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.

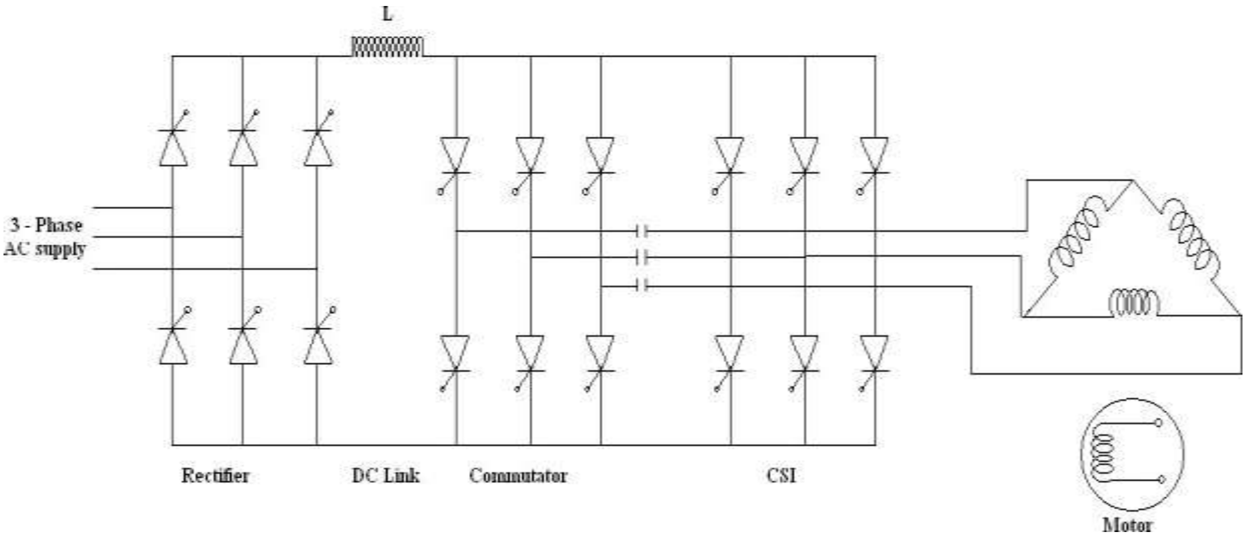


Figure 4.5.1 Current Source Inverter Fed SM Drive

(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.

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.

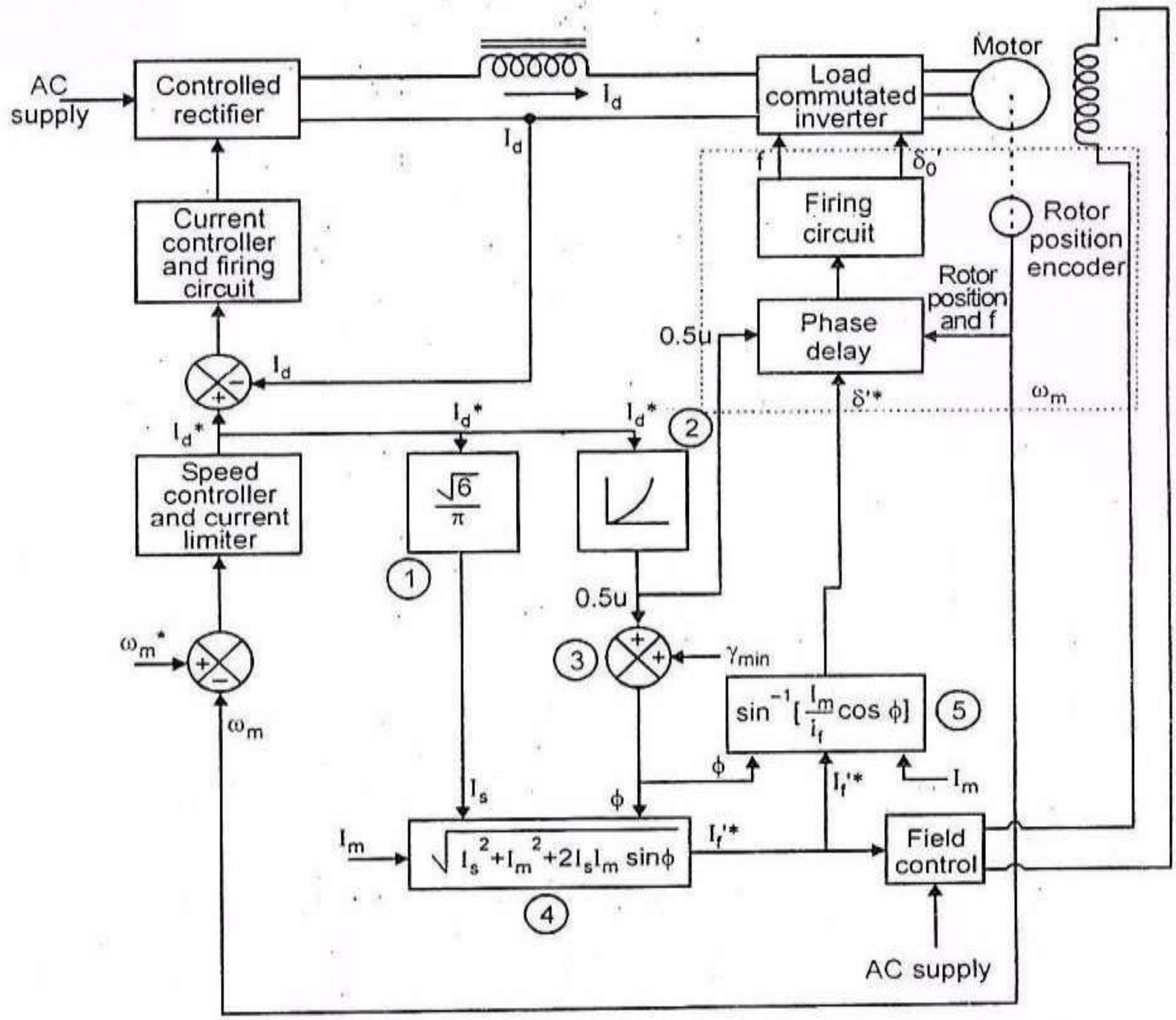


Figure 4.3.1Constant Marginal Angle Control

(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 POWER FACTOR CONTROL

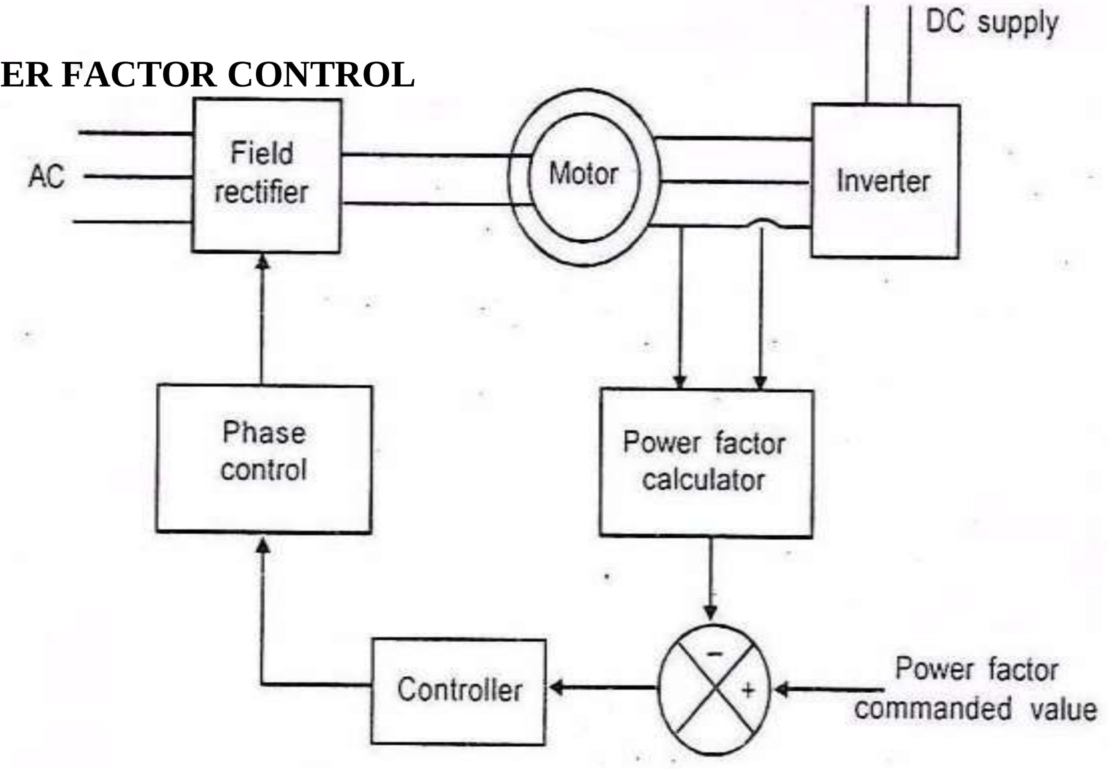


Figure 4.4.1 Power Factor Control

(Source:"Fundamentals of Electrical Drives" by G.K.Dubey,page-314)

Fig shows the block diagram of automatic closed loop adjustment of power factor.The main aim of adjustment of power factor is the variation of the field current.This is possible in a wound field machine. If the motor is operated at a power factor of unity,the current drawn by it will have the lowest magnitude for a given power input and therfore the lowest internal copper losses.

From this diagram, the motor voltage and current are sensed and fed to the power factor calculator. The power factor calculator computes the phase angle between the two and therefore the power factor. It is the actual power factor value. The computed power factor value is compared against the power factor commanded value by using error detector. The error is amplified by the error amplifier, and its output varies the field current power factor confirm to the commanded value.

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.

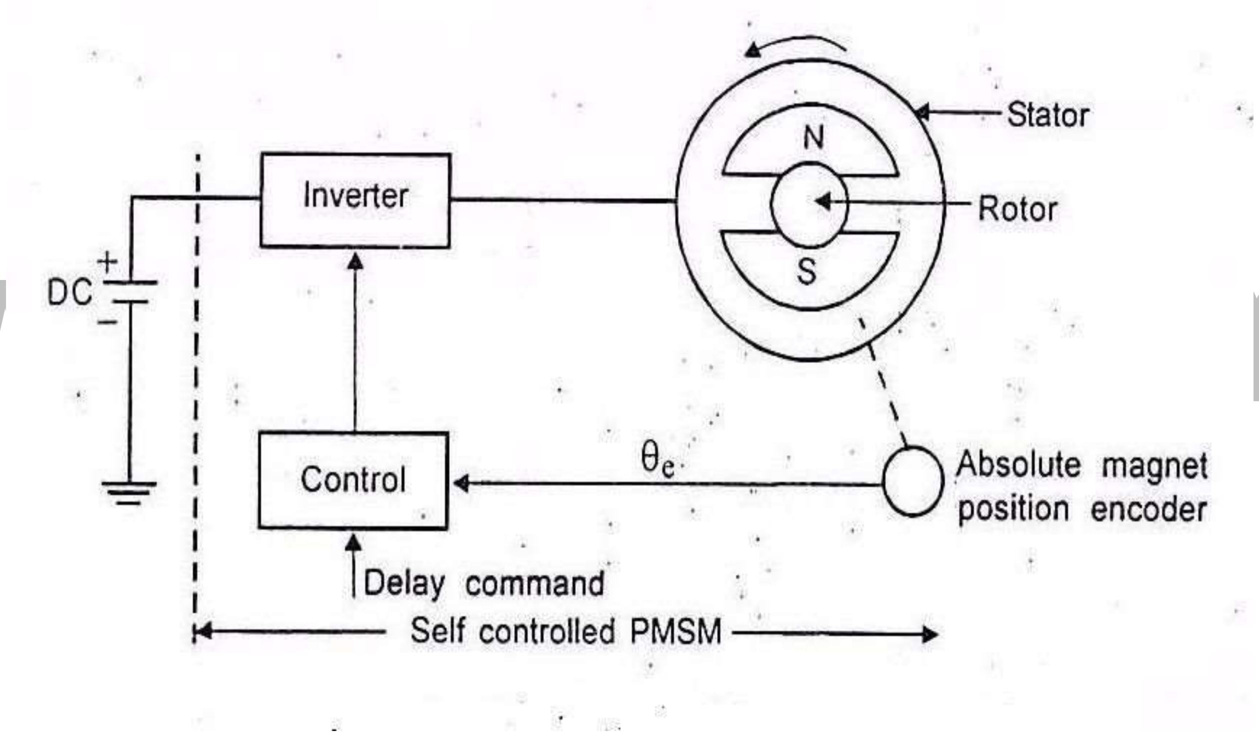


Figure 4.2.1 Self Controlled Mode

(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

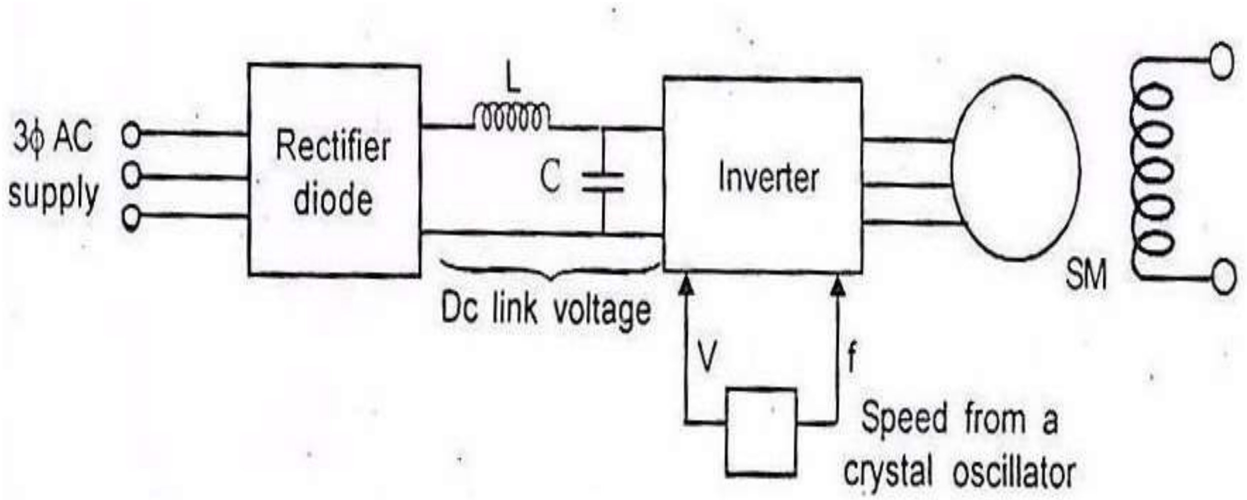


Figure 4.2.2 Separate Control of SM fed from PWM inverter

(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

$$\beta l = 180^{o} - \alpha l$$

if commutation overlap is neglected ,the input ac current of the converter will lag behind input ac voltage by angle ǂl.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.

4.4 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.

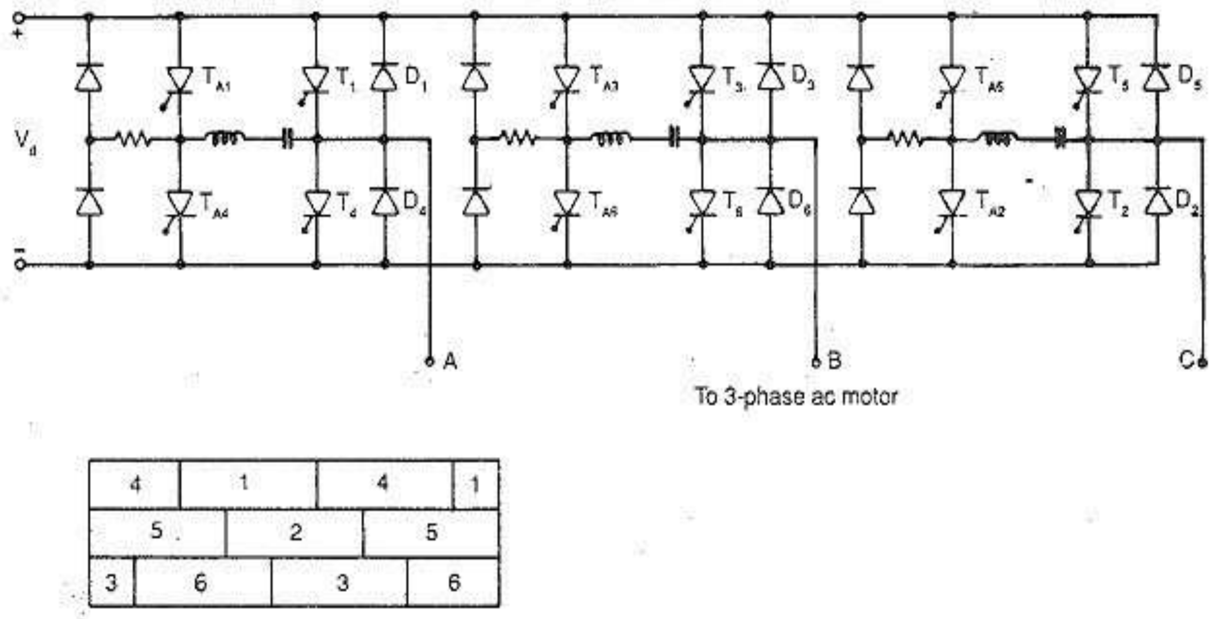


Fig. 4.41 *Power circuit of a VSI*

(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.

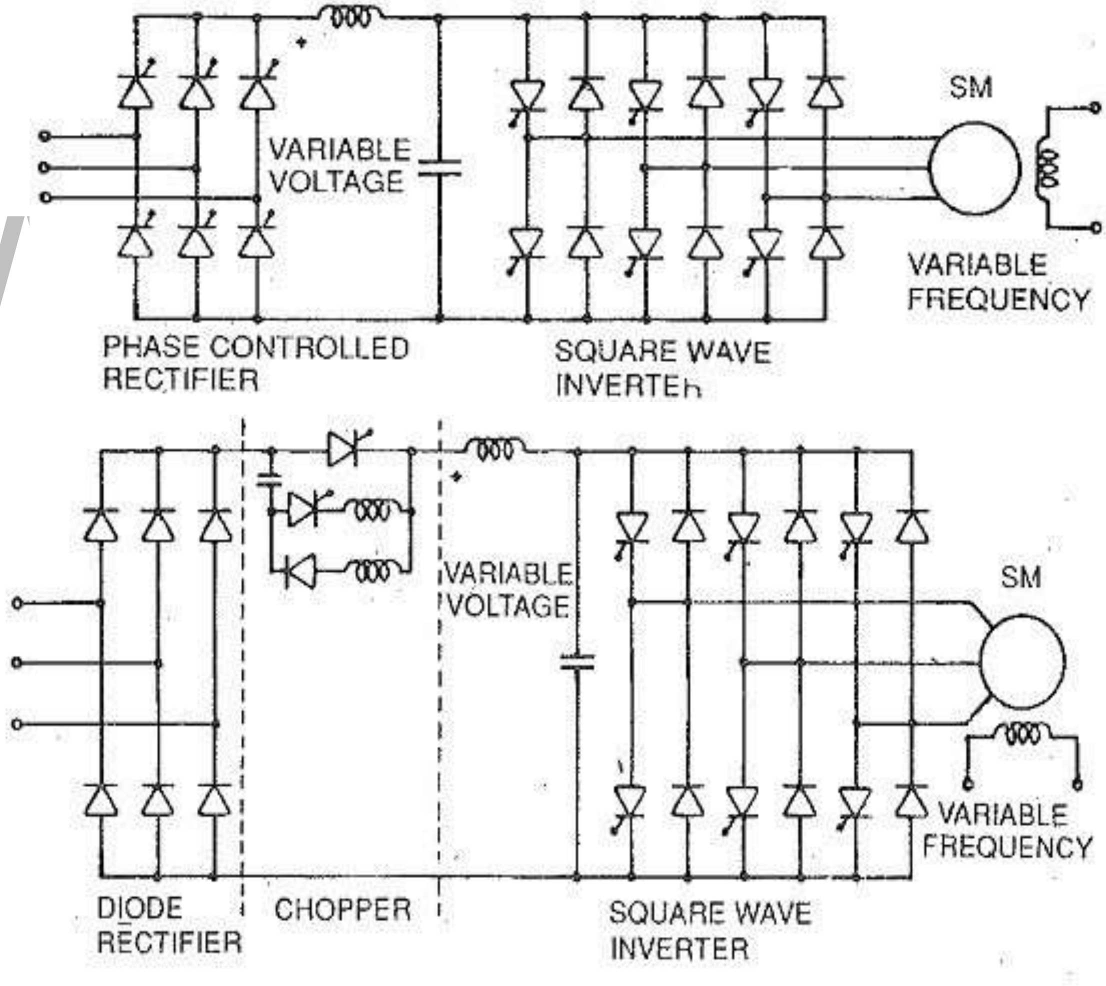
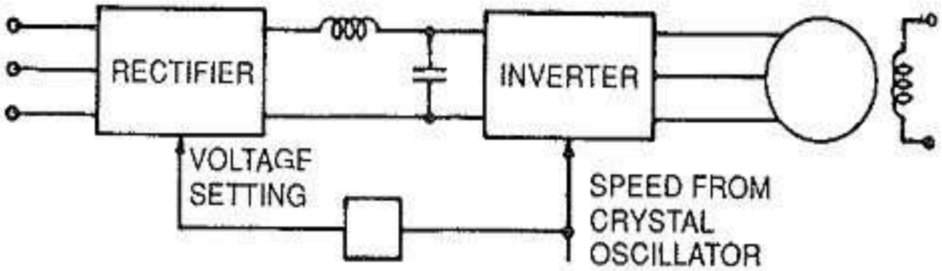
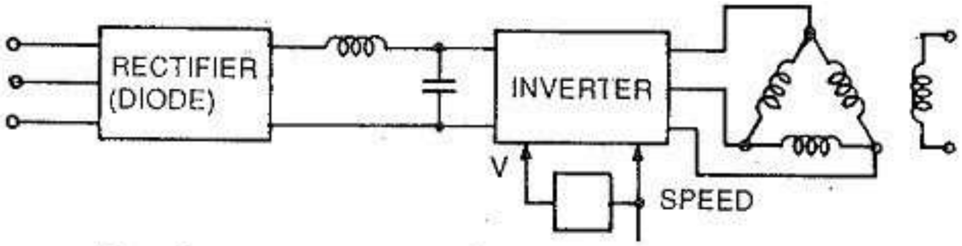


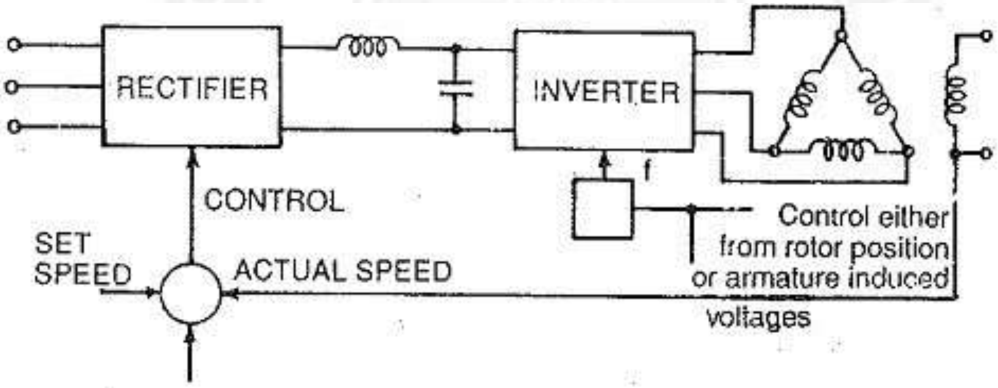
Fig. 4.42 *Possible combinations of voltage source dc link converters to obtain a variable voltage variable frequency supply to feed a synchronous motor*



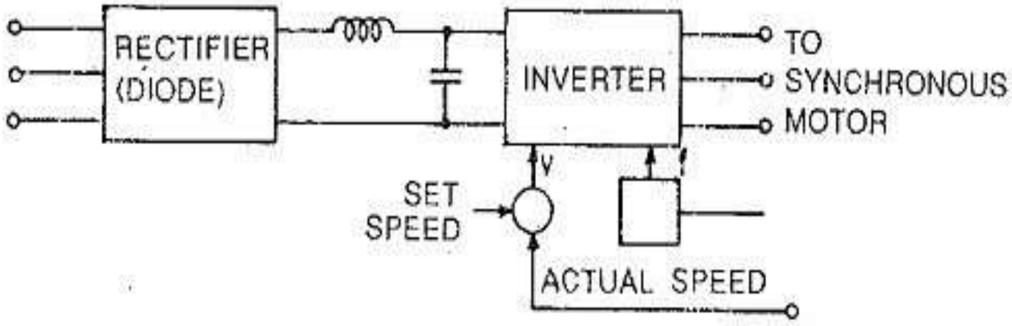
(a) Separate control of synchronous motor fed from square wave inverter.



(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.

4.1 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

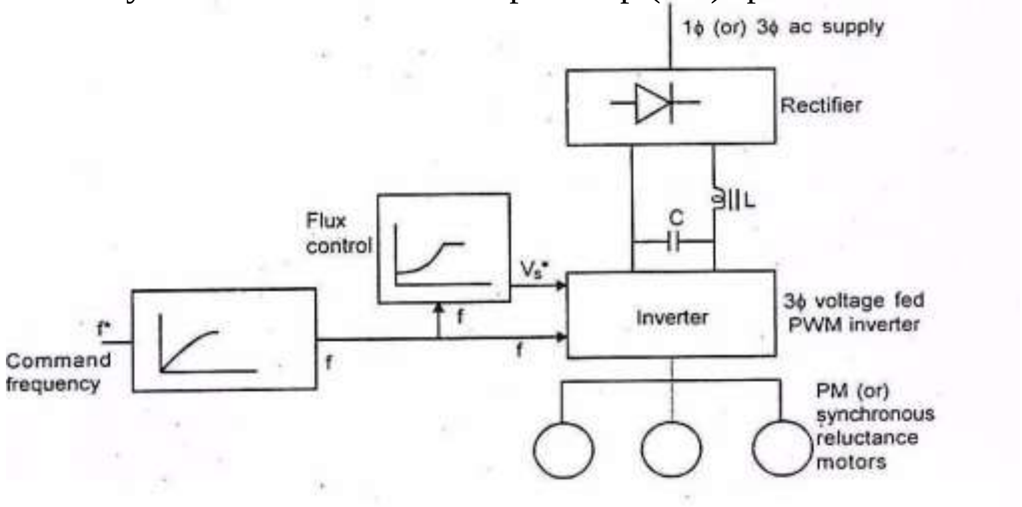


Figure3.1.1 Separate Controlled Mode

(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.