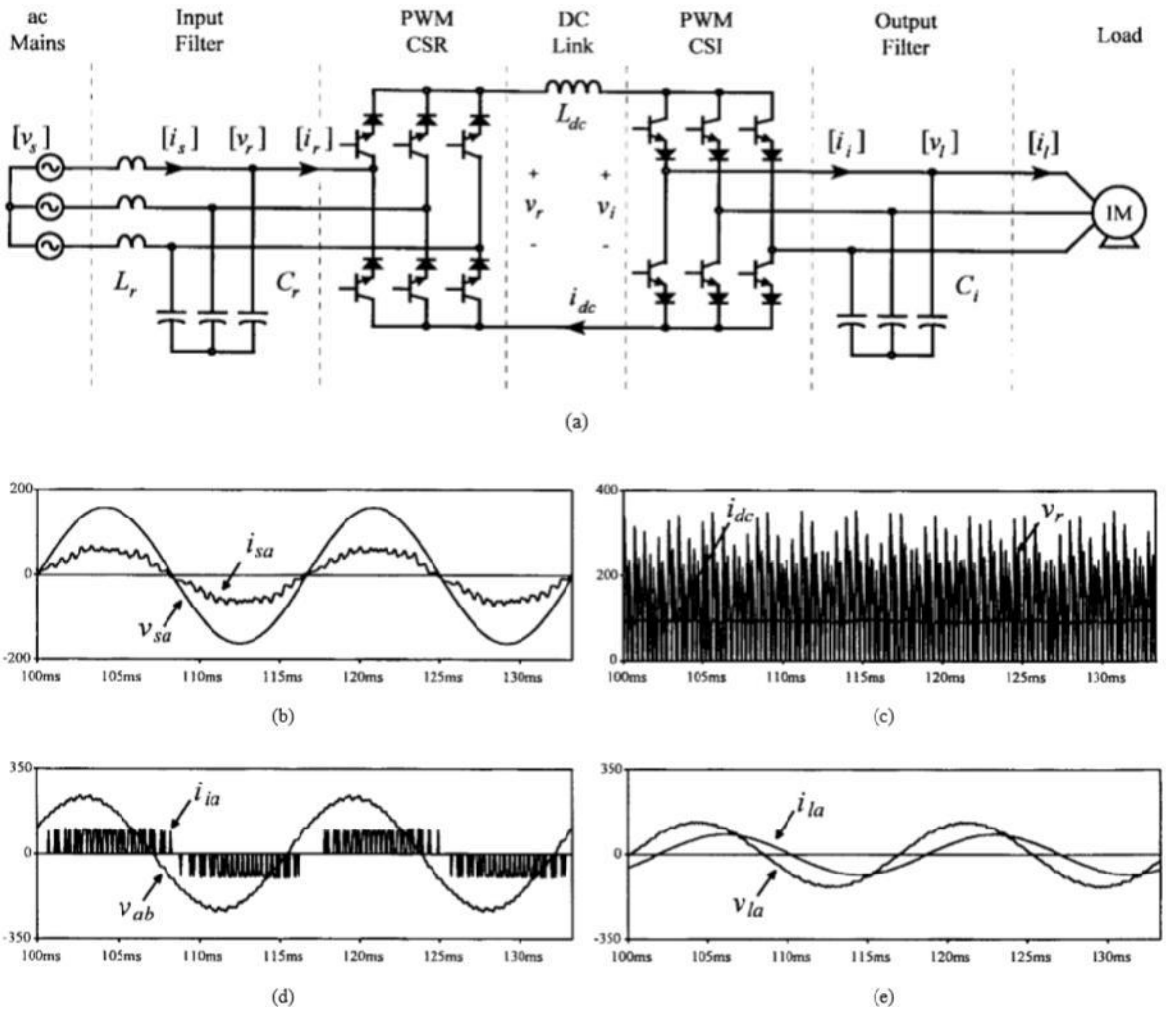
(a) Power topology. (b) Supply phase voltage and supply line current. (c) DC rectifier voltage and dc-link current. (d) CSI line current and load line voltage. (e) Load phase voltage and load line current.

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

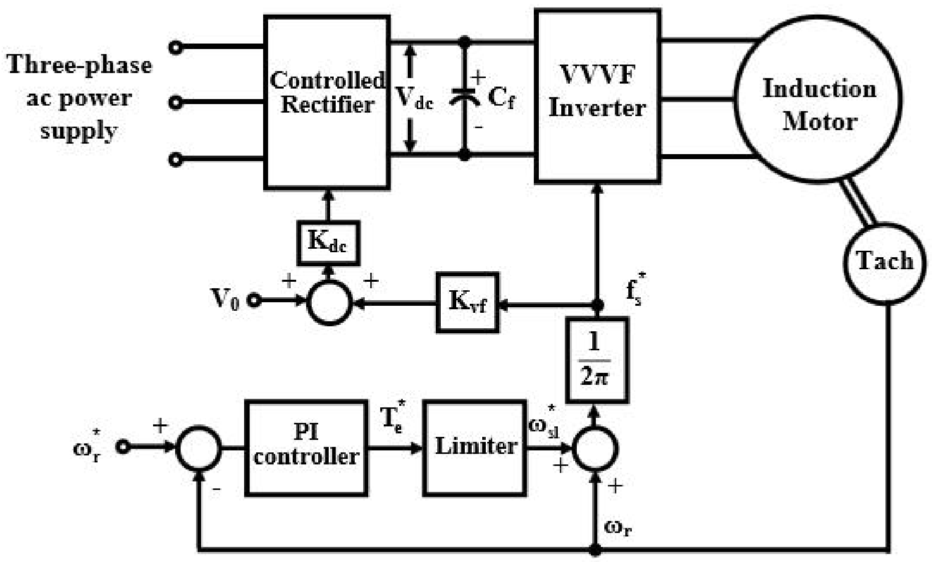
Unlike phase-controlled rectifier topologies, this topology uses a PWM rectifier. This allows a reduction in the harmonics injected into the ac supply. The rectifier is operated with a fixed dc-link current. Fig. 2 shows typical waveforms of the converter. The PWM pattern is adjusted on a continuous 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.



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.

Closed-loop control of induction motor



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

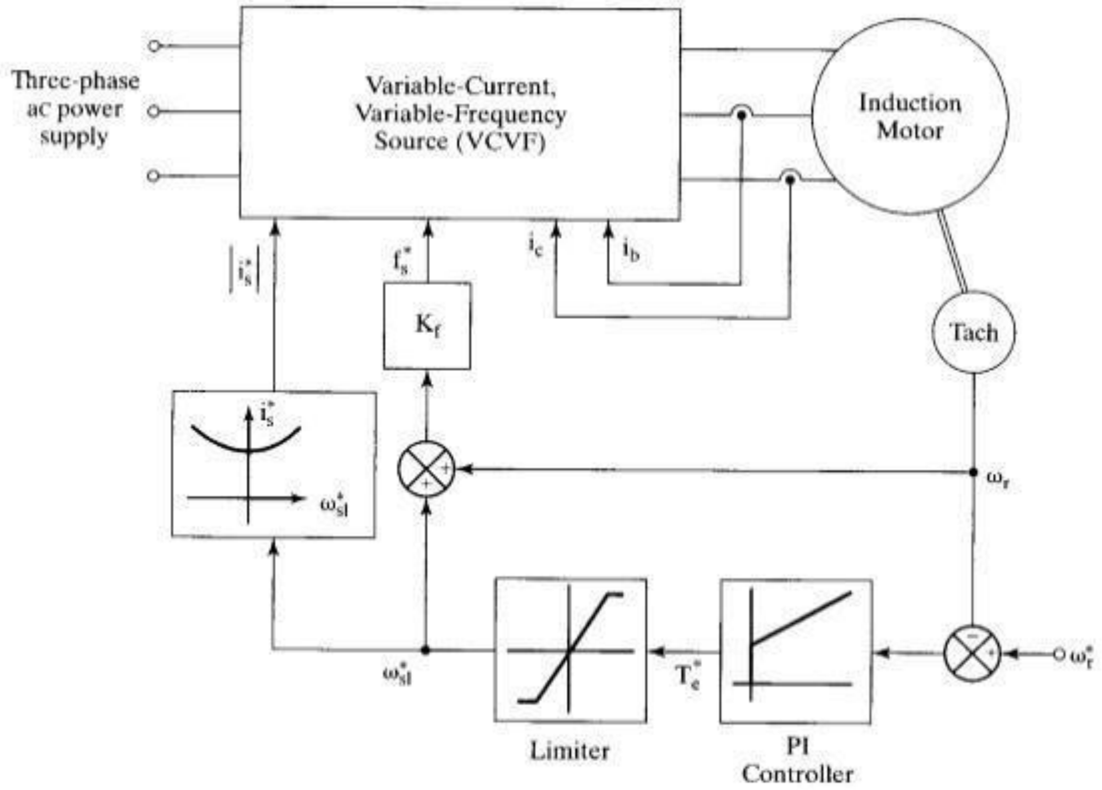
An outer speed PI control loop in the induction motor drive, shown in Figure computes the frequency and voltage set points for the inverter and the converter respectively. The limiter ensures that the slip-speed command is within the maximum allowable slip speed of the induction motor. The slip- speed 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.

<u>**Constant air gap flux control:**</u>

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

Slip power recovery schemes

Slip power recovery schemes are of two types

1. Static krammer drive

2. Static scherbius drive

Static Kramer Drive.

A static kramer drive is a method to obtain an injected voltage that is in phase with the rotor current. The schematic circuit for a static kramer drive is shown below

The voltage at the slip rings is forced to be in phase with the rotor currents by the diode rectifier. The magnitude of the slip ring voltage is set by the DC link voltage, which is in turn set by the inverter connected back to the AC supply. In the diagram above and the analysis presented, the inverter used is a thyristor converter. However, a PWM inverter can also be used.

Simple Analysis

This simple analysis of the static kramer drive illustrates the operation of the drive. It neglects the voltage drops in the drive and any possible commutation overlap in the diode rectifier.

The voltage at the input to the diode rectifier is given by

$$V_{LLiR} = \sqrt{3}\,\frac{V_i}{a_{eff}}$$

and the dc link voltage can be found from the diode input line-line voltage as

$$V_{DC} = \frac{3\sqrt{2}}{\pi} V_{LLiR}$$

Considering the thyristor converter, this circuit can be thought of as a thyristor rectifier connected in reverse, and the DC link voltage is related to the line-line inverter voltage as

$$V_{DC} = -\frac{3\sqrt{2}}{\pi} V_{LLinv} \cos\alpha = \frac{3\sqrt{2}}{\pi} V_{LLinv} \left|\cos\alpha\right|$$

Substituting the above expressions, the voltage injected into the rotor can be calculated as

$$V_i = \frac{a_{eff}}{\sqrt{3}} V_{LLinv} \left|\cos\alpha\right|$$

In the case that the inverter line-line voltage is connected to the supply through a transformer, as shown in the diagram above, the injected voltage can be related to the supply voltage as

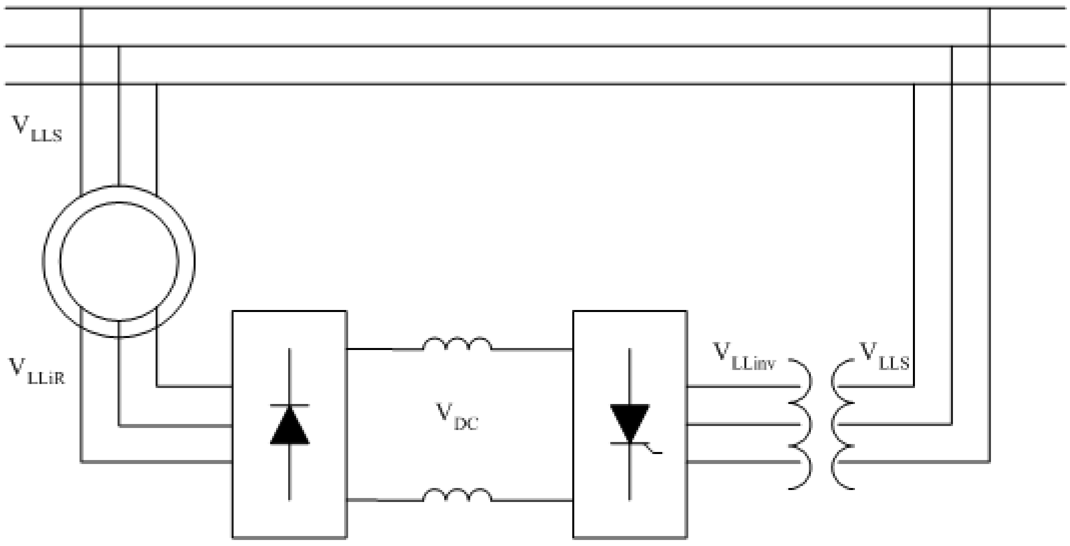
$$V_i = \frac{a_{eff}}{\sqrt{3}} \frac{N_{inv}}{N_{Line}} V_{LLS} \left|\cos\alpha\right|$$

Using this simplified analysis together with the slip energy recovery torque equations, the thyristor firing angle required for a particular torque at a particular speed can be found. If necessary, more detailed analysis can be carried out by repeating the above process, but including device voltages and commutation overlap.

Torque-Speed

Because the slip ring voltage is derived using a diode bridge, the torque speed curve for a motor operated using a static kramer drive does not produce a negative torque as soon as the speed exceeds the no-load speed. If the slip is too low for a given injected voltage, the voltage induced in the rotor circuit by the stator will have a lower magnitude than the DC link voltage. As a result, no rotor current will flow and the torque will be zero.

Static Scherbius drive.



Static scherbius drives are capable of bi-directional power flow, with both positive and negative injected voltages possible, in phase with or opposing the rotor current. As a result, a wider set of operating conditions is possible. Considering the torque equation for slip energy recovery:

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

when motoring, torque is positive, when generating torque is negative.

Operating Modes

Sub-synchronous motoring

In this mode, operation is similar to that obtained with a static kramer drive. Slip and torque are both positive, therefore injected voltage must be in phase with rotor current. Power flows into the stator and back out of the rotor circuit.

Super-synchronous motoring

Above synchronous speed, the slip is negative. In order for the torque to be positive,

$$I_r^2 R_r + I_r V_i$$

must be negative. Therefore, voltage and current must be out of phase with each other. Power is being injected into the rotor from the drive circuit connected to the slip rings, in addition to input power flowing into the stator

Sub-synchronous generating

If generation below synchronous speed is required, torque must be negative whilst slip is positive. Again,

$$I_r^2 R_r + I_r V_i$$

must be negative. Power is being injected into the rotor from the slip rings.

Super-synchronous generating

If generating above synchronous speed, slip and torque are both negative, therefore

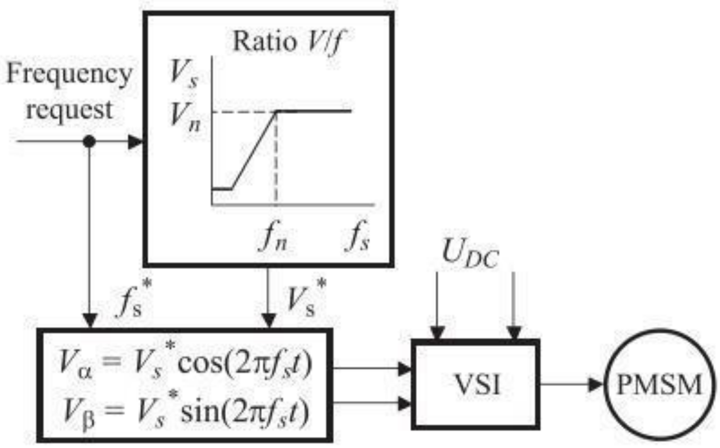
$$I_r^2 R_r + I_r V_i$$

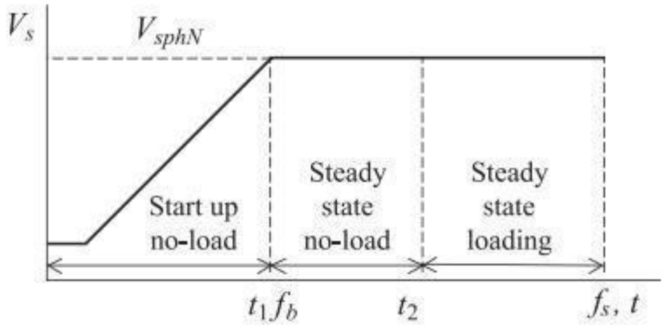
is positive and injected voltage is in phase with rotor current. In this case, mechanical input power is being supplied from the shaft and both the stator and rotor circuits are providing output power.

UNIT V

CONTROL OF SYNCHRONOUS MOTORS

V/F control of permanent magnets 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 ω_S is proportional to the frequency f_S 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 R_S is not negligible, is given

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

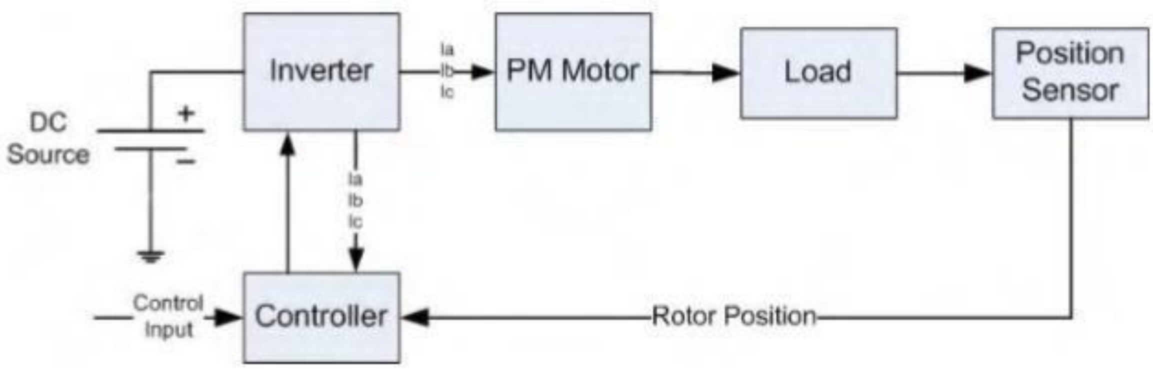
$$T_m = \frac{3p}{2\pi f_s}\frac{V_{sph}E_{PM}}{2\pi f_s L_d} = \frac{3p}{2\pi f_s}\frac{V_{sph}2\pi f_s \Psi_{PM}}{2\pi f_s L_d} .$$

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

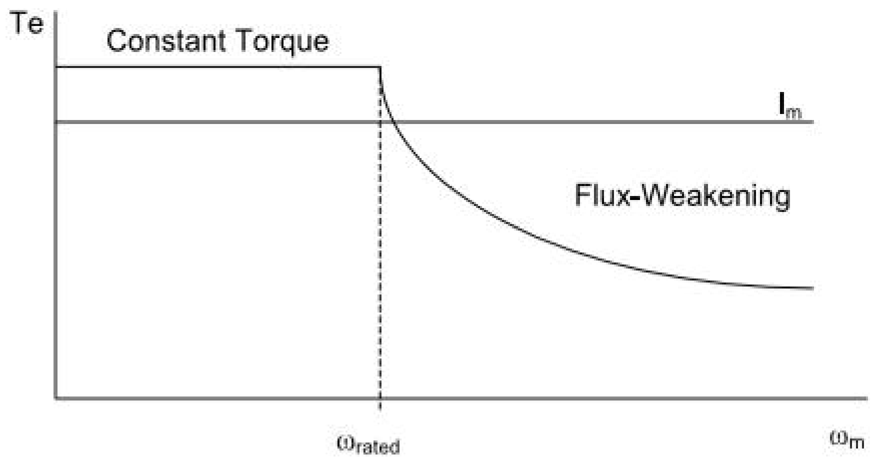
$$\frac{V_{sph}}{f_s} = \text{const.}$$

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:

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

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

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

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

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*

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

1) Calculate Id* using equation:

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

2) Calculate α using equation

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

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

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

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

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.

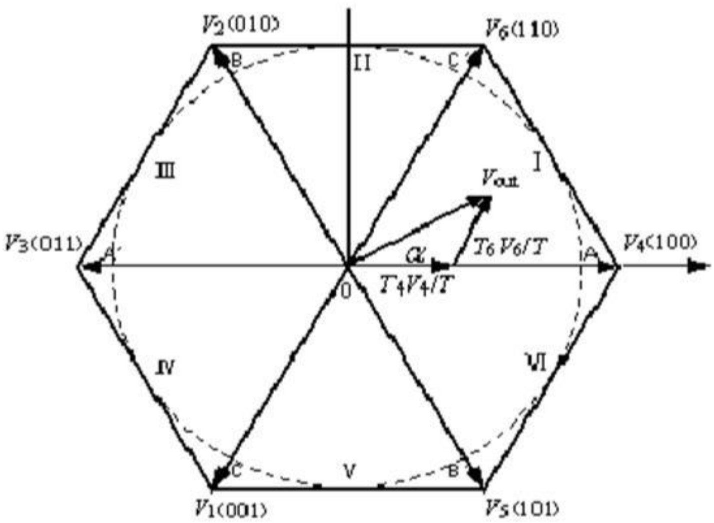
5. The current error signals are used in controllers to generate reference voltages for the inverter.

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.

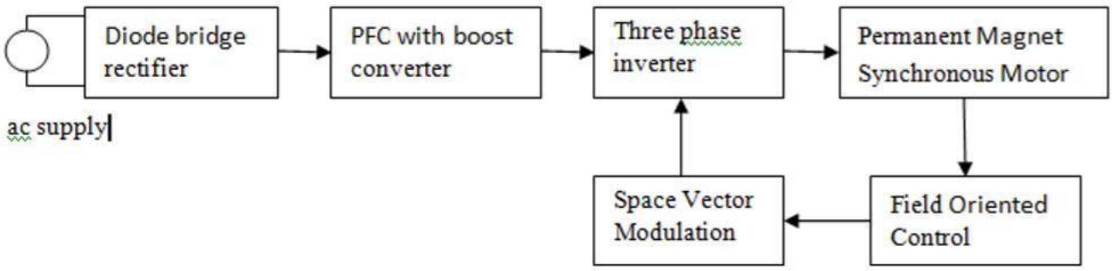
The basis of SVPWM is different from that of sine pulse width modulation (SPWM). SPWM aims to achieve symmetrical 3-phase sine voltage waveforms of adjustable voltage and frequency, while SVPWM takes the inverter and motor as a whole, using the eight fundamental voltage vectors to realize variable frequency 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.



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

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

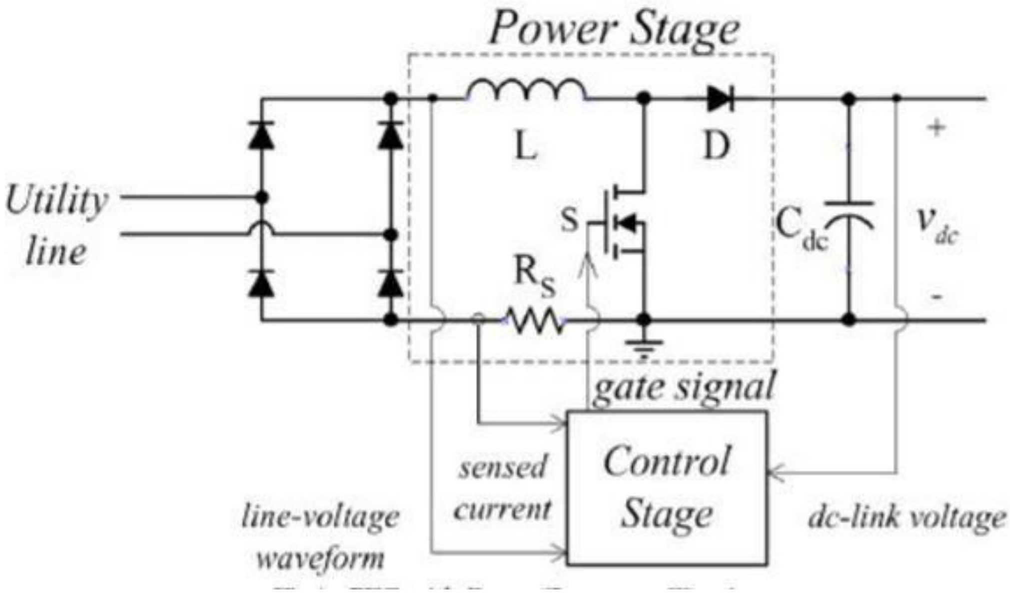
PMSM Drive with Active Power Factor Correction (Apfc):



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 aregiven 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.

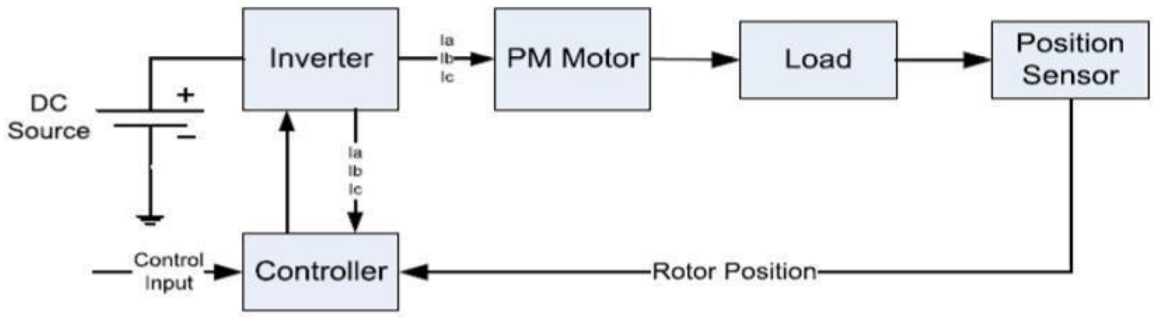
The boost converter is the widely used topology for achieving power factor correction. This converter draws nearly unity power factor current from the AC mains and eliminates a harmonic current which regulates the DC link voltage even under fluctuating voltage conditions of AC mains.

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.

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.

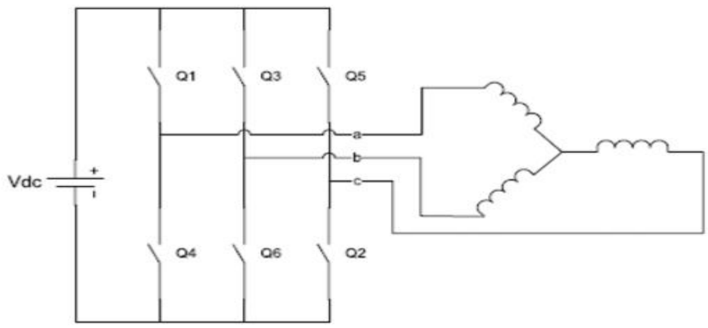


There are four basic component

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

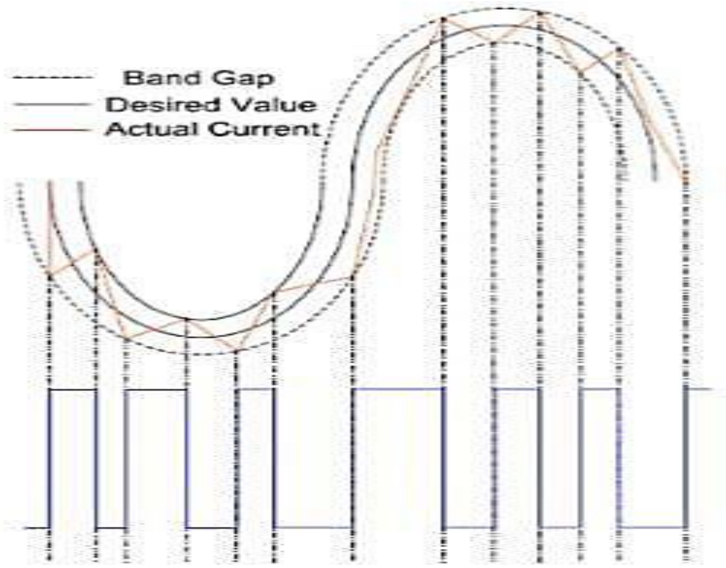
A permanent magnet synchronous motor (PMSM) is a motor that uses permanent magnets to produce the air gap magnetic field rather than using electromagnets. These motors have significant advantages, attracting the interest of researchers and industry for use in many applications. The properties of the 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.



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.