ADVANCE ELECTRIC DRIVE
Section-C

SYNCHRONOUS MOTOR:

Synchronous motor drives are close competitors to induction motor drives in many industrial applications.

They are generally more expensive than induction motor drives,but the advantages is that the efficiency is higher,which is tends to lower the life cycle cost.

The development of semiconductor variable frequency sources,such as inverters and cycloconverters has allowed their use in variable speed applications such as high power and high speed compressors,blowers ,induced and forced draft fans,main line traction,servo drives etc...

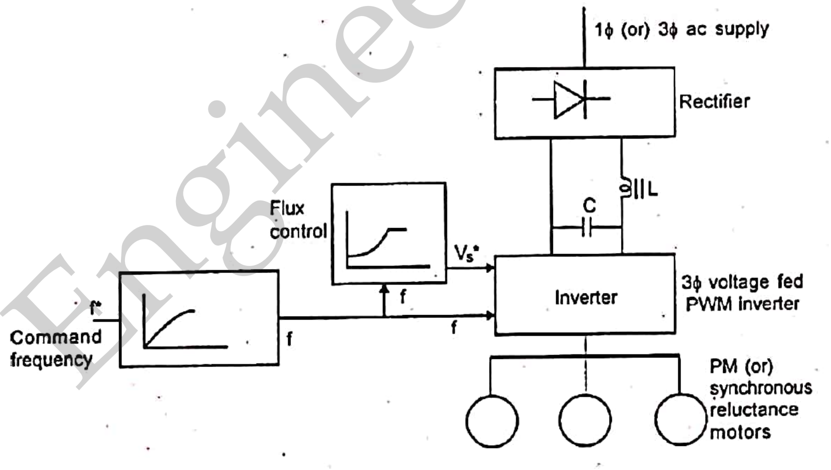
Synchronous motor variable speed Drives

VOLTAGE / FREQUENCY CONTROL (OR) VOLTS / HERTZ CONTROL (V/F):

Synchronous speed is directly proportional to frequency, similar ti induction motors constant flux operation below base speed is achieved 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.True synchronous mode
2.Separate controlled mode
3.Self-controlled mode

1. 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.



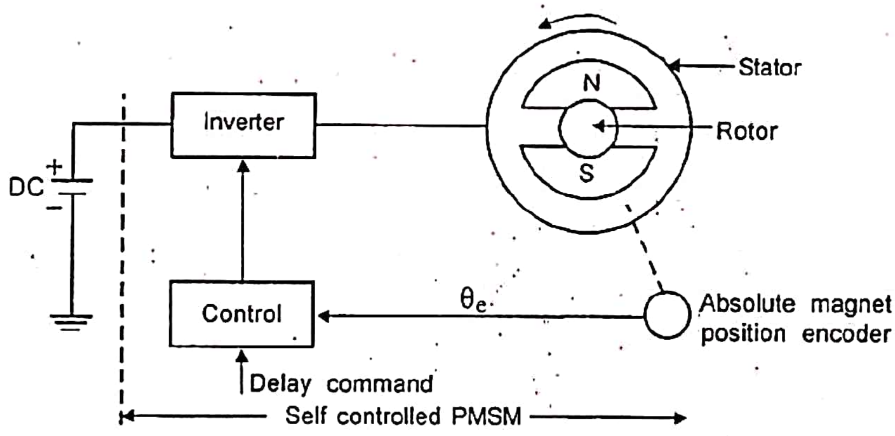
A flux control black is used which changes the stator voltage with frequency so as to maintain constant flux for speed below base speed and constant terminal voltage for speed above base speed.

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.

ADVANCE ELECTRIC DRIVE

Section-C



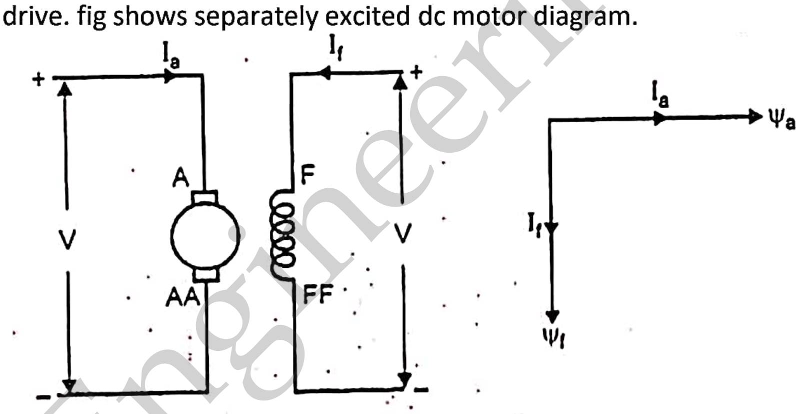
In this kind of control the machine behaviour is decided by the torque angle and voltage/ current. Such a machine can be looked upon as a dc motor having its commutator replaced by a converter connected to stator. The self controlled motor run has properties of a dc motor both under steady state and dynamic conditions and therefore, is called commutator less motor (CLM).These machines have better stability behaviour.

VECTOR CONTROL OF SYNCHRONOUS MOTOR

The vector control decouples the two components of stator current, one providing the air gap flux and the other producing the torque. It provides independent control of flux and torque, and the control characteristic is linearized.

Operating principles of vector control

Generally a vector controlled induction motor drive can operate as a separately excited dc motor drive. fig shows separately excited dc motor diagram.



In a DC machine ,the developed torque is given by

$$Td = K_t I_a I_f$$

Where

Kt – torque constant

Ia – Armature current(torque component)

If – Field current (Field component)

The construction of a DC machine is such that the field flux linkage Ψf produce by If is perpendicular to the armature flux linkage Ψa produced by Ia.

There are two current inputs are fed to the vector control.one is i*ds and other i*qs.

i*ds= direct –axis component of stator current

i*qs = quadrature –axis component of stator current

these currents are synchronously rotating reference frame.with vector control ,ids is analogous to the field current If and iqs is analogous to armature current Ia of dc motor .therefore the torque developed in an induction motor is given by

$$T_d = K_m \bar{\Psi}_r I_f$$

$$= K_t\, i_{ds}\, i_{qs}$$

$\bar{\Psi}_r$ = absolute peak value of the sinusoidal space flux linkage vector $\bar{\Psi}_r$

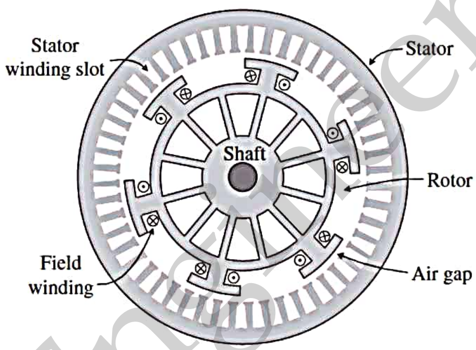
ids = field component

iqs = torque component

MODELING OF SYNCHRONOUS MOTOR:

The synchronous motor used in high-power medium voltage (MV) drives can be generally classified into two categories:wound rotor synchronous motor(WRSM)and permanent magnet synchronous motor (PMSM).

In the WRSM, the rotor magnetic flux is generated by the current in the rotor field winding while the PMSM uses permanent magnets to produce the rotor flux. Depending on the shape of the rotor and the distribution of the air gap along the perimeter of the rotor, the synchronous motor can be classified into salient-pole and cylindrical (non-salient-pole) machines.



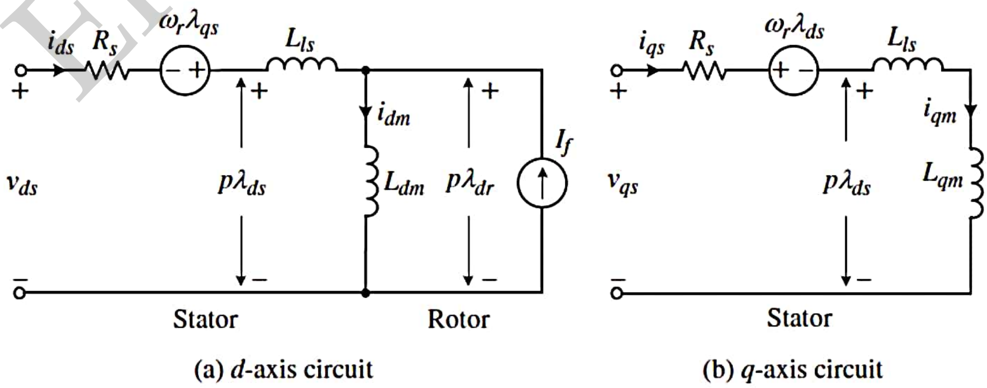


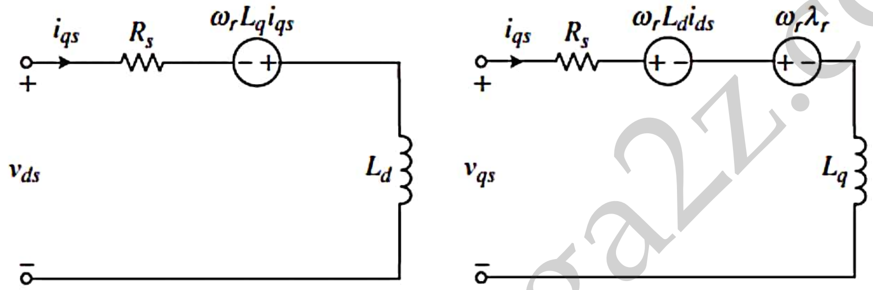
Figure 15.2-4 General *dq*-axis model of a synchronous motor in the rotor synchronous reference frame.

To simplify the synchronous motor model presented in Fig. 15.2-4, the following mathematical manipulations can be performed. The stator voltage equations for the motor can be expressed as

$$\begin{cases} v_{ds} = R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \\ v_{qs} = R_s i_{qs} + \omega_r \lambda_{ds} + p\lambda_{qs} \end{cases} \tag{15.2-1}$$

where λ_{ds} and λ_{qs} are the d- and q-axis stator flux linkages, respectively, which are given by

$$\begin{cases} \lambda_{ds} = L_{ls} i_{ds} + L_{dm}(I_f + i_{ds}) = L_d i_{ds} + \lambda_r \\ \lambda_{qs} = (L_{ls} + L_{qm}) i_{qs} = L_q i_{qs} \end{cases} \tag{15.2-2}$$



(a) d-axis circuit (b) q-axis circuit

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.

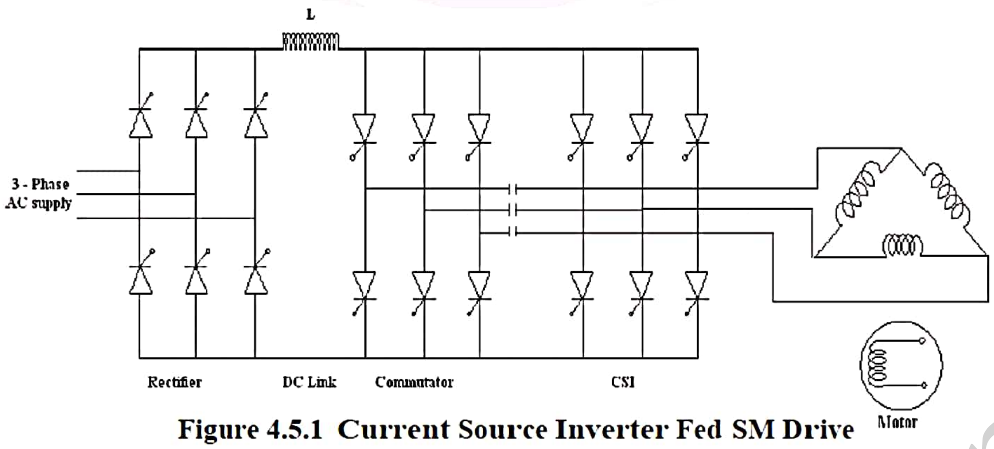


Figure 4.5.1 Current Source Inverter Fed SM Drive

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.

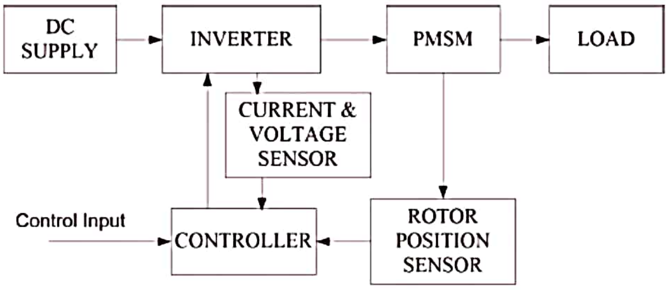
Permanent Magnet Synchronous Motor (PMSM):

One of the types of synchronous motor is the PMSM. The PMSM consists of conventional three phase windings in the stator and permanent magnets in the rotor. The purpose of the field windings in the conventional synchronous machine is done by permanent magnets in PMSM. The conventional synchronous machine requires AC and DC supply, whereas the PMSM requires only AC supply for its operation. One of the greatest advantages of PMSM over its counterpart is the removal of dc supply for field excitation

Types of PMSM
The PMSM are classified based on the direction of field flux are as follows,
1.Radial field
2.Axial field

In radial field, the flux direction is along the radius of the machine. The radial field permanent magnet motors are the most commonly used. In axial field, the flux direction is parallel to the rotor shaft. The axial field permanent magnet motors are presently used in a variety of numerous applications because of their higher power density and quick acceleration.

Section-C



The motor drive essentially consists of four main components such as the PMSM, the inverter, the main control unit and the position sensor. Interconnections of the components are shown in Figure.

BRUSHLESS DC MOTOR (BLDC):

Brushless DC motors, rather surprisingly, is a kind of permanent magnate synchronous motor. Permanent magnet synchronous motors are classified on the basis of the wave shape of their induce emf, i.e, sinusoidal and trapezoidal. The sinusoidal type is known as permanent magnet synchronous motor; the trapezoidal type goes under the name of PM Brushless dc (BLDC) machine. Permanent magnet (PM) DC brushed and brushless motors incorporate a combination of PM and electromagnetic fields to produce torque (or force) resulting in motion. This is done in the DC motor by a PM stator and a wound armature or rotor. Current in the DC motor is automatically switched to different windings by means of a commutator and brushes to create continuous motion. In a **brushless motor**, the rotor incorporates the magnets, and the stator contains the windings. As the name suggests brushes are absent and hence in this case, commutation is implemented electronically with a drive amplifier that uses semiconductor switches to change current in the windings based on rotor position feedback. In this respect, the BLDC motor is equivalent to a reversed DC commutator motor, in which the magnet rotates while the conductors remain stationary. Therefore, BLDC motors often incorporate either internal or external position sensors to sense the actual rotor.

Structure of Permanent Magnet Brushless DC Motor

BLDC motors come in single-phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. Here we focus on 3-phase motors.

Principle of operation and dynamic model of a BLDC Motor

The coupled circuit equations of the stator windings in terms of motor electrical constants are

$$v_{an} = R_a i_a + \frac{d}{dt}(L_{aa} i_a + L_{ba} i_b + L_{ca} i_c) + e_a$$

$$v_{bn} = R_b i_b + \frac{d}{dt}(L_{ab} i_a + L_{bb} i_b + L_{cb} i_c) + e_b$$

$$v_{cn} = R_c i_c + \frac{d}{dt}(L_{ac} i_a + L_{bc} i_b + L_{cc} i_c) + e_c$$

$R_a = R_b = R_c = R$

$L_{aa} = L_{bb} = L_{cc} = L_s$

$L_{ba} = L_{ab} = L_{ca} = L_{ac} = L_{bc} = L_{cb} = M$

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s & M & M \\ M & L_s & M \\ M & M & L_s \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

Since, $i_a + i_b + i_c = 0$, and with $(L_s - M) = L$, we have,

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

where,

R : Stator resistance per phase, assumed to be equal for all phases

L_s : Stator inductance per phase, assumed to be equal for all phases.

M : Mutual inductance between the phases.

i_a, i_b, i_c : Stator current/phase.

The instantaneous induced emfs can be written as given in equation (35.1), (35.2) and (35.3).

$$e_a = f_a(\theta_r)\lambda_p \omega_m \quad (35.1)$$

$$e_b = f_b(\theta_r)\lambda_p \omega_m \quad (35.2)$$

$$e_c = f_c(\theta_r)\lambda_p \omega_m \quad (35.3)$$

where, ω_m is the rotor mechanical speed and θ_r is the rotor electrical position.

The torque equation is given as,

$$T_e = \lambda_p [\, f_a(\theta_r) i_a + f_b(\theta_r) i_b + f_c(\theta_r) i_c \,]$$

The equation of motion for simple system is,

$$T_e = J\frac{d\omega_m}{dt} + T_l + B\omega_m$$

where, J is the inertia of the motor and B is the friction coefficient.

$$\Rightarrow \frac{d\omega_m}{dt} = \frac{1}{J}(T_e - T_l - B\omega_m) \quad (35.4)$$

The relation between angular velocity and angular position (electrical) is given by

$$\frac{d\theta_r}{dt} = \frac{P}{2}\omega_m \quad (35.5)$$

Advantage of Permanent Magnet Brushless DC Motor

BLDC motors have many advantages over brushed DC motors and induction motors. A few of these are:

- Better speed versus torque characteristics
- Faster dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

Section-C

COMPARISON BETWEEN BLDC AND PMSM:

- **BLDC Motors**
  - Easier to control (6 Step) and only dc currents required
  - Torque ripple at commutations
  - Lower cost but poor performance
  - Needs Hall sensors
    - sensorless is possible

- **PMSM Motors**
  - Very commonly used in servo drives with integrated shaft encoder
    - Sensorless is possible for speed control
  - More complex control (needs 3 phase sinusoidal PWM)
  - No torque ripple at commutation
  - Higher efficiency, higher Torque
  - Higher cost but high performance