1.1 Introduction Electrical Drives:

Nowadays, modern power electronics and drives are used in electrical as well as mechanical industry. The power converter or power modulator circuits are used with electrical motor drives, providing either DC or AC outputs, and working from either a DC (battery) supply or from the conventional AC supply. Here we will highlight the most important aspects which are common to all types of drive converters. Although there are many different types of converters, all except very low-power ones are based on some form of electronic switching. The need to adopt a switching strategy is emphasized in the Wrist example, where the consequences are explored in some depth. We will see that switching is essential in order to achieve high-efficiency power conversion, but that the resulting waveforms are inevitably less than ideal from the point of view of the motor.

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.

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.

1.2 Equations governing motor load dynamics:

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.

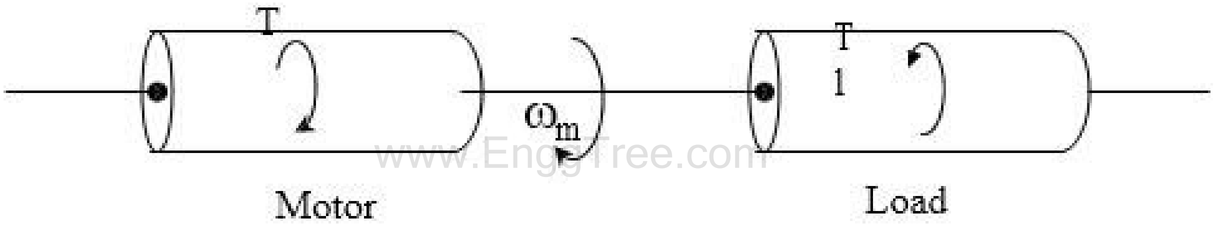


Figure 1.2.1 Motor Load System

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-11)

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

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

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

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

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

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

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

For drives with constant inertia

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

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

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)

Eg:

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

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

Eg:

- ✓ Torque due to friction, cutting etc.

Components of Load Torques:

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

- ✓ Friction Torque (TF):

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

- ✓ Windage Torque (TW)

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

- ✓ Torque required to do useful mechanical work

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

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

Friction torque can also be resolved into three components

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

$$T_V = B\ _m$$

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.

1.3 Steady State Stability:

Equilibrium speed of motor-load system can be obtained when motor torque equals the load torque. Electric drive system will operate in steady state at this speed, provided it is the speed of stable state equilibrium.

Concept of steady state stability has been developed to readily evaluate the stability of an equilibrium point from the steady state speed torque curves of the motor and load system. In most of the electrical drives, the electrical time constant of the motor is negligible compared with the mechanical time constant. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation. Now, consider the steady state equilibrium point A shown in figure below

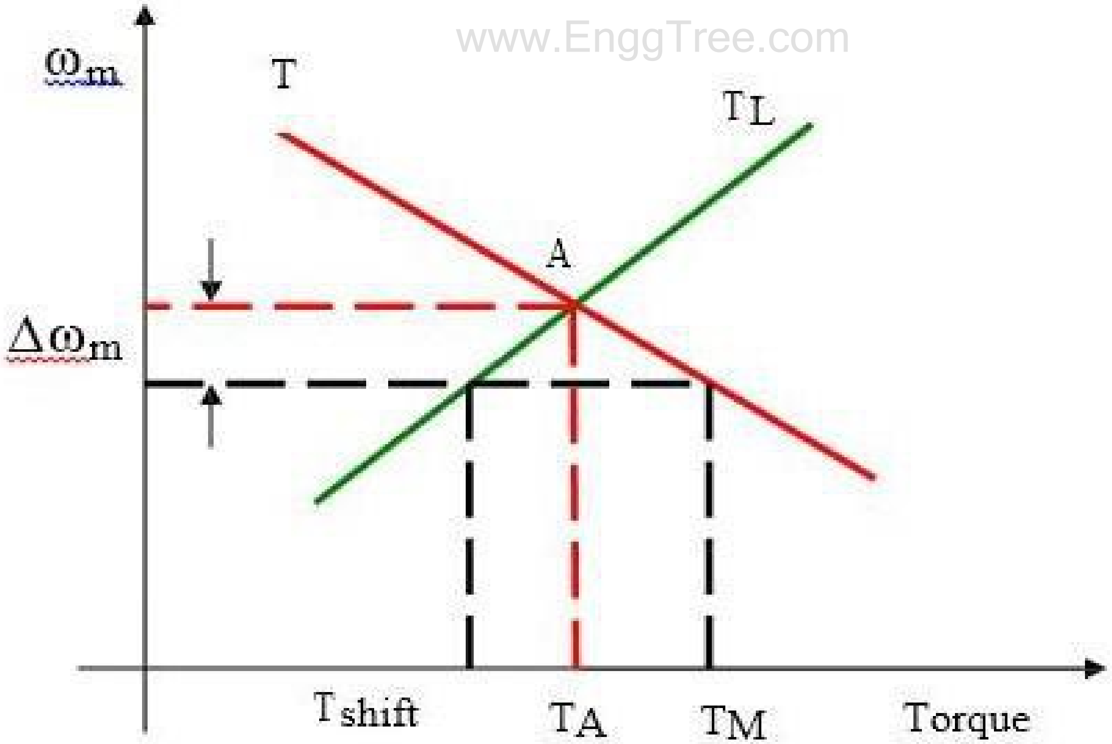


Figure 1.3.1 Steady state stability

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-23)

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

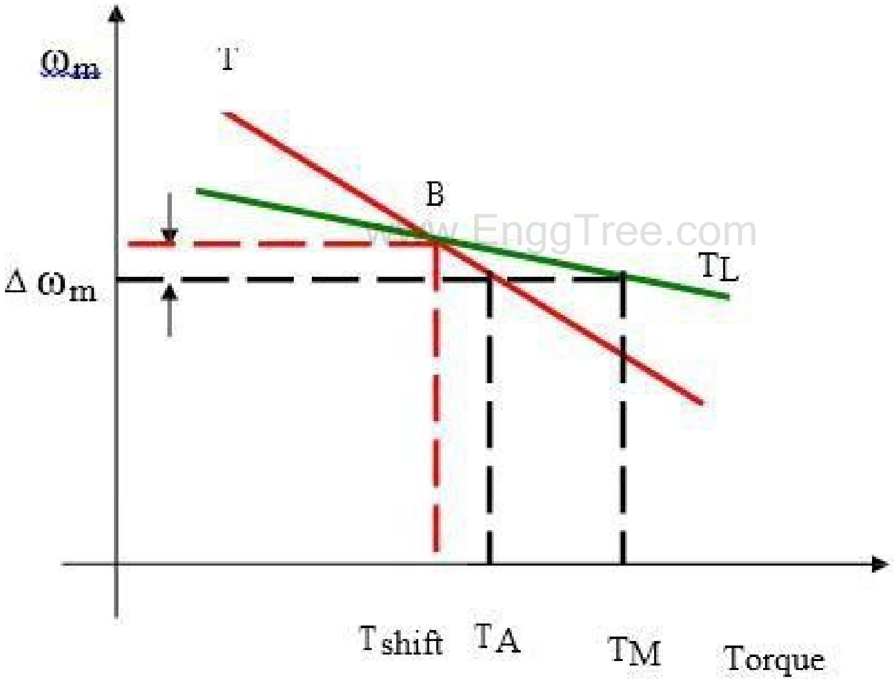


Figure 1.3.1 Steady state equilibrium point

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-23)

1.4 Multi quadrant Dynamics:

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 below 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.

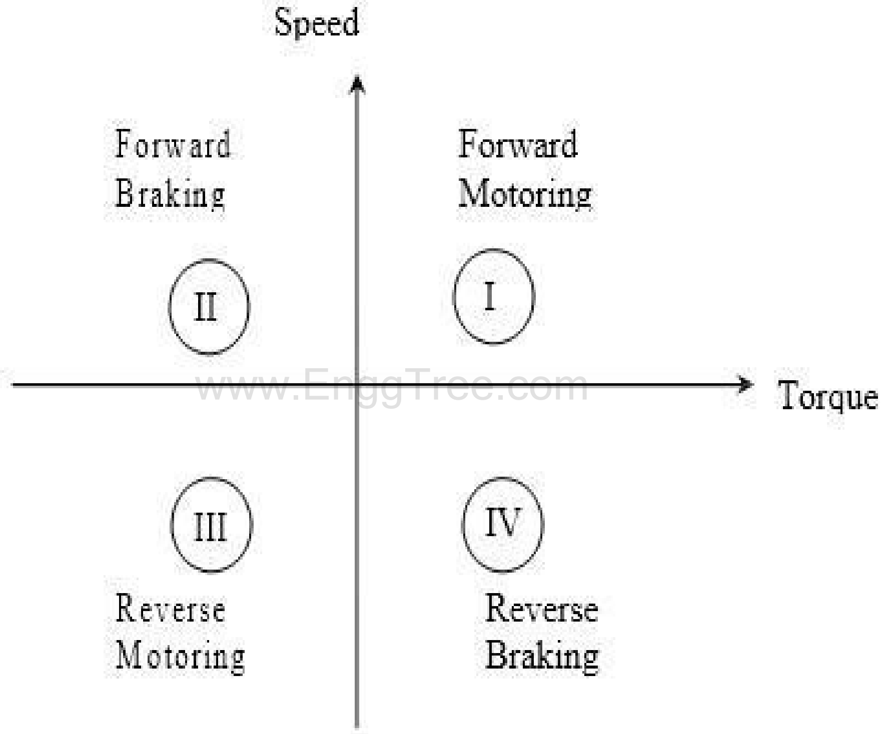


Figure 1.4.1 Four quadrant operation of drives

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-12)

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.

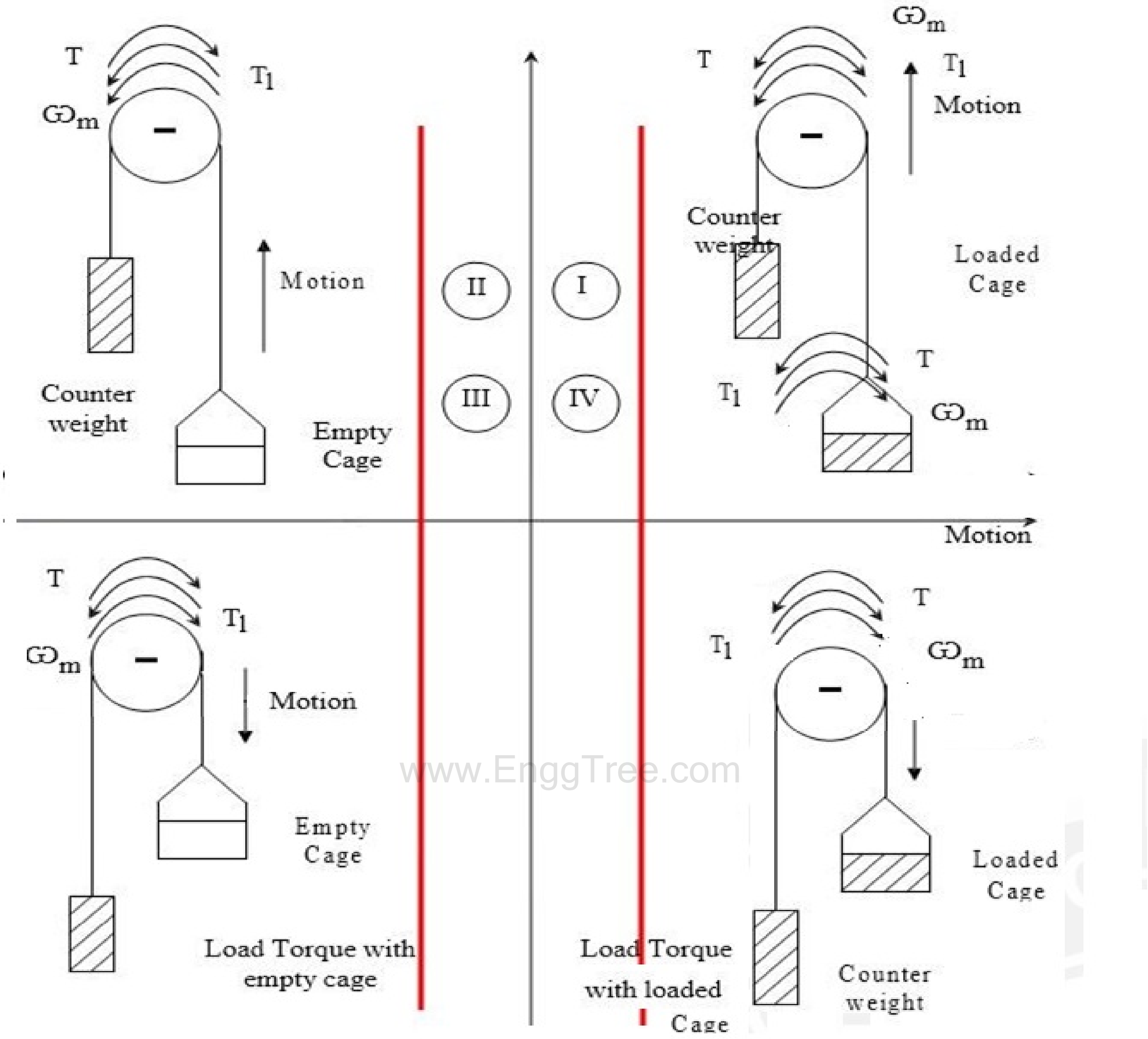


Figure 1.4.2 Operation of hoist in four quadrants

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-13)

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

Forward direction of motor speed will be one which gives upward motion of the cage. Load torque line in quadrants I and IV represents speed-torque characteristics of the loaded hoist. This torque is the difference of torques due to loaded hoist and counter weight. The load torque in quadrants II and III is the speed-torque characteristics for an empty hoist.

This torque is the difference of torques due to counter weight and the empty hoist. Its sigh is negative because the counter weight is always higher than that of an empty cage. The quadrant I operation of a hoist requires movement of cage upward, which corresponds to the positive motor speed which is in counter clockwise direction here. This motion will be obtained if the motor products positive torque in CCW direction equal to the magnitude of load torque T_{L1}.

Since developed power is positive, this is forward motoring operation. Quadrant IV is obtained when a loaded cage is lowered. Since the weight of the loaded cage is higher than that of the counter weight
.It is able to overcome due to gravity itself.

In order to limit the cage within a safe value, motor must produce a positive torque T equal to T_{L2} in anticlockwise direction. As both power and speed are negative, drive is operating in reverse braking operation. Operation in quadrant II is obtained when an empty cage is moved up. Since a counter weigh is heavier than an empty cage, its able to pull it up.

In order to limit the speed within a safe value, motor must produce a braking torque equal to T_{L2} in clockwise direction. Since speed is positive and developed power is negative, it's forward braking operation.

Operation in quadrant III is obtained when an empty cage is lowered. Since an empty cage has a lesser weight than a counter weight, the motor should produce a torque in CW direction. Since speed is negative and developed power is positive, this is reverse motoring operation. During transient condition, electrical motor can be assumed to be in electrical equilibrium implying that steady state speed torque curves are also applicable to the transient state operation.

1.5 Acceleration, deceleration, starting & stopping:

An electrical drive operates in three modes

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

We know that

$$T = T_1 + J \frac{d}{dt}(\omega_m)$$

According to the above expression the steady state operation takes place when motor torque equals the load torque. The steady state operation for a given speed is realized by adjustment of steady state motor speed torque curve such that the motor and load torques are equal at this speed. Change in speed is achieved by varying the steady state motor speed torque curve so that motor torque equals the load torque at the new desired speed. In the figure shown below when the motor parameters are adjusted to provide speed torque curve 1, drive runs at the desired speed ω_m.

Speed is changed to $\omega_{m\,2}$ when the motor parameters are adjusted to provide speed torque curve

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.

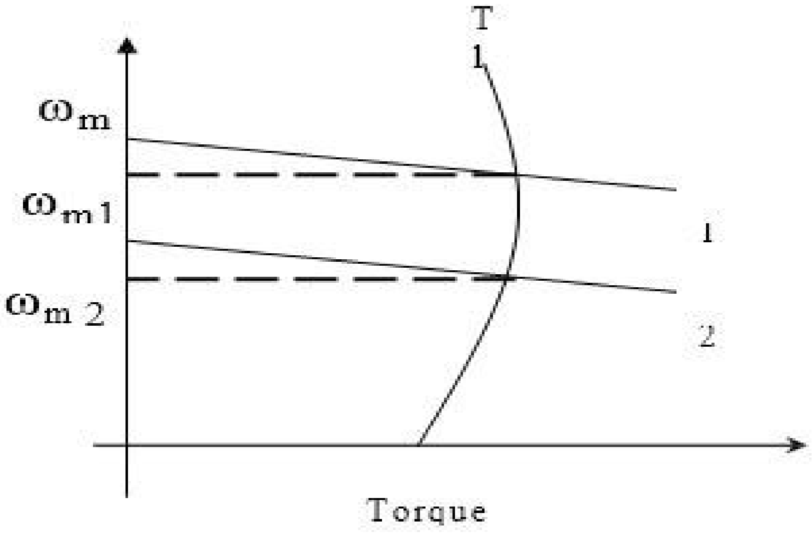


Figure 1.2.1 Speed Torque principle

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-32)

Acceleration and Deceleration modes are transient modes. Drive operates in acceleration mode whenever an increase in its speed is required. For this motor speed torque curve must be changed so that motor torque exceeds the load torque. Time taken for a given change in speed depends on inertia of motor load system and the amount by which motor torque exceeds the load torque.

Increase in motor torque is accompanied by an increase in motor current. Care must be taken to restrict the motor current with in a value which is safe for both motor and power modulator. In applications involving acceleration periods of long duration, current must not be allowed to exceed the rated value.

When acceleration periods are of short duration a current higher than the rated value is allowed during acceleration.

In closed loop drives requiring fast response, motor current may be intentionally forced to the maximum value in order to achieve high acceleration. Figure shown below shows the transition from operating point A at speed.

Point B at a higher speed $\omega_{m\,2}$, when the motor torque is held constant during acceleration. The path consists of AD1E1B. In the figure below, 1 to 5 are motor speed torque curves. Starting is a special case of acceleration where a speed change from 0 to a desired speed takes place. All points mentioned in relation to acceleration are applicable to starting.

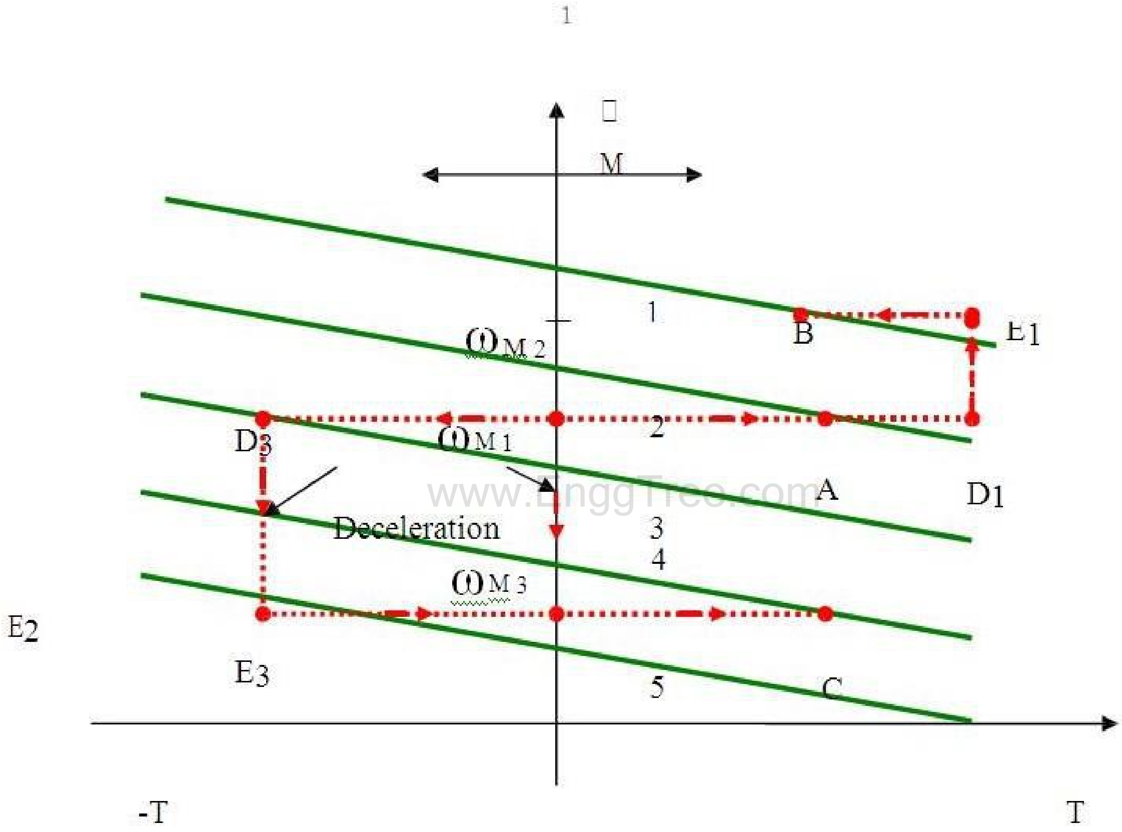


Figure 1.5.2Acceleration and Deceleration of motor

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-33)

The maximum current allowed should not only be safe for motor and power modulator but drop in source voltage caused due to it should also be in acceptable limits. In some applications the motor should accelerate smoothly, without any jerk. This is achieved when the starting torque can be increased stepless from its zero value. Such a start is known as soft start.

2.1 Steady state analysis of single phase converter fed separately excited DC motor drive:

INTRODUCTION

Direct-current motors are extensively used in variable-speed drives and position-control systems where good dynamic response and steady-state performance are required. Examples are in robotic drives, printers, machine tools, process rolling mills, paper and textile industries, and many others. Control of a dc motor, especially of the separately excited type, is very straightforward, mainly because of the incorporation of the commutator within the motor. The commutator brush allows the motor-developed torque to be proportional to the armature current if the field current is held constant. Classical control theories are then easily applied to the design of the torque and other control loops of a drive system.

DCMOTORS AND ITS CHARACTERISTICS

When a DC supply is applied to the armature of the dc motor with its field excited by a dc supply, torque is developed in the armature due to interaction between the axial current carrying conductors on the rotor and the radial magnetic flux produced by the stator. If the voltage V is the voltage applied to the armature terminals, and E is the internally developed motional e.m.f. The resistance and inductance of the complete armature are represented by R_a and L_a in Figure 2.1(a). Under motoring conditions, the motional e.m.f. E always opposes the applied voltage V, and for this reason it is referred to as 'back e.m.f.' For current to be forced into the motor, V must be greater than E, thearmature circuit voltage equation being given by

$$V = E \quad I_a R_a L \, \underline{dI} \, \underline{a/} dt$$

SinglePhase rectifierfed separatelyExcited DCmotor drive

The thyristor D.C. drive remains an important speed-controlled industrial drive, especially where the higher maintenance cost associated with the D.C. motor brushes is tolerable. The controlled (thyristor) rectifier provides a low-impedance adjustable 'D.C.' voltage for the motor armature, thereby providing speed control. For motors up to a few kilowatts the armature converter can be supplied from either single-phase or three-phase mains, but for larger motors three-phase is always used. A separate thyristor or diode rectifier is used to supply the field of the motor: the power is much less than the armature power, so the supply is often single-phase. Figure 2.9 shows the setup for single phase controlled rectifier fed separately excited dc motor drive. Field circuit is also excited by a dc source, which is not shown in the figure just for simplicity.

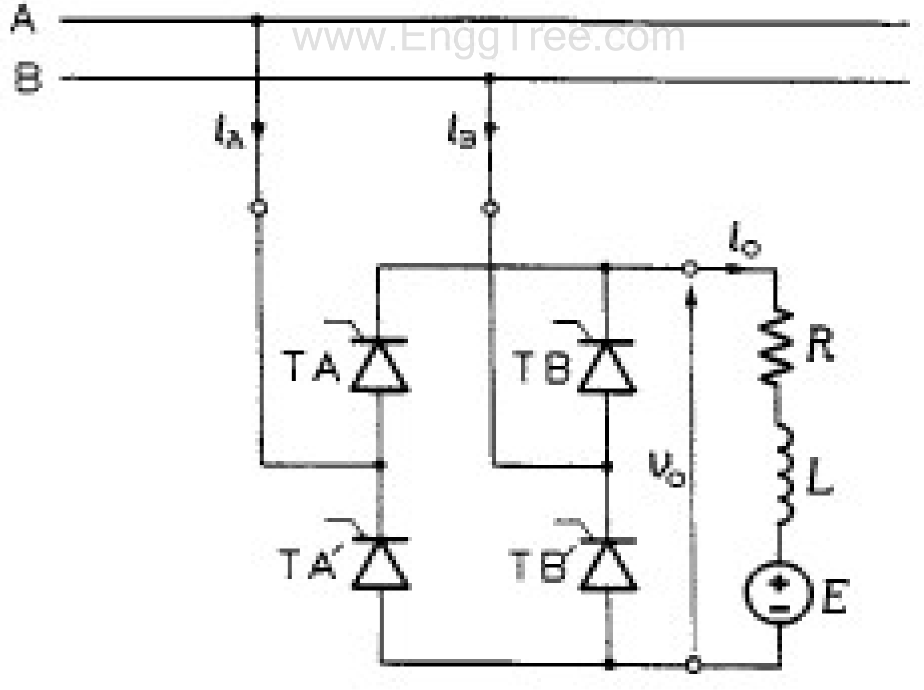


Figure 2.1.1 SinglePhase rectifierfed DCmotor drive

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-108)

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

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

Basic Equation I

The armature circuit of the de motor is represented by its back voltage e_g, armature resistance Ra, and armature inductance La as showninFig.

Back voltage:

$$e_g = K_a \Phi n$$

Average Back Voltage

$$E_g = K_a \Phi N$$

The armature circuit voltage equation is

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

Interms of average values,

$$E_a = R_a I_a + E_g$$

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.

2.2 Steady state analysis of three phase converter fed separately excited DC motor drive:

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

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

Three phase drives are used for high power applications up to megawatts power level. The ripple frequency of armature voltage is greater than that of the single phase drives and its requires less inductance in the armature circuit to reduce the armature current ripple.Three phase full converter are used in industrial application up to 1500KW drives. It is a two quadrant converter.

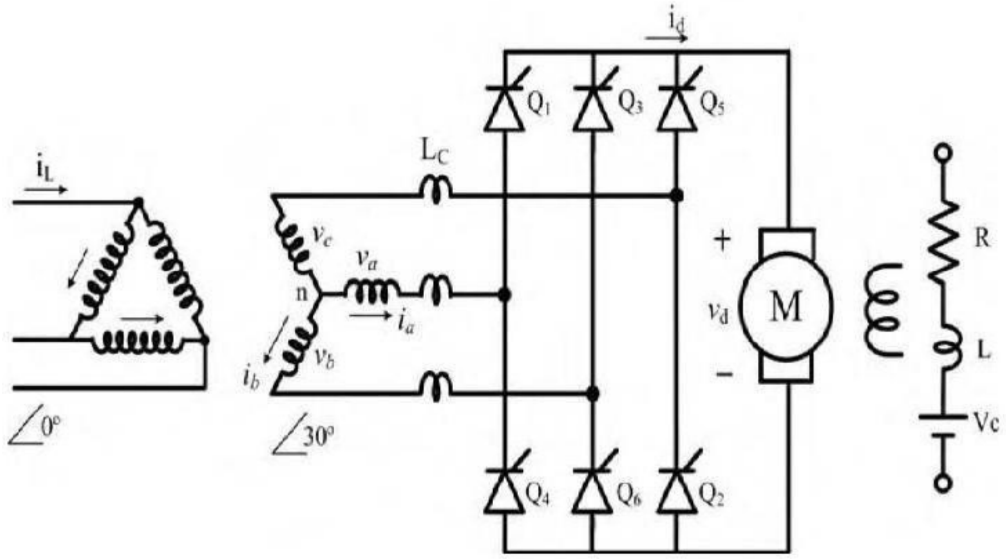


Figure 2.2.1 Three Phase rectifierfed DCmotor drive

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-111)

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 fedDC motor is performed where generation of power is required.

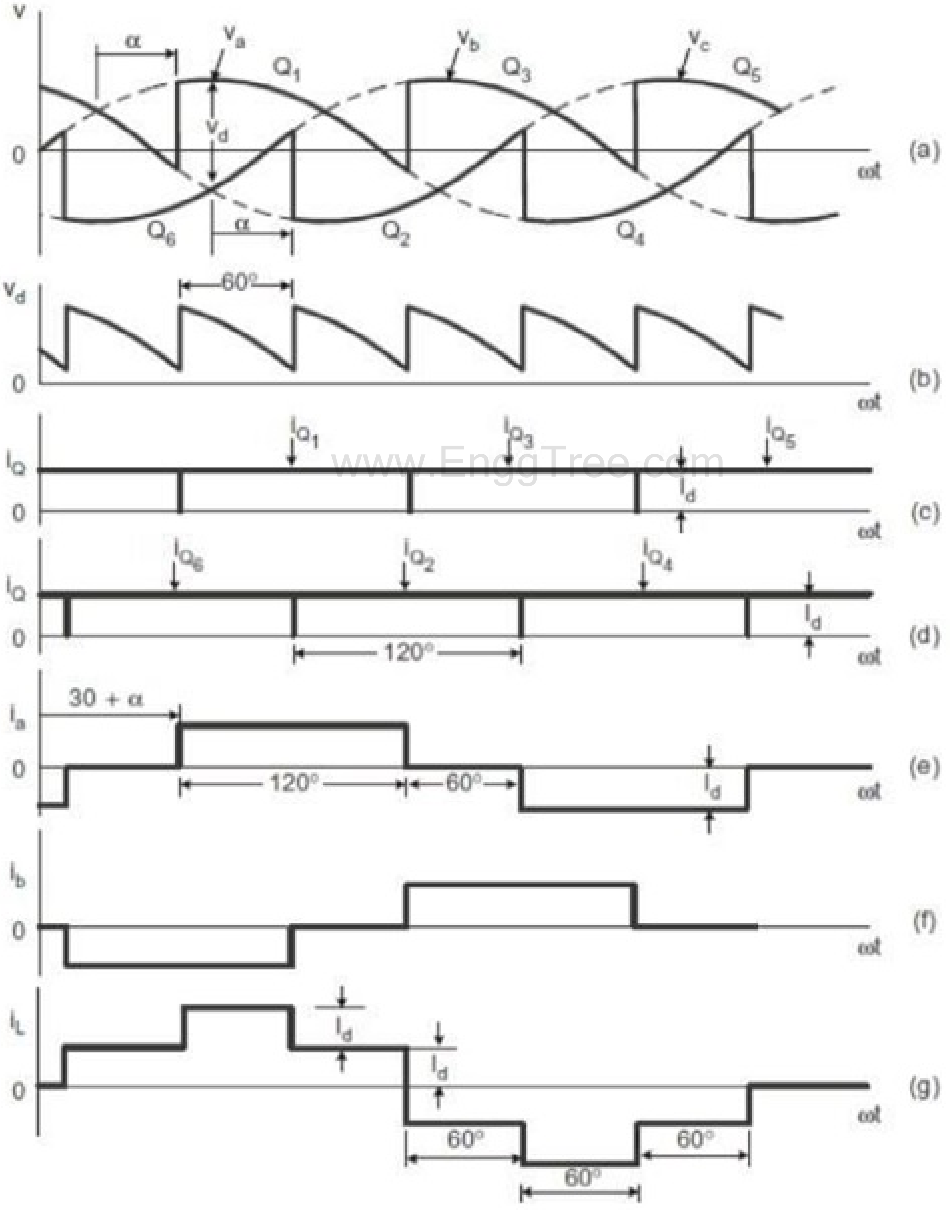


Figure 2.2.2 Three Phase rectifierwaveforms

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-111)

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

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

2.3 Continuous conduction

Let us assume that the armature current is continuous over the whole range of operation. Typical voltage and current waveforms are shown in Fig for semi-converter and full-converter systems, respectively. The thyristors are symmetrically triggered. In the semi-converter system shown in Fig. 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. thyristors S,and S3 are simultaneously triggered at a, thyristors S2 and S4 are triggered at 7T +a.

In Fig. the motor is connected to the input supply for the period a<wt<7T through Sl and D_2, and the motor terminal voltage e_a is the same as the supply input voltage v. Beyond 7T, e_a tends to reverse as the input voltage changes polarity. This will forward-bias the free-wheeling diode and D_{FW} will start conducting. The motor current i_a, which was flowing from the supply through Sl' is transferred to D_{FW} (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.

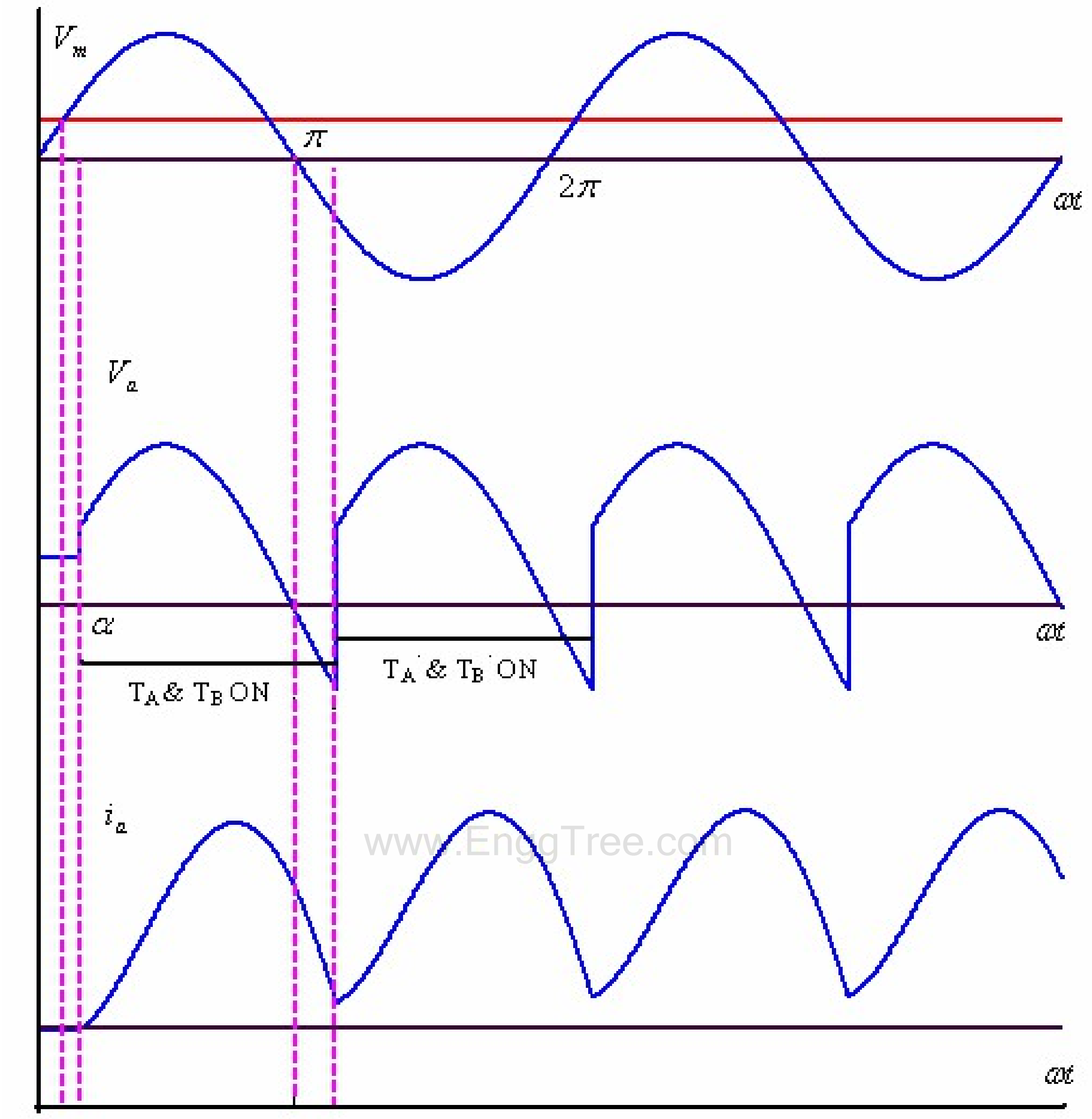


Figure 2.3.1 Continuous conduction waveform

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-108)

In Fig. the motor is always connected to the input supply through the thyristors. Thyristors Sl and S3conduct during the interval a<wt <(7T +a) and connect the motor to the supply. At 7T +a, thyristors S2 and S4aretriggered.Immediately the supply voltage appears across the thyristors Sl and S3asareverse- bias voltage and turns them off. This is called natural or line commutation. The motor current i_a, 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 are positive, and eo and io are positive, signifying positive power flow). However, during 7T to 7T +a, some of the motor system energy is feedback to the input supply(v and I have opposite polarities and likewise e_a and i_o' signifying reverse power flow).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.

2.4 Time-ratio Control

In the time ratio control the value of the duty ratio, D is varied. There are two ways, which are constant frequency operation, and variable frequency operation.

Constant Frequency Operation

In this control strategy, the ON time, TON is varied, keeping the frequency , or time period (f=1/T) constant. This is also called as pulse width modulation control (PWM). Two cases with duty ratios, as (a) 0.25 (25%), and (b) 0.75 (75%) are shown. Hence, the output voltage can be varied by varying TON.

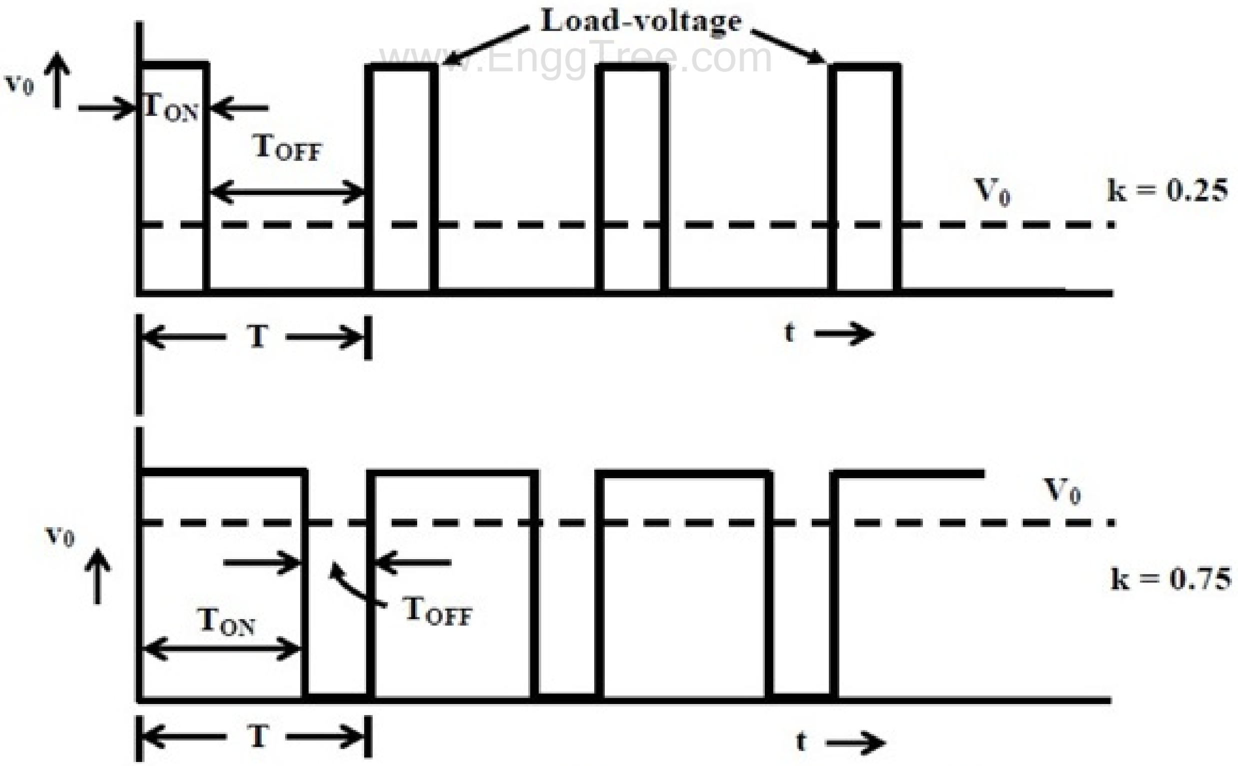
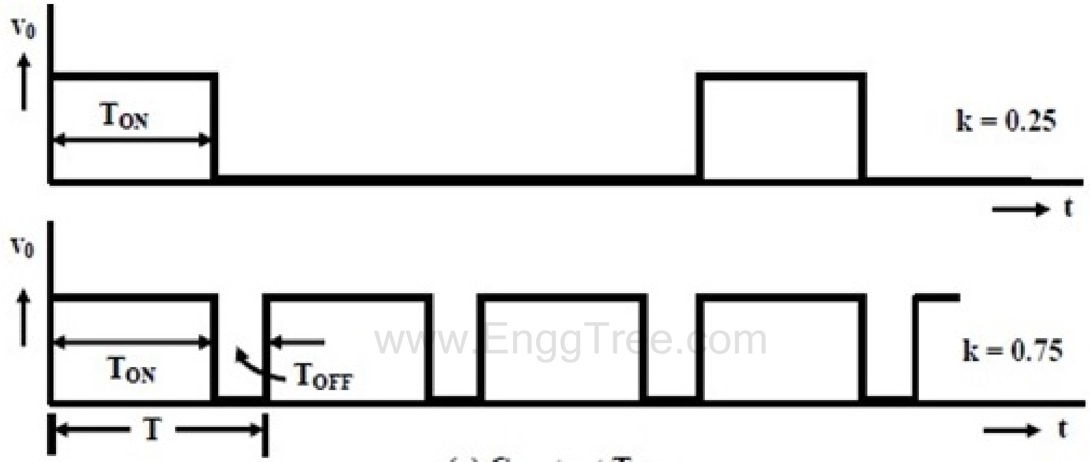


Fig. 2.4.1 : Pulse-width modulation control (constant frequency)

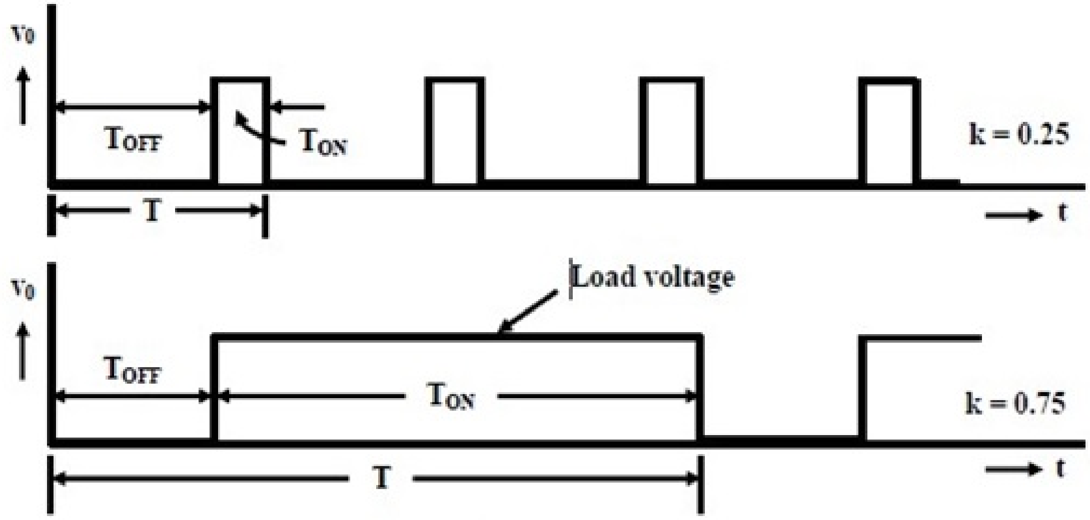
(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-122)

Variable Frequency Operation

In this control strategy, the frequency (f=1/T), or time period *T* is varied, keeping either (a) the ON time, constant, or (b) the OFF time, constant. This is also called as *frequency modulation control*. Two cases with (a) the ON time, constant, and (b) the OFF time, constant, with variable frequency or time period are shown in Fig. The output voltage can be varied in both cases, with the change in duty ratio.



(a) Constant T_{ON}



(b) Constant T_{OFF}

Fig. 2.4.2 : Output voltage waveforms for variable frequency system

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-123)

There are major disadvantages in this control strategy. These are:

(a) The frequency has to be varied over a wide range for the control of output voltage in frequency modulation. Filter design for such wide frequency variation is, therefore, quite difficult.

(b) For the control of a duty ratio, frequency variation would be wide. As such, there is a possibly of interference with systems using certain frequencies, such as signaling and telephone line, in frequency modulation technique.

(c) The large OFF time in frequency modulation technique, may make the load current discontinuous, which is undesirable.

Thus, the constant frequency system using PWM is the preferred scheme for dc-dc converters.

Current Limit Control

As can be observed from the current waveforms for the types of dc-dc converters described earlier, the current changes between the maximum and minimum values, if it (current) is continuous. In the current limit control strategy, the switch in dc-dc converter (chopper) is turned ON and OFF, so that the current is maintained between two (upper and lower) limits.

When the current exceed upper (maximum) limit, the switch is turned OFF. During OFF period, the current freewheels in say, buck converter (dc-dc) through the diode, , and decreases exponentially. When it reaches lower (minimum) limit, the switch is turned ON. This type of control is possible, either with constant frequency, or constant ON time, . This is used only, when the load has energy storage elements, i.e. inductance, L. The reference values are load current or load voltage. This is shown in Fig. In this case, the current is continuous, varying between and , which decides the frequency used for switching. The ripple in the load current can be reduced, if the difference between the upper and lower limits is reduced, thereby making it minimum. This in turn increases the frequency, thereby increasing the switching losses.

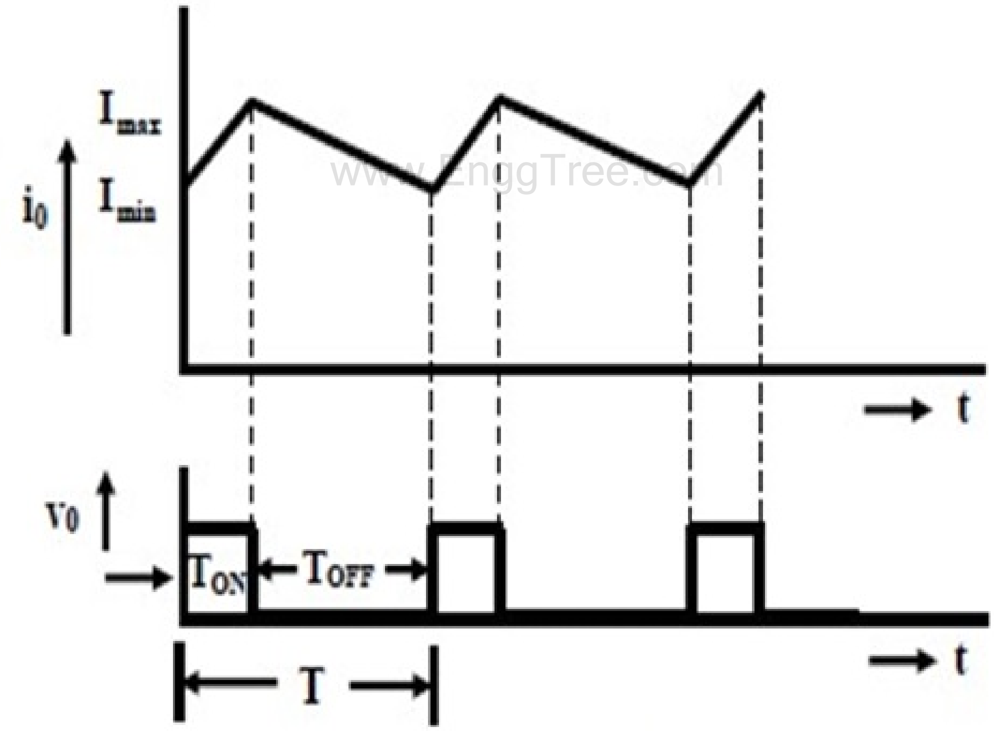


Fig. 2.4.3 : Current limit control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-125)

2.5 Four Quadrant Operation of a Converters:

FirstQuadrant–Forwardmotoringmode

For first quadrant operation, thyristor S4 is kept on, thyristor S3 is kept off and thyristor switch S1 is operated. With S1, S4 ON, armature voltage $V_a = V_s$ and armature control I_a begins flow. Here both V_a and I_a are positive giving first quadrant operation, when S1 is turned off, positive current freewheels through S4, D2. In this manner, V_a, I_a can be controlled in this first quadrant, and operation gives forward motoring mode.

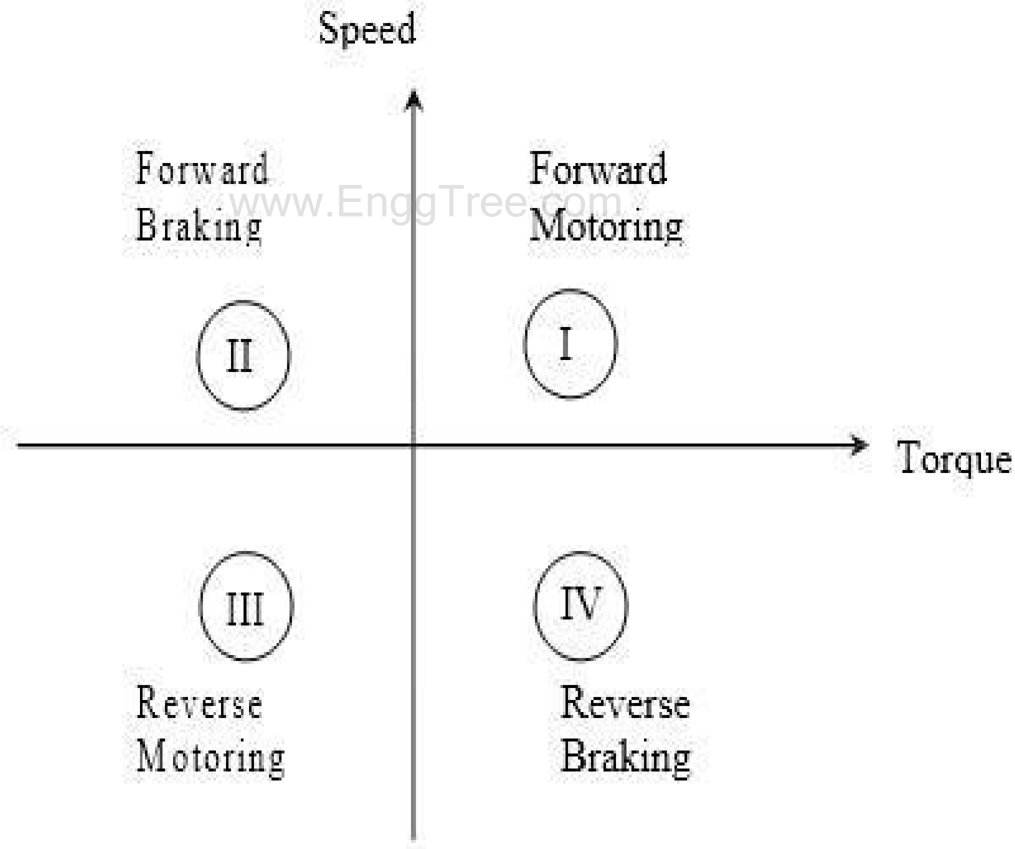


Figure 2.5.1 Four quadrant operation of drives

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-12)

SecondQuadrant–Forwardbrakingmode

Here thyristor S2 is operated and S1 , S3 and S4 are kept off. With S4 on, reverse or negative current flows through L_a, S2, D4 and E_b. During the operation time of S2, the armature inductance 'L_a' stores energy during the time S2 is on. When S2 is turned off, current is fed back to source through diodes D1 , D4 . Note that here (E+L(di/dt)) is more than the source voltage V_s .As the V_s is positive and I_a is negative, it is a second quadrant operation gives forward braking mode. In that power is fed back from armature to source.

ThirdQuadrant–Reversemotoringmode

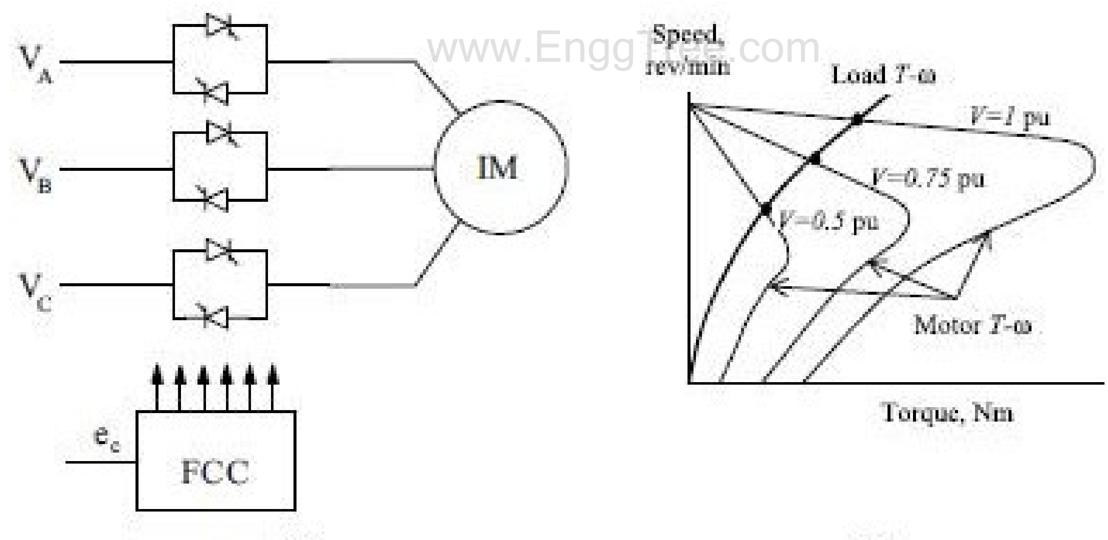
For third quadrant operation, thyristor S1 is kept off, S2 is kept on and S3 is operated, polarity of armature back emf E_b must be reversed for this quadrant operation. With thyristor S3 is on, armature gets connected to source $V_.$ so that both V_a , I_a are negative, leading to third quadrant operation. When S3 is turned off,negative current free wheels through S2,D4. In this manner only V_a and I_a can be controlled in the third quadrant.

FourthQuadrant–ReverseBrakingmode

Here thyristor S4 is operated and other devices kept off, back emf E_b must have its polarity reversed as in third quadrant operation. With S4 on, positive current flows through S4,D2,L_a and E_b (armature). Armature inductance L_a stores energy during the time S4 is on. When S4 is turned off, current is fed back to source through diodes D2, D3.Here armature voltage V_a is negative, but I_a is positive, leading to the chopper drive operation in the fourth quadrant. Also power is fed back from armature to source.

3.1 Stator Voltage Control

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



(a) (b)

Figure 3.1.1 (a) Stator voltage controller.

(b) Motor and load torque–speed characteristics under voltage control.

(Source:”Fundamentals of Electrical Drives” by G.K.Dubey,page-184)

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.

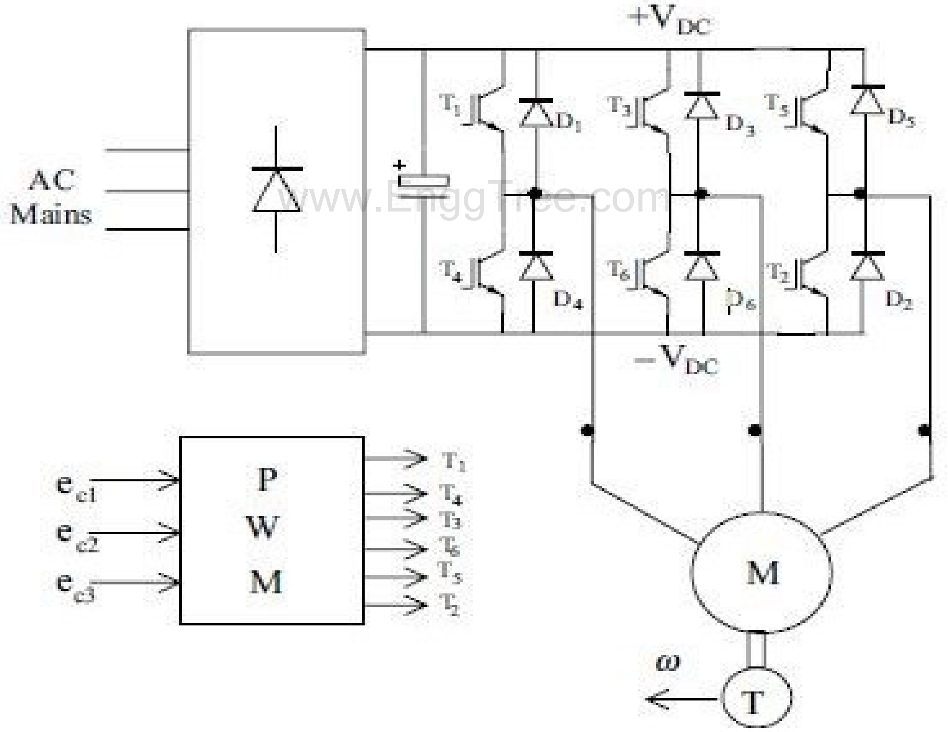


Figure 3.1.2 Inverter fed Induction motor Drive

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-192)

3.2 V/F Control

Open Loop V/F Control

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

$$\Psi_s = V_s / \omega_s$$

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

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

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

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

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

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

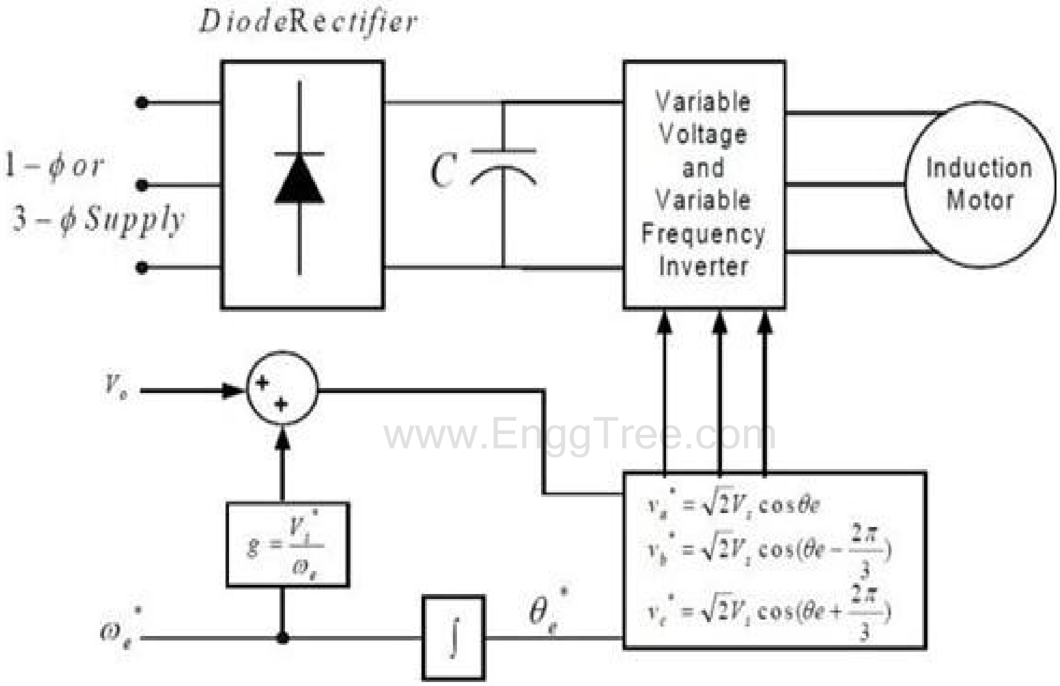


Figure 3.2.1Open loop V/F Control for an IM

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-189)

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.

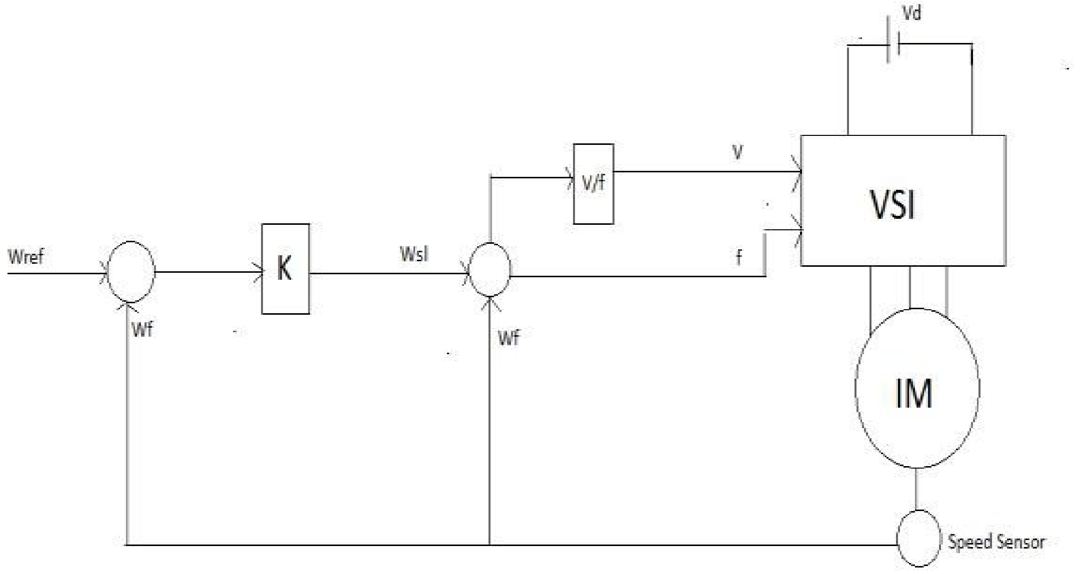


Figure 3.2.2 Closed loop V/F control for an IM

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-189)

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. Thesynchronous 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.

3.3 Rotor Resistance Control of Induction Motor:

Speed-torque curves for Rotor Resistance Control of Induction Motor are given in Fig. 6.50. While maximum torque is independent of rotor resistance, speed at which the maximum torque is produced changes with rotor resistance. For the same torque, speed falls with an increase in Rotor Resistance Control of Induction Motor.

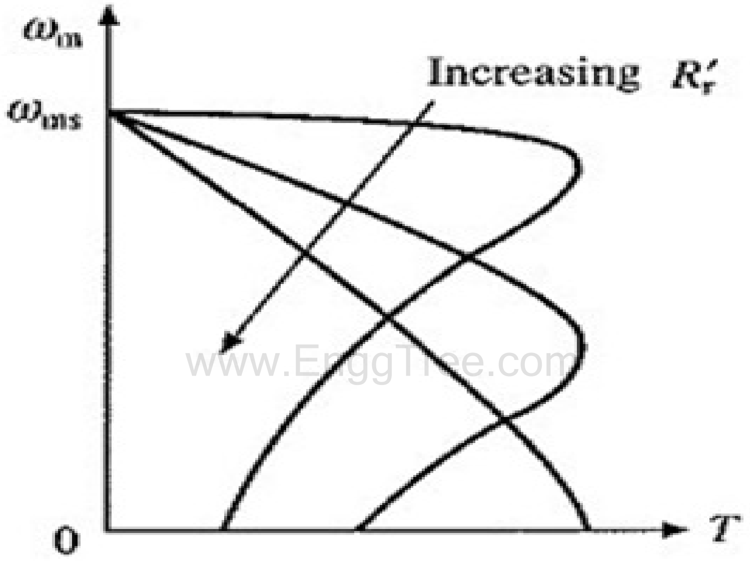


Figure 3.3.1 Rotor resistance control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-214)

Advantage of Rotor Resistance Control of Induction Motor is that motor torque capability remains unaltered even at low speeds. Only other method which has this advantage is variable frequency control. However, cost of Rotor Resistance Control of Induction Motor is very low compared to variable frequency control. Because of low cost and high torque capability at low speeds, rotor resistance control is employed in cranes, Ward Leonard Drives, and other intermittent load applications.

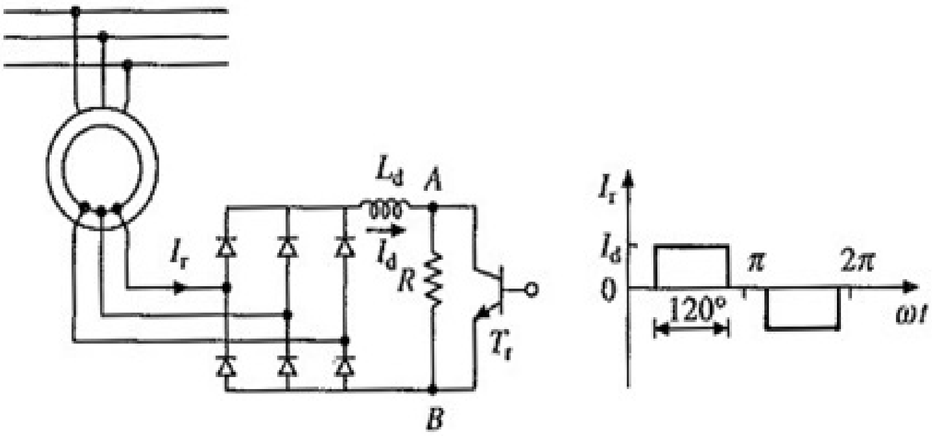
Major disadvantage is low efficiency due to additional losses in resistor connected in the rotor circuit. As the losses mainly take place in the external resistor they do not-heat the motor.

Conventional Methods:

A number of methods are used for obtaining variable resistance. In drum controllers, resistance is varied by using rotary switches and a resistance divided in few steps. Variable resistance can also be obtained by using contactors and resistors in series. High power applications use a slip-regulator, which consists of three electrodes submerged in an electrolyte, consisting of saline water. Resistance is varied by changing the distance between electrodes and earth electrode. When the power is high, electrodes are driven by a small motor. Advantage of this method is that resistance can be changed steplessly.

Static Rotor Resistance Control:

Rotor resistance can also be varied steplessly using circuit of Fig.. The ac output voltage of rotor is rectified by a diode bridge and fed to a parallel combination of a fixed resistance R and a semiconductor switch realized by a transistor T_r.



(a) Circuit diagram (b) Rotor current waveform

Figure 3.3.2 Rotor resistance control employing semiconductor converters

(Source: "Fundamentals of Electrical Drives" by G.K.Dubey,page- 216)

Effective value of resistance across terminals A and B, R_{AB}, is varied by varying duty ratio of transistor T_r, which in turn varies rotor circuit resistance. Inductance L_d is added to reduce ripple and discontinuity in the dc link current I_d. Rotor current waveform will be as shown. in Fig. when the ripple is neglected. Thus rms rotor current will be

$$I_r = \sqrt{\frac{2}{3}}\, I_d$$

Resistance between terminals A and B will be zero when transistor is on and it will be R when it is off. Therefore, average value of resistance between the terminals is given by

$$R_{AB} = (1 - \delta)R$$

where δ is the duty ratio of the transistor and is given by Eq

Power consumed by R_{AB} is

$$P_{AB} = I_d^2\, R_{AB} = I_d^2 R(1 - \delta)$$

From Eqs. (6.88) and (6.89), power consumed by R_{AB} per phase is

$$\text{Power consumed per phase} = \frac{P_{AB}}{3} = 0.5R(1 - \delta)\, I_r^2$$

Equation (6.90) suggests that rotor circuit resistance per phase is increased by 0.5R(1 – δ). Thus, total rotor circuit resistance per phase will now be

$$R_{rT} = R_r + 0.5R\,(1 - \delta)$$

R_{rT} can be varied from R_r to (R_r + 0.5R) as δ is changed from 1 to 0.

A closed-loop speed control scheme with inner current control loop is shown in Fig. 6.52. Rotor current I_r and therefore, I_d has a constant value at the maximum torque point, both during motoring and plugging. If the current limiter is made to saturate at this current, the drive will accelerate and decelerate at the maximum torque, giving very fast transient response. For plugging to occur, arrangement will have to be made for reversal of phase sequence.

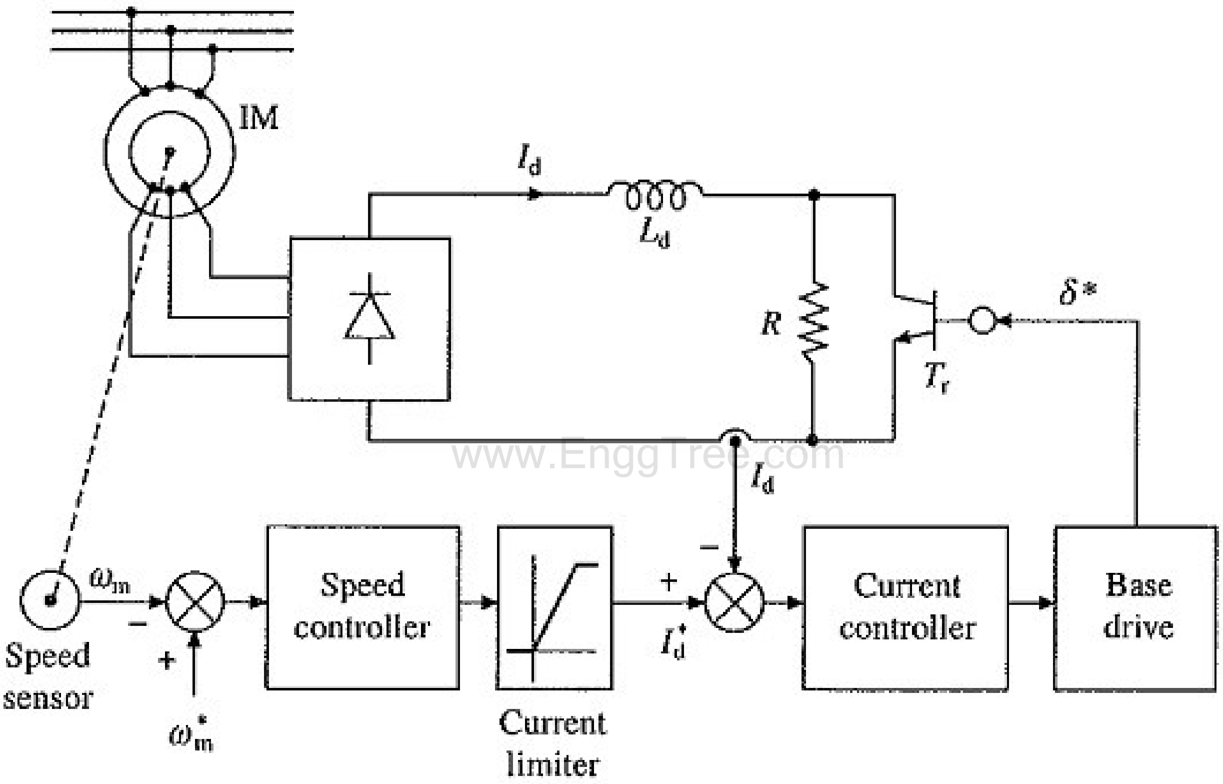


Fig 3.3.3 Closed-loop speed control with static rotor resistance control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-217)

Compared to conventional Rotor Resistance Control of Induction Motor, static rotor resistance control has several advantages such as smooth and stepless control, fast response, less maintenance, compact size, simple closed-loop control and rotor resistance remains balanced between the three phases for all operating points.

3.4 Qualitative treatment of slip power recovery drives:

Kramer System:

- It consists of main induction motor M, the speed of which is to be controlled.
- The two additional equipments are, d.c. motor and rotary converter.
- The d.c. side of rotary converter feeds a d.c. shunt motor commutator, which is directly connected to the shaft of the main motor.
- A separate d.c. supply is required to excite the field winding of d.c. motor and exciting winding of a rotary converter.
- The variable resistance is introduced in the field circuit of a d.c. motor Which acts as s field regulator.
- The speed of the set is controlled by varying the field of the d.c. motor with the rheostat R.When the field resistance is changed, the back e.m.f. of motor changes.
- Thus the d.c. voltage at the commutator changes.

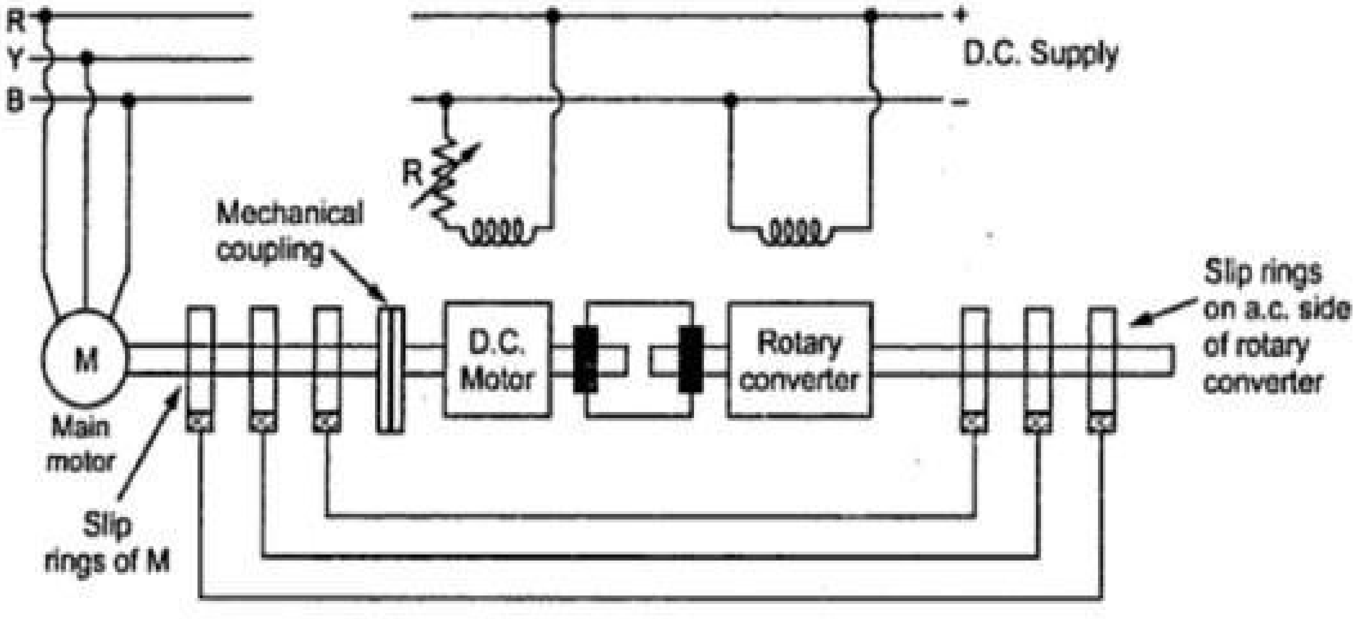


Figure 3.4.1 Static Kramer System

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-222)

- This changes the d.c. voltage on the d.c. side of a rotary converter.
- Now rotary converter has a fixed ratio between its a.c. side and d.c. side voltages.
- Thus voltage on its a.c. side also changes. This a.c. voltage is given to the slip Rings of the main motor.
- So the voltage injected in the rotor of main motor changes which produces the required speed control.
- Very large motors above 4000 kW such as steel rolling mills use such type of Speed control.
- The main advantage of this method is that a smooth speed control is possible. Similarly wide range of speed control is possible.
- Another advantage of the system is that the design of a rotary converter is practically independent of the speed control required.
- Similarly if rotary converter is overexcited, it draws leading current and thus power factor improvement is also possible along with the necessary speed control.

Scherbius System:

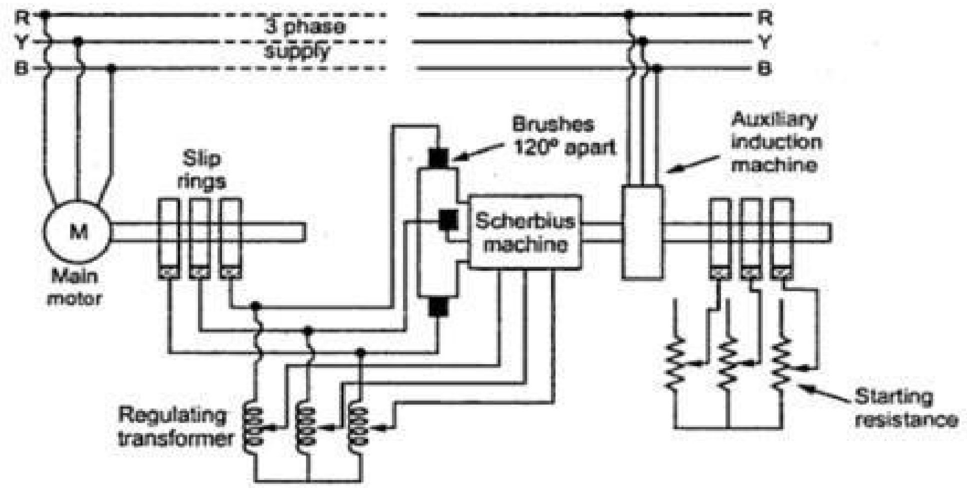


Figure 3.4.2 Static Scherbius System

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-220)

- This method requires an auxiliary 3 phase or 6 phase a.c. commutator machine which is called Scherbius machine.
- The difference between Kramer system and this system is that the Scherbius machine is not directly connected to the main motor, whose speed is to be controlled.
- The Scherbius machine is is excited at a slip frequency from the rotor of a main motor through a regulation transformer.
- The taps on the regulating transformer can be varied, this changes the voltage developed in the rotor Scherbius machine, which is injected into the rotor of main motor.
- This control the speed of the main motor, the scherbius machine is connected directly to the induction motor supplied from main line so that its speed deviates from a fixed value only to the extent of the slip of the auxiliary induction motor.
- For any given setting of regulating transformer, the speed of the main motor remains substantially constant irrespective of the load variations.
- Similar to the Kramer system, this method is also used to control speed of Large induction motors.
- The only disadvantage is that these methods can be used only for slip ring induction motors.

3.5 Closed-loop control of induction motor

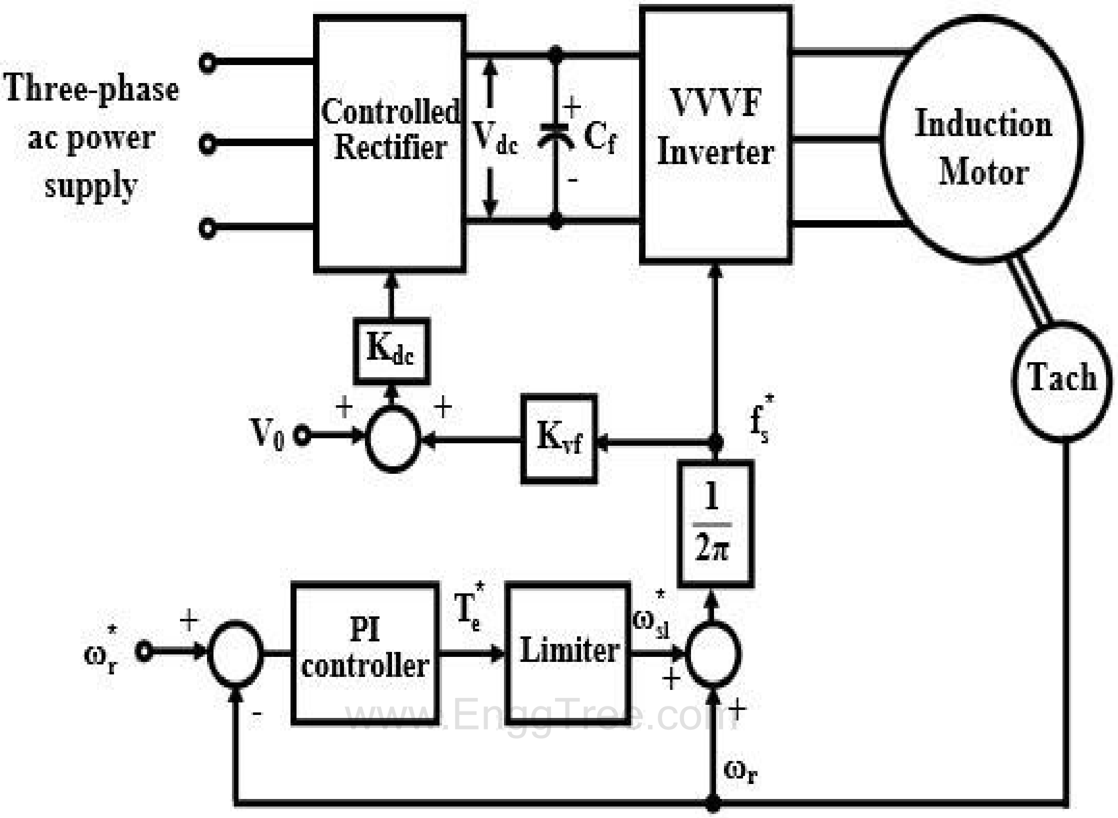


Fig 3.5.1 Closed-loop induction motor drive with constant volts/Hz control strategy

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-198)

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. Kdc is the constant of proportionality between the dc load voltage and the stator frequency.

Constant air gap flux control:

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

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

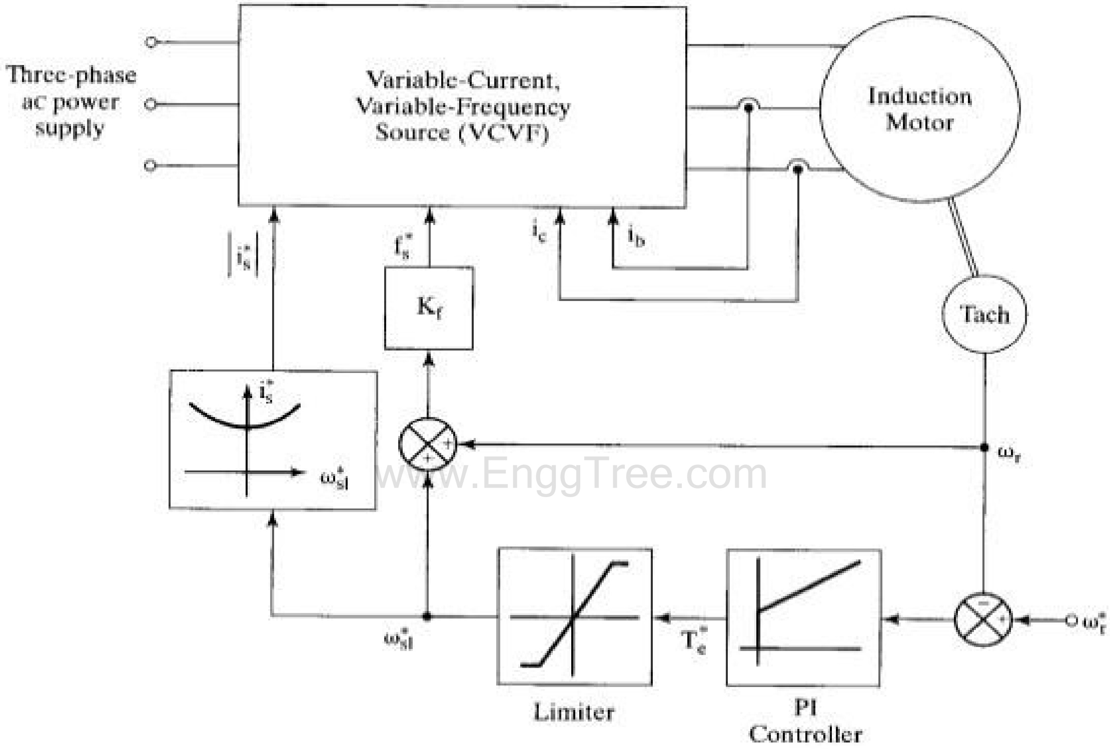


Fig 3.5.2 Closed-loop VCVF Control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-208)

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 statorvoltages and currents. It is calculated in the stationary reference frame (α,β) attached to the stator. The errorin the calculated value of the rotor flux, influenced by the changes in temperature, is negligible for this rotor flux model.

4.1 V/F control

Synchronous speed is directly proportinal to frequency,similar ti induction motors constant flux operation below base speed is achiecved by operating the synchronous motor with constant (V / f) ratio.

The synchronous motor either run at synchronous speed (or) it will not run at all. Hence variable frequency control may employ any of the following two modes

1.Separate controlled mode
2.Self controlled mode

SEPARATE CONTROLLED MODE

This method can also be used for smooth starting and regenerative braking.An example for true synchronous mode is the open loop (V/f) speed control shown in fig

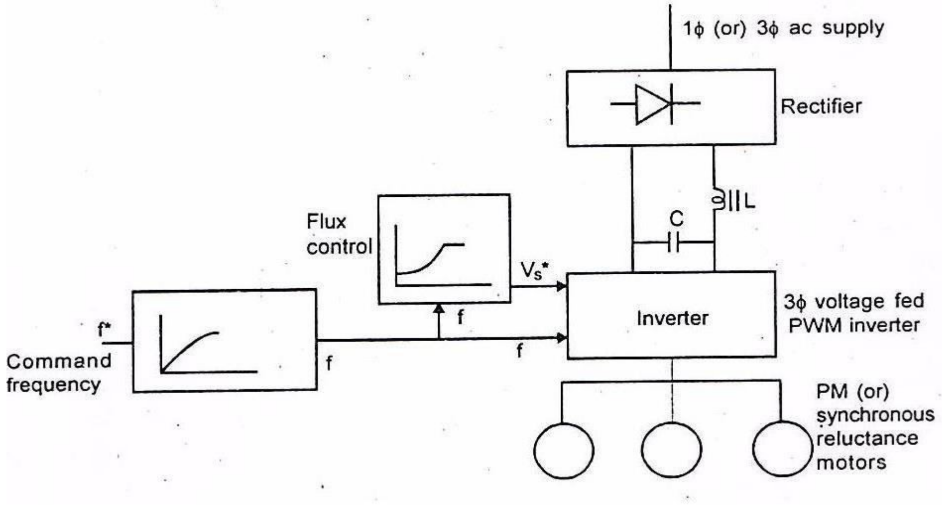


Figure 3.1.1 Separate Controlled Mode

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-257)

Here all the machines are connected in parallel to the same inverter and they move in response to the command frequency f* at the input. The frequency command f* after passing through the delay circuit is applied to the voltage source inverters (or) a voltage fed PWM inverter. This is done so that the rotor source is able to track the change in frequency.

A flux control black is used which changes the stator voltage with frequency so as to maintain constant flux for speed below base speed and constant terminal voltage for speed above base speed.The front end of the voltage fed PWM inverter is supplied from utility line through a diode rectifier and LC filter.the machine can be built with damper winding to prevent oscillations.

4.2 SELF CONTROLLED MODE

In self controlled mode, the supply frequency is changed so that the synchronous speed is same as that of the rotor speed.Hence, rotor cannot pull-out of slip and hunting eliminations are eliminated. For such a mode of operation the motor does not require a damper winding.

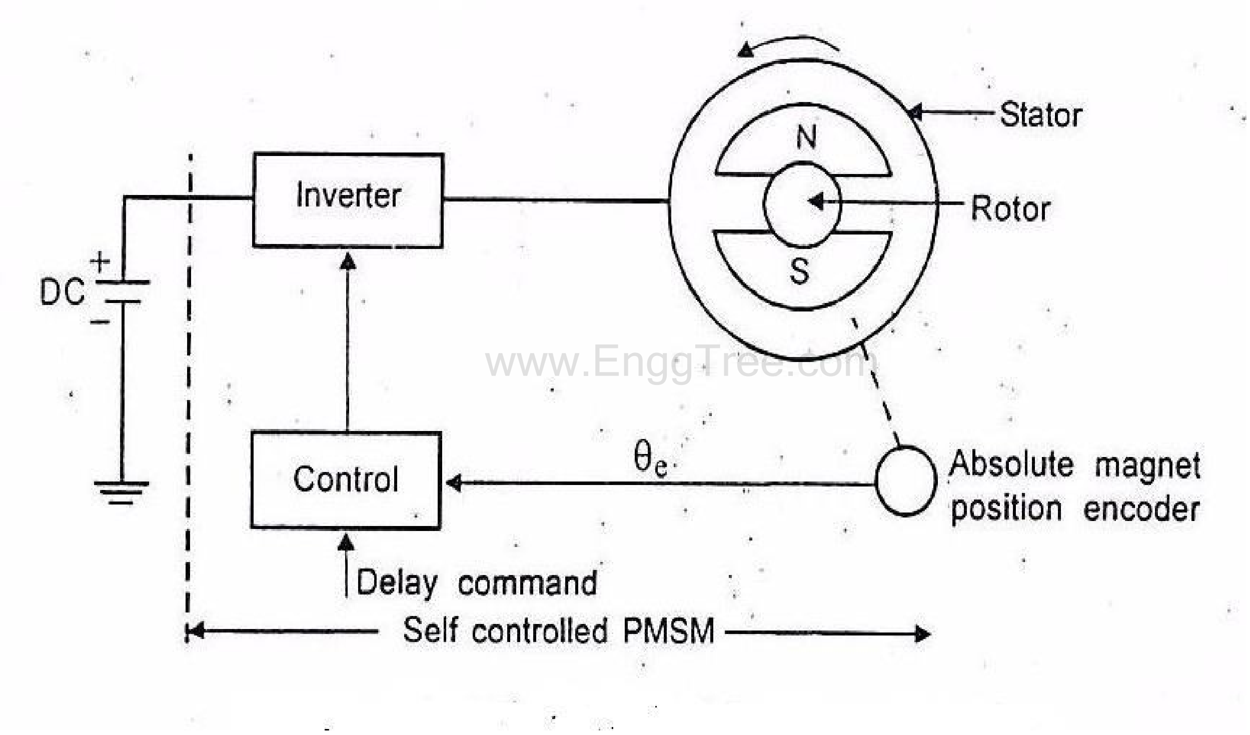


Figure 4.2.1 Self Controlled Mode

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-257)

Fig shows a synchronous permanent magnet machine with self control.The stator winding of the machine is fed by an inverter that generates a variable frequency voltage sinusoidal supply. Here the frequency and phase of the output wave are controlled by an absolute position sensor mounted on machine shaft, giving it self-control characteristics. Here the pulse train from position sensor may be delayed by the external command as shown in fig.

In this kind of control the machine behavior is decided by the torque angle and voltage/ current. Such a machine can be looked upon as a dc motor having its commutator replaced by a converter connected to stator. The self controlled motor runhas properties of a dc motor both under steady state and dynamic conditions and therefore, is called commutator less motor (CLM).These machines have better stability behavior.Alternatively, the firing pulses for the inverters can also be obtained from the phase position of stator voltages.

When synchronous motor is over excited they can supply the reactive power required for commutation thyristors. In such a case the synchronous machine can supply with inverter works similar to the line commutated inverter where the firing signals are synchronized with line voltages.

Here, the firing signals are synchronized with the machine voltages then these voltages can be used both for control as well as for commutation.Hence,the frequency of the inverter will be same as that of the machine voltages. This type of inverters are called load commutated inverter (LCI).Hence the commutation has simple configurations due to the absence of diodes, capacitors and auxiliary thyristors.

But then this natural commutation its not possible at low speeds upto 10% of base speed as the machine voltage are insufficient to provide satisfactory commutation. At that line some forced commutations circuit must be employed.

Self controlled synchronous motor Drive empolying load commuated Thyristor Inverter

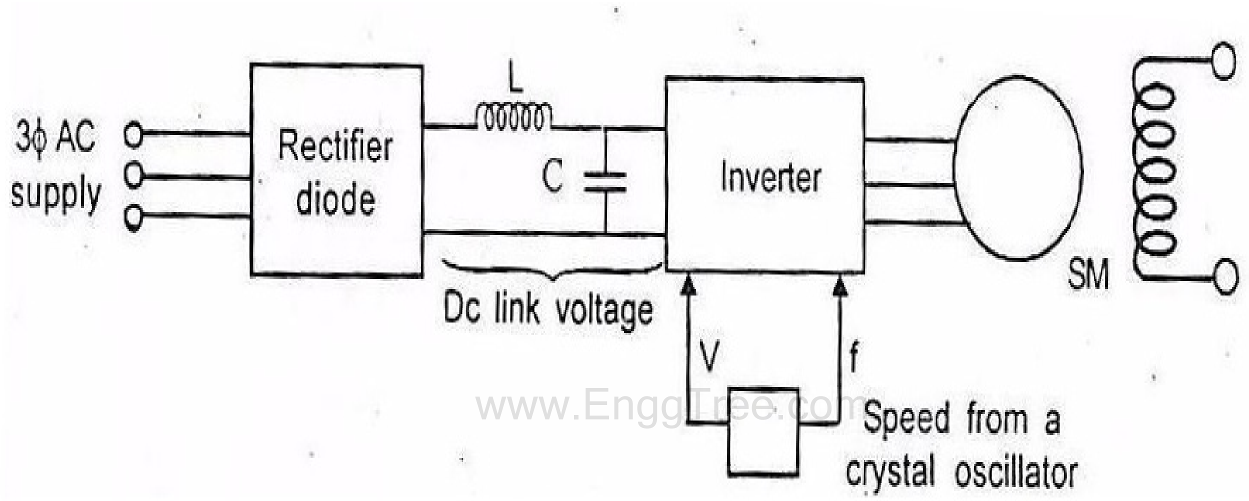


Figure 4.2.2 Separate Control of SM fed from PWM inverter

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-264)

In fig wound field synchronous motor is used for large power drives.Permanent magnet synchronous motor is used for medium power drives.This drive consists of two converters.i.e source side converter and load side converter.

The source side converter is a 3 phase 6 pulse line commutated fully controlled rectifier .When the firing angle range 0≤ǂs≤90º,it acts as a commutated fully contrlled rectifier.

During this mode ,output volatge Vds and output current Ids is positive.When the firing angle range is 90º≤ǂs≤180º,it acts as an line commutated inverter.During this mode,output voltage Vds is negative and output current Ids is positive.

When synchronous motor operates at a leading power factor thyristors of the load side 3φ converter can be commutated (turn off) by the motor induced voltages in the same way,as thyristors of a 3φ line commutated converter are commutated by supply voltage Load commutation is defined as commutation of thyristors by induced voltages of load (here load is synchronous motor).

Triggering angle is measured by comparison of induced voltage in the same way as by the comparison of supply voltages in a line commutated converter.Loas side converter operates as a rectifier when the firing angle range is 0≤ǂl≤90º.It gives positive Vdl and Id.When the firing angle range is 90º≤ǂl≤180º,it gives negative Vdl and positive Id.

For 0≤ǂs≤90º, 90º≤ǂl≤180º and with Vds >Vdl,the source side converter works as a line commutated rectifier and load side converter,causing power flow from ac source to the motor,thus giving motoring operation.

When firing angles are changed such that 90º≤ǂs≤180º and 0º≤ǂl≤90º,the load side converter operates as a rectifier and source side converter operates as an inverter. In this condition , the power flow reverses and machine operates in regerative braking.The magnitude of torque value depends on (Vds – Vdl).Synchronous motor speed can be changed by control of line side converter firing angles.When working as an inverter ,the firing angle has to be less than 180° to take care of commutation overlap and turn off of thyristors.The commutation lead angle for load side converter is

$$\beta l = 180^\circ - \alpha l$$

if commutation overlap is neglected ,the input ac current of the converter will lag behind input ac voltage by angle ǂ1.Here synchronous motor input current has an opposite phase to converter input current,the motor current will lead its terminal voltage by a commutation lead angle β.

Therefore the synchronous motor operates at a leading power factor. The commutation lead angle is low value, due ti this higher the motor power factor and lower the inverter rating.

4.3 MARGINAL ANGLE CONTROL

The operation of the inverter at the minimum safe value of the margin angle gives the highest power factor and the maximum torque per ampere of the armature current,thus allowing the most efficient use of both the inverter and motor.

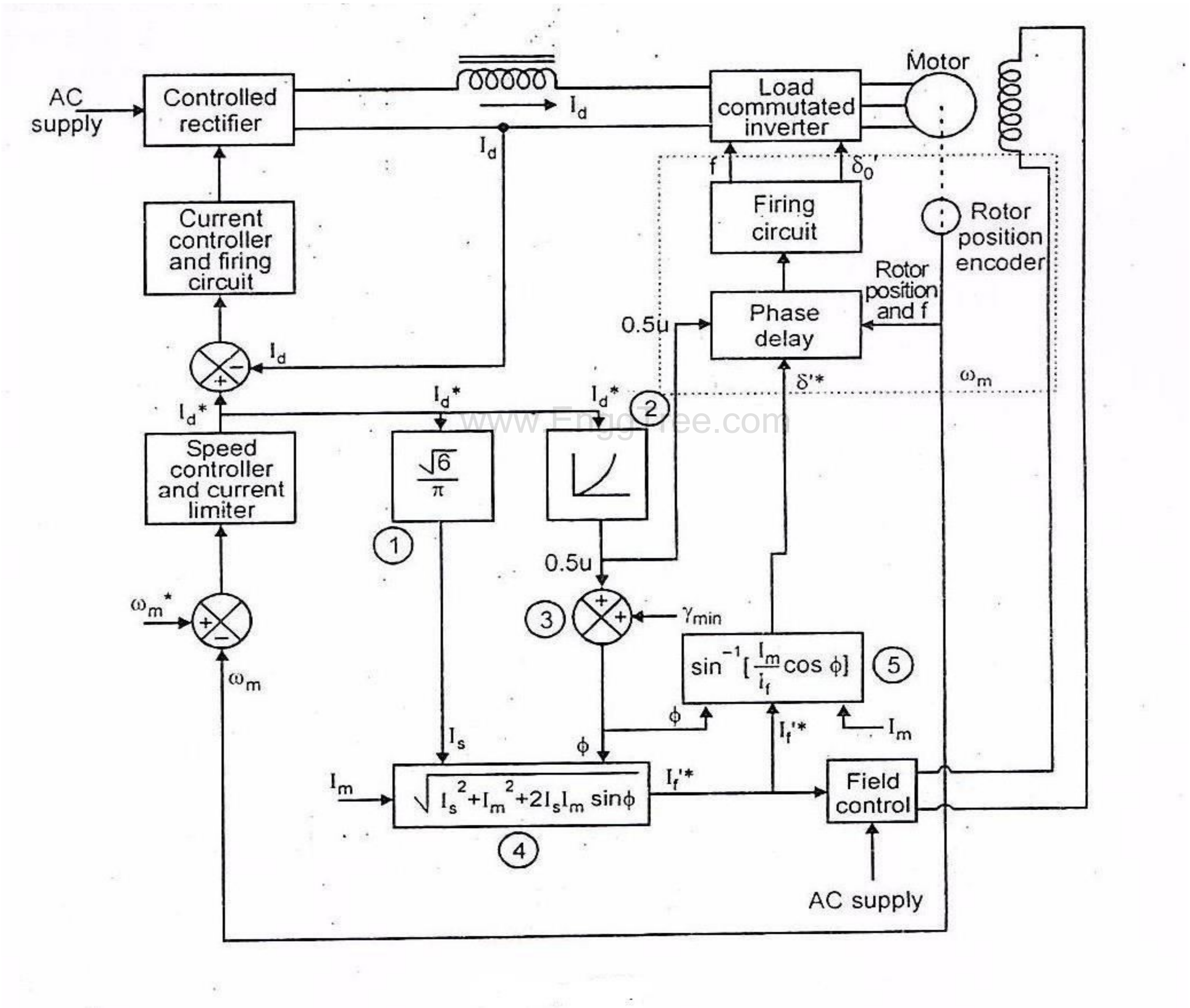


Figure 4.3.1Constant Marginal Angle Control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-270)

Fig shows the constant margine angle control for a wound field motor drive employing a rotor position encoder.This drive has an outer speed loop and an inner current loop.The rotor position can be sensed by using rotor position encoder.It gives the actual value of speed ωm.This signal is fed to the comparator.This comparator compares ωm and ωm* (ref value).

The output of the comparator is fed to the speed controller and current limiter.It gives the reference current value Id*.Id is the DC link current.It is sensed by current sensor and fed to the comparator.The comparator compares Id and Id*.The output of the comparator is fed to the currrent controller.It generates the trigger pulses.

It is fed to the cotrolled rectifier circuit.In addition ,it has an arrangement to produce constant flux operation and constant margin angle control.From the value of dc link current command Id*,Is and 0.5u are produced by blocks (1) and (2) respectivly .The signal φ is generated from Ǆmin and 0.5u in adder (3).

In block (4) If' is calculated from the known values of Is,φ and Im.Note that the magnetizing current Im is held constant at its rated value Im to keep the flux constant.

If* sets reference for the closed loop control of the field current IF.Blocks (5) calculates'* from known,values of φ and If*

The phase delay circuit suitably shifts the pulses produced by the encoder to produce the desired value of 0'.This signal is fed to the load commutated inverter.

The load commutated inverter drives are used in medium power, high-power and very high power drives, and high speed drives such as compressors, extractors, induced and forced draft fans, blowers, conveyers, aircraft test facilities, steel rolling mills, large ship propulsion, main line traction, flywheel energy storage and so on.

This drive also used for the starting of large synchronous machines in gas turbine and pumpled storage plant.

High power drives employ rectifiers with higher pulse numbers,to reduce torque pulsations.The converter voltage ratings are also high so that efficient high voltage motors can be employed.

4.4 Voltage Source Inverter Fed Synchronous Motor Drive:

An inverter fed synchronous motor has been very popular as a converter motor in which the synchronous motor is fed from a CSI having load commutation. Of late more attention is being paid towards understanding the behaviour of synchronous motors fed from a Voltage Source Inverter. These drives can also be developed to have self control, using a rotor position sensor or phase control methods. It has been reported in the literature that these drives might impose fewer problems both on machine as well as on the system design. A normal VS1 with 180° conduction of thyristors requires forced commutation and load commutation is not possible.

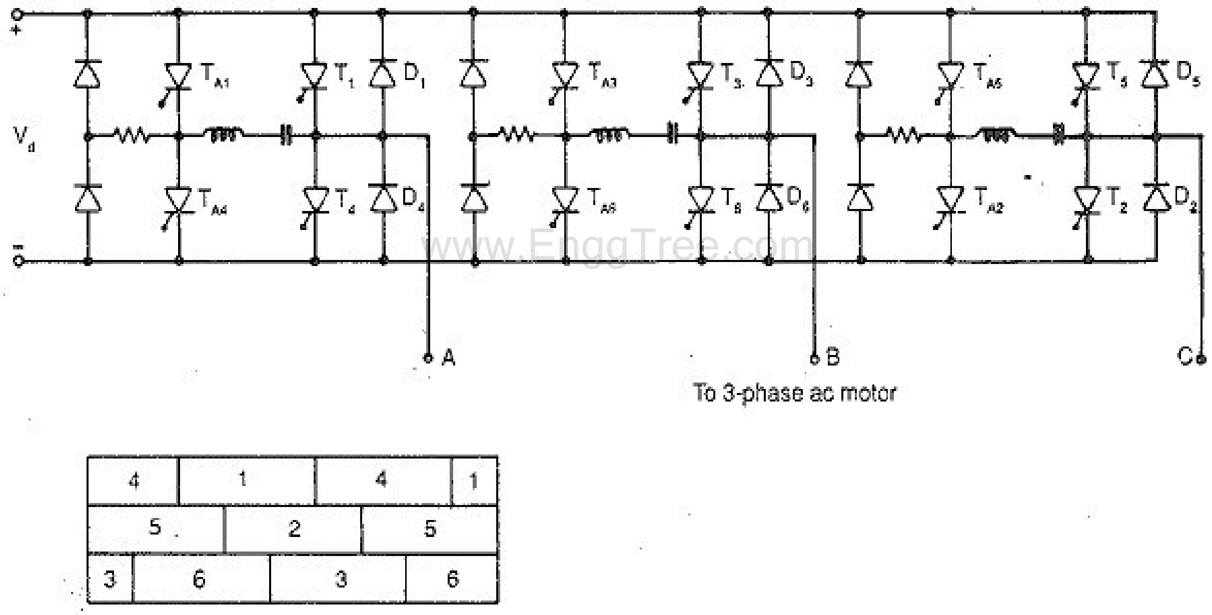


Fig. 4.41 *Power circuit of a VSI*

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-211)

A typical power circuit of a voltage source inverter is shown in Fig. 4.41. Three combinations are possible, to provide a variable voltage variable frequency supply to a synchronous motor (Fig. 4.42). The voltage control can be obtained external to the inverter using a phase controlled rectifier. The link voltage is variable. This has the disadvantage that commutation is difficult at very low speeds. As the output voltage is a square wave the inverter is called variable voltage inverter or square wave inverter. The second alternative is to have voltage control in the inverter itself, using principles of PWM or PSM. The inverter is fed from a constant link voltage. A diode rectifier would be sufficient on the line side. This does not have difficulties of commutation at low speeds. Very low speeds up to zero can be obtained. The third alternative is to interpose a dc chopper in between the rectifier and the inverter. The system may appear cumbersome at first sight, but it has advantages. Three simple converters are used to give the desired result. It is possible to reduce the size of link inductance by having a synchronous control of the chopper.

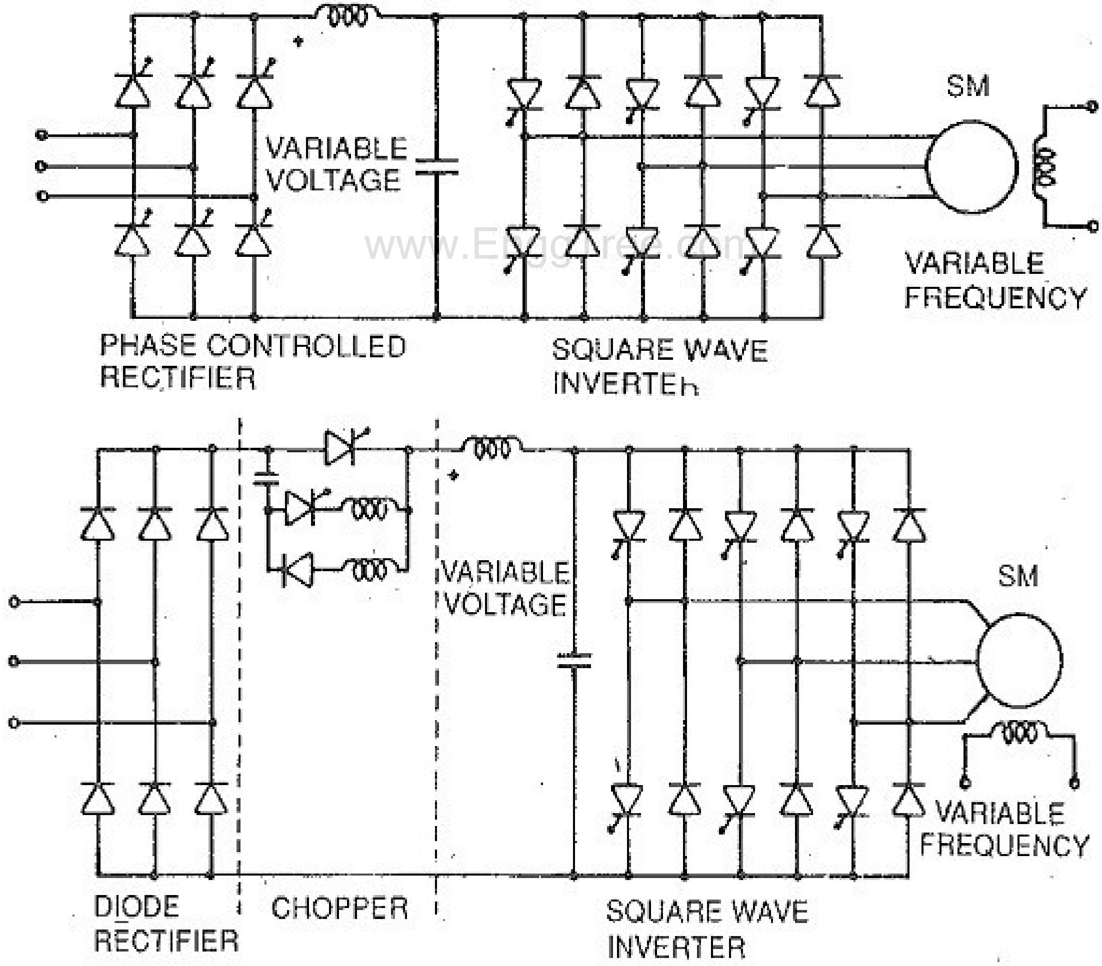
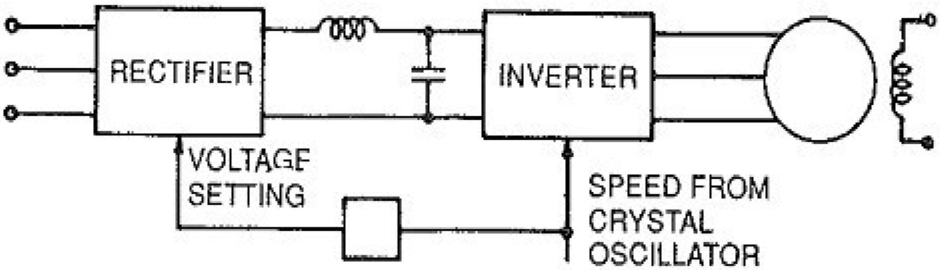
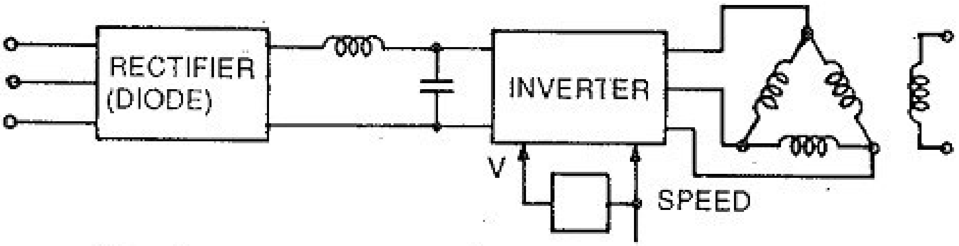


Fig. 4.42 *Possible combinations of voltage source dc link converters to obtain a variable voltage variable frequency supply to feed a synchronous motor*

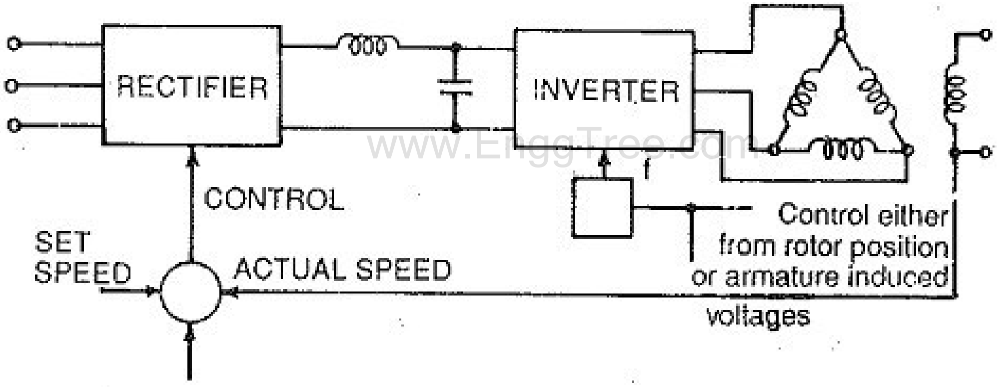
(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-346)



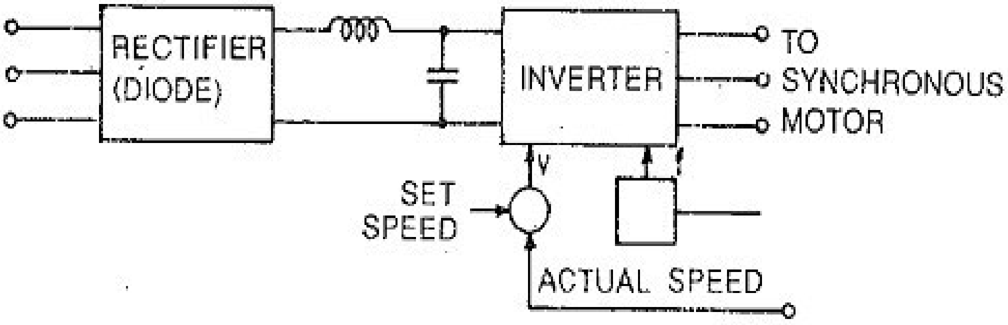
(a) Separate control of synchronous motor fed from square wave inverter.



(b) Separate control of synchronous motor fed from a PWM inverter.



(c) Self control of synchronous motor fed from square wave inverter.



(d) Self control of synchronous motor fed from a PWM inverter.

Fig. 4.43 *Principles of separate and self control*

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-347)

A voltage source inverter feeding a synchronous motor can have either separate control or self control. In the former the speed of the motor is determined by external frequency from a crystal oscillator. Open loop control is possible. The motor has instability problems and hunting, similar to a conventional motor. In the latter the inverter is controlled by means of firing pulses obtained from a rotor position sensor or induced voltage sensor. The motor is in the CLM mode and has better stability characteristic (Fig. 4.43).

The output voltage of the inverter is non-sinusoidal. The behaviour of the motor supplied from the inverter is entirely different from the behaviour of the motor operating on a conventional sinusoidal supply. A knowledge of the behaviour is essential. The steady-state performance enables one to have a proper choice of the thyristors, and also to determine the effects of non-sinusoidal waveforms on torque developed and machine losses.

The stator current drawn by the motor when fed from the square wave inverter has sharp peaks and is rich in harmonic content. These harmonics can cause additional losses and heating of the motor. They also cause pulsating torques which are objectionable at low speeds. Thus the performance with respect to additional heating due to harmonics, and pulsating torques is similar to that of an induction motor.

When a PWM inverter is used, these harmonic effects are reduced. The stator currents are less peaky and have reduced harmonic content. Accordingly additional losses due to harmonics, consequent motor heating and torque pulsations are decreased. These effects become minimal.

The discussion on regeneration given for induction motors holds good for these cases also. With the square wave inverter another phase controlled rectifier is required on the line side. Dynamic braking can be employed. When a PWM inverter is used, two cases may arise. The inverter may be fed from a constant dc source in which case regeneration is straight forward. The dc supply to the inverter may be obtained from a diode rectifier. In this case an additional phase controlled converter is required on the line side.

A square wave inverter drive must have a phase controlled converter on the line side. Due to phase control the line power factor is very poor. A diode rectifier is sufficient in the case of PWM inverter. The line pl. improves to unity. In either case the machine p.f. can be improved by field control. With a view to minimizing the inverter size as well as losses in the inverter and motor, it is advantageous to operate the motor at UPF.

A VSI drive provides reasonably good efficiency. Converter cost is high and inultimotor operation is possible. Open loop (separate) control may pose stability problems at low speeds. CLM mode is very stable. PWM drive has a better dynamic response than a square wave drive. This finds application as a general purpose industrial drive for low and medium powers.

4.5 Current Source Inverter Fed Synchronous Motor Drive:

A synchronous motor draws a stator current which is independent of stator frequency when V/f and E/f are maintained constant and armature resistance is neglected. The motor also develops constant torque. The flux also remains constant. Therefore, by controlling the stator current of a synchronous motor we can have flux control as well as torque control. As has been discussed in the case of the induction motor, current control is simple and straightforward. A synchronous motor is fed from a Current Source Inverter Fed Synchronous Motor Drive. A synchronous motor can have either separate control or self control. Due to stable operation self control is normally employed, by using either rotor position sensing or induced voltage sensing. The motor operates in CLM mode. When fed from a CSI the synchronous motor can be operated at leading power factor so that the inverter can be commutated using machine voltages. A load commutated, CSI fed self controlled synchronous motor is very well known as a converter motor. It has very good stability characteristics and dynamic behavior similar to a dc motor.

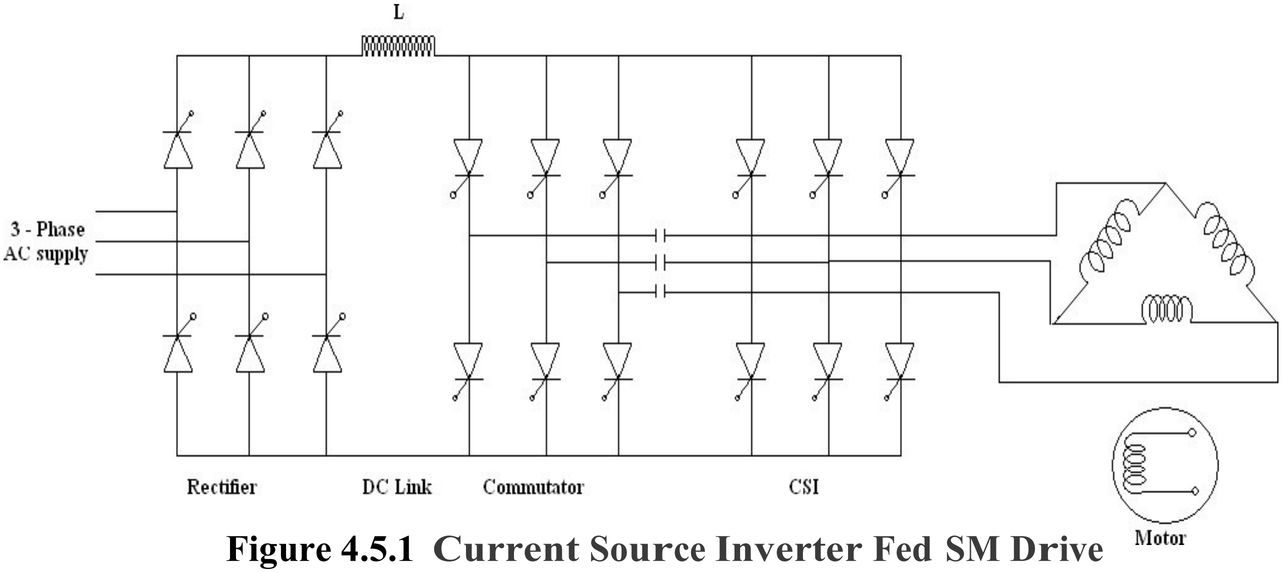


Figure 4.5.1 Current Source Inverter Fed SM Drive

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-211)

Due to machine commutation the working speed range starts typically above 10% of base speed and extends up to base speed. By using (assisted) forced commutation the lower speed limit can be extended to zero. During the operation in the speed range from 0 to 10% of base speed (above which load commutation is possible) the machine can be operated at UPF.

When fed from a CSI, the synchronous motor is supplied with currents of variable frequency and variable amplitude. The dc link current is allowed to flow through the phases of the motor alternately. The motor currents are quasi-square wave if the commutation is instantaneous. The motor behaviour is very much affected by the square wave currents. The harmonics present in the stator current cause additional losses and heating. They also cause torque pulsations, which are objectionable at low speeds. A Current Source Inverter Fed Synchronous Motor Drive is inherently capable of regeneration. No additional converter is required, and four quadrant operation is simple and straight forward.

Due to over excitation the machine power factor is leading. The motor is utilised less. The phase control on the line side converter for current control in the dc link causes the power factor to become poor at retarded angles of firing. The cost of the inverter is medium, due to absence of commutation circuit. The drive has moderately good efficiency and is popular as CLM in medium to high power range. Voltage spikes during commutation occur in the terminal voltage. These depend on the sub transient leakage reactance and affect the insulation of the motor also. The motor must have damper windings to limit the Voltage spikes. Application of this type of drive is in gas turbine starting, pumped hydro turbine starting, pump and blower drives, etc.

5.1 Transfer Function for DC Motor

Consider a separately excited DC motor with armature voltage control. In armature voltage control field current is constant but armature voltage is varied.

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

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

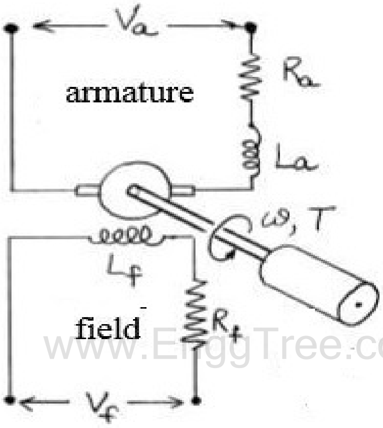


Figure 5.1.1 Speed Controller

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-142)

Field-Current Controlled:

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

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

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

$$V_f = V_R + V_L$$
$$= R_f i_f + L_f \left(di_f / dt \right)$$

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

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

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

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

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

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

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

or

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

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

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

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

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

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

5.2 Closed Loop Control with Current and Speed Feedback

Closed loop control improves on the drives performance by increasing speed of response andimproving 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

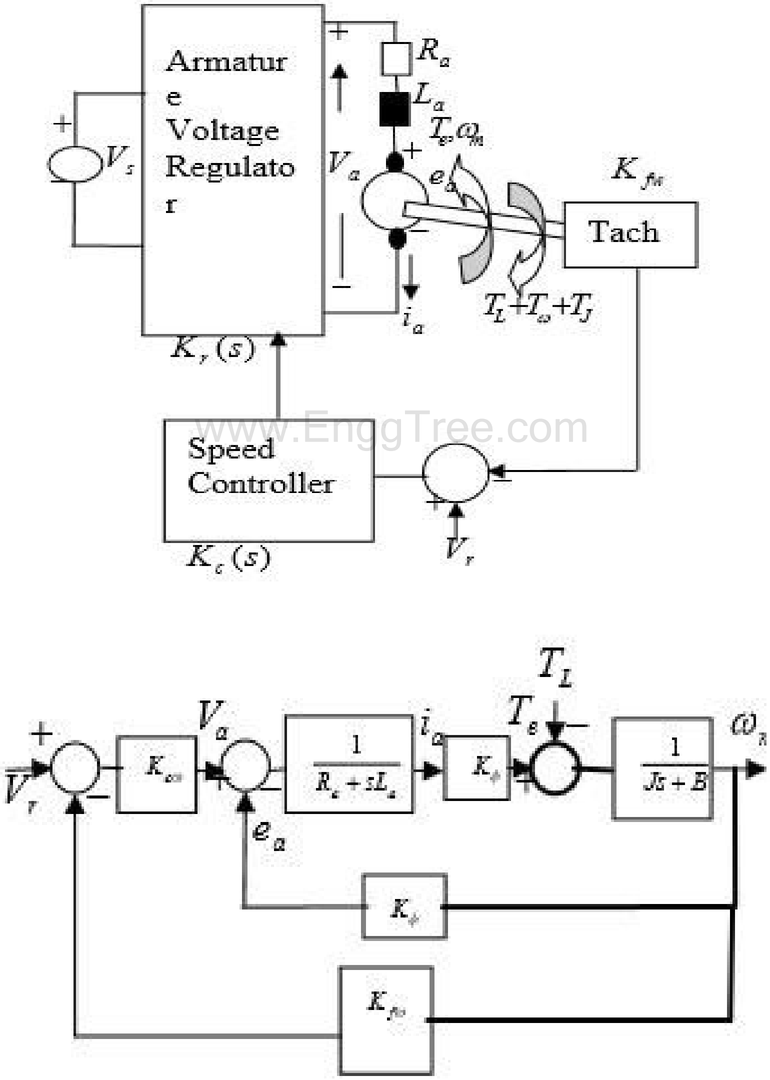


Figure 5.2.1 Closed Loop Speed Control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-192)

Where,

$K_{f\omega}$ is the tachometer feed back gain

$K_c(s)$ is the speed controller gain

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

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,

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

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

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

Where,

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

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

Last Equation is a second order system

The Natural Frequency of Oscillation, $\omega_n$is,

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

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

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

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

This is lower than in the open loop case due to the increase in ω_n Speed Regulation (SR) is also derived as

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

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.

5.3 Armature voltage control

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

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

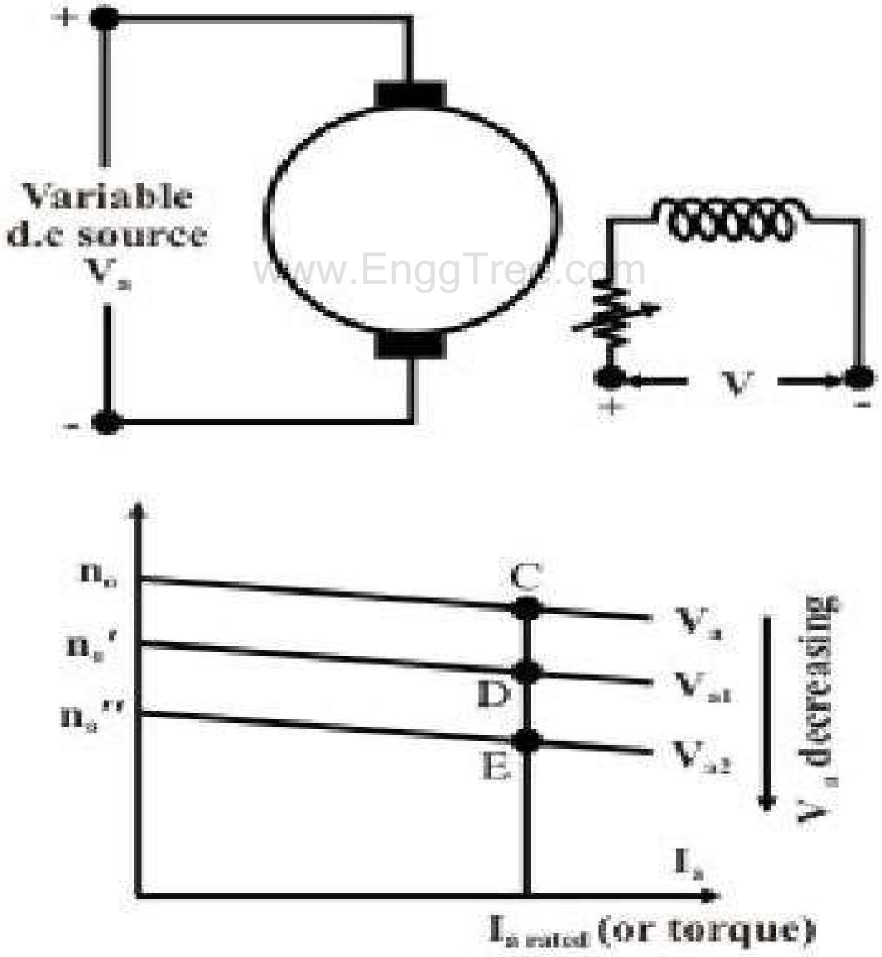


Figure 5.3.1 Armature voltage control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-242)

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 a cross the armature a voltage, which is higher than the rated voltage.

5.4 Flux-field 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 i_d 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 also 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 ,i_d.

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)i_d current increases, a phase current vector i_s 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 i_q current,i.e v_d 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 i_d 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

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

5.5 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 (input) 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.

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 non linearities appearing during discontinuous conduction, a feed forward termis added to the firing angle.

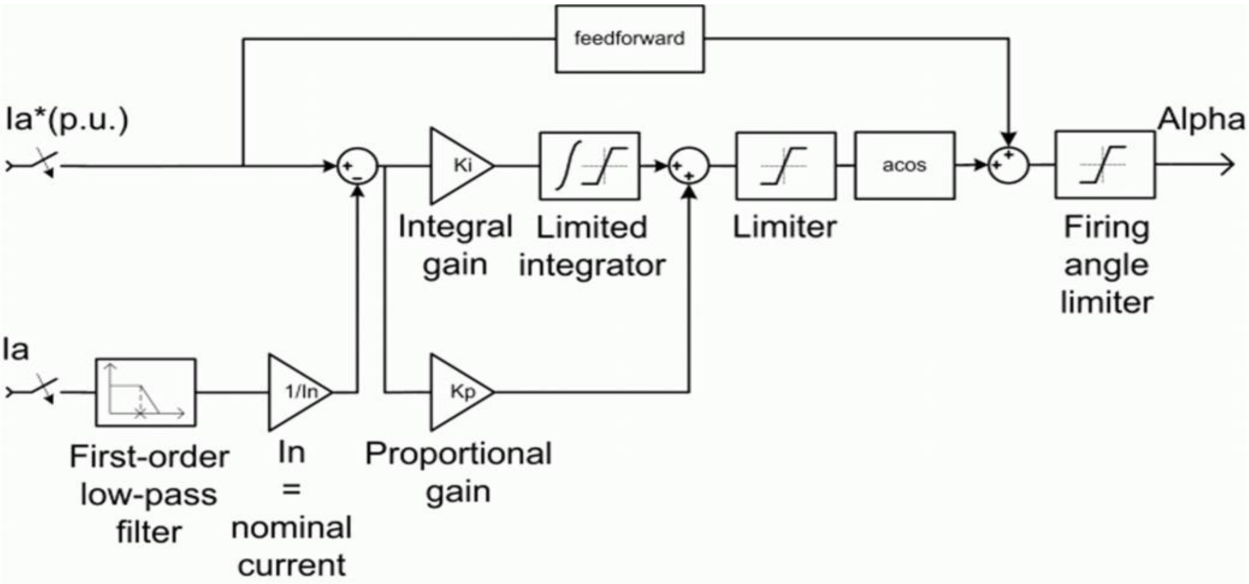


Figure 5.5.1 Speed Controller

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-342)