

# An Approach to Design and Simulate Synchronous Machine with Excitation System Modeling

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**Abstract:** Synchronous motors are designed to run at synchronous speed. Synchronous speed defines the natural rate of rotation of the magnetic field generated in the stator of an AC machine. This rate of rotation is governed by the frequency of the voltage applied to the machine and the number of pole pairs built into the stator, and is defined by the following equation:

$$\text{Synchronous Speed, } N_s = (60 \text{ seconds/minute}) * (\text{Cycles per Second}) / (\text{RPM}) [2]$$

The stator of a synchronous motor is wound in the same manner as a three-phase induction motor, with distributed poles. When a three-phase source is applied to the stator, a rotating magnetic field develops at synchronous frequency. The rotor of a synchronous motor, however, differs greatly from that of an induction motor. In an induction motor, voltages are induced in the rotor as its windings cut lines of flux created by the rotating stator field. The induced voltages cause a flow of current in the rotor winding, creating a magnetic field in the rotor and developing torque.[2]

In a synchronous motor, applying a DC current to the rotor winding via a separate source creates the magnetic field in the rotor. This constant magnetic field could be considered a "sail" which is caught in the rotating stator field, forcing the rotor to turn at synchronous frequency. However, it must be noted that synchronous motors are not self-starting. The DC field in the rotor will only synchronize with the rotating field in the stator if the rotor is already turning at some high percentage (say 90%) of synchronous speed. Therefore, synchronous motors are never started under load and must use some sort of starter that will accelerate the rotor to near-synchronous speed while the DC excitation circuit is de-energized. A starter may be an external motor, connected to the rotor shaft during startup and disconnected when the rotor is able to synchronize with the stator field. More commonly, a squirrel cage winding is incorporated

into the rotor assembly, allowing the synchronous motor to self-start as an induction motor.[2]

**Index Terms-** AC, Ns, RPM

## I. INTRODUCTION

A Power system is said to be stable when perturbed synchronous machines: (1) come back to their original state when there is no net change of power (2) obtain a new state without losing synchronism. For large systems stability study, state space modeling technique is used. Techniques of linear system analysis such as root-locus plots, Nyquist criterion and Routh-Hurwitz criterion are used to understand dynamic behavior of the system. The given system consists of synchronous machine, exciter, amplifier portion, and regulator components.

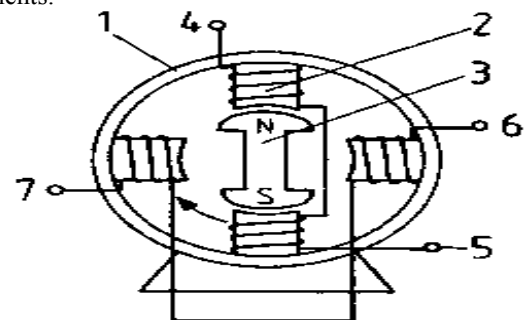


Figure 1.1: A Synchronous Machine

The numbers in the figure depicts the following

1 Casing, 2 Stator, 3 Field spider, 4 Beginning winding one, 5 End winding one, 6 Beginning winding two, 7 End winding two

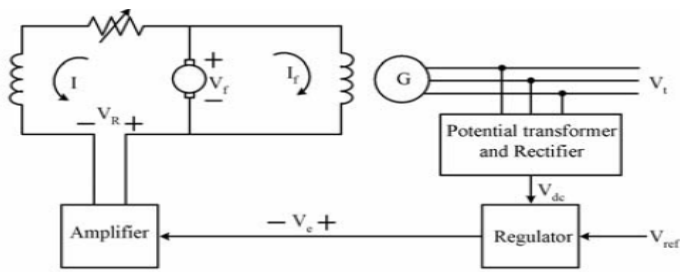


Figure:1.2 Synchronous Machine and its excitation system [1]

Three phase synchronous generators driven by turbines are used for large scale power generation. It consists of a stationary and rotating parts called as stator and rotor respectively. Armature windings arranged on stator are used for generating three phase balanced voltages and developing magnetic poles as the field winding on the rotor. A short circuited winding called as damper winding is also placed on rotor. The field circuit is excited by DC and excitation is done through slip rings and brushes by AC generators. The given synchronous machine is assumed to have three stator windings, one field winding and two damper windings. All these windings are magnetically coupled which is a function of rotor position. Therefore, flux linkage is also function of the rotor position. The instantaneous terminal voltage V of any winding is given by  $V = \pm \sum ri \pm \sum \lambda$  here ' $\lambda$ ' is the flux linkage, ' $r$ ' is winding resistance and I is stator current in a direction flowing out of the generator terminals.[3]

## II. MATHEMATICAL MODELING OF A SYNCHRONOUS MACHINE CONNECTED TO AN INFINITE BUS SYSTEM

For transient analysis, the idealized synchronous machine is represented as a group of magnetically coupled circuits with inductances which depend on the angular position of the rotor. The resulting differential equations describing the machine have time varying coefficients, and a closed form of solution is not feasible. A great simplification can be made by transformation based on two-axis theory. Park's Transformation for space vector control:

For obtaining mathematical model of synchronous machine, certain transformation of variables called as Park's transformation is done which converts all stator quantities from three phases to equivalent d-q axis. Axis along rotor winding is called direct axis and that of along neutral axis of the field winding is called quadrature axis.

$$i_{qaxis} = \left(\frac{2}{3}\right) \left[ i_a \sin \theta + i_b \sin \left(\theta - \frac{2\pi}{3}\right) + i_c \sin \left(\theta + \frac{2\pi}{3}\right) \right]$$

$$i_{daxis} = \left(\frac{2}{3}\right) \left[ i_a \cos \theta + i_b \cos \left(\theta - \frac{2\pi}{3}\right) + i_c \cos \left(\theta + \frac{2\pi}{3}\right) \right]$$

By definition of park's transformation

$$i_{odq} = P i_{abc}, V_{odq} = P V_{abc}, \lambda_{odq} = P \lambda_{abc} \text{ Where } P \text{ is given by}$$

$$P = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos \theta & \cos \left(\theta - \frac{2\pi}{3}\right) & \cos \left(\theta + \frac{2\pi}{3}\right) \\ \sin \theta & \sin \left(\theta - \frac{2\pi}{3}\right) & \sin \left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}$$

The above matrix is for RMS quantities. (Constant 2/3 is used for peak value quantities)

Location of d-axis of rotor is given by

$$\theta = \omega_R t + \delta + \pi/2$$

Where  $\delta$  is the location of q-axis or the angle between machine

EMF E and terminal voltage V and  $\omega_R t$  is the location of reference axis.

Figure given below is the schematic diagram of synchronous machine. [2]

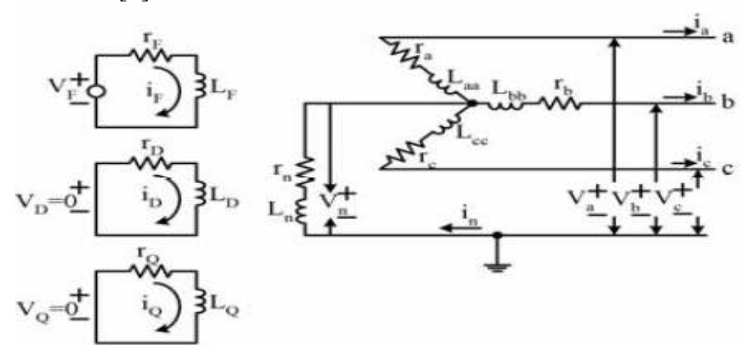


Figure: 2.1 Schematic diagram of synchronous machine

The voltages of generator in the rotor frame of reference in per unit is given by the equation

$$v = -ri - \dot{\lambda} + v_n$$

Where  $v_n$  is the neutral voltage matrix, r is the resistance diagonal matrix.

The machine equation in the rotor frame of reference following a three phase short circuit is given by

$$\begin{bmatrix} \dot{i}_d \\ -\dot{v}_F \\ v_d - 0 \\ v_q \\ \dot{i}_q \\ v_q = 0 \end{bmatrix} = \begin{bmatrix} r & 0 & 0 & \omega L_q & \omega kM_q \\ 0 & r_F & 0 & 0 & 0 \\ 0 & 0 & r_D & 0 & 0 \\ -\omega L_d & -\omega kM_d & -\omega kM_q & r & 0 \\ 0 & 0 & 0 & 0 & r_Q \end{bmatrix} \begin{bmatrix} i_d \\ i_F \\ i_D \\ i_q \\ i_Q \end{bmatrix} = \begin{bmatrix} L_d & kM_d & kM_q & 0 & 0 \\ kM_d & L_F & M_D & 0 & 0 \\ kM_q & M_D & L_D & 0 & 0 \\ 0 & 0 & 0 & L_q & kM_q \\ 0 & 0 & 0 & kM_q & L_Q \end{bmatrix}$$

The above matrix is written by omitting the zero- sequence voltage which is dependent on  $v_o$  and  $i_o$ . i.e. we are assuming that system is balanced but not necessarily steady state conditions.

The above matrix is converted to per unit values by considering three base quantities such as voltage, current and time. (Time base is fixed by rated radian frequency)

Compact notation in state space of above matrix is given by

$$V = -(R + wN)t - L\dot{i} \quad (\text{Or})$$

$$\dot{i} = -L^{-1}(R + wN)t - L^{-1}v$$

Where

$$L_d = L_s + M_s + \frac{3}{2}L_m, \quad L_q = L_s + M_s - \frac{3}{2}L_m$$

R- Resistance matrix

N- Matrix of speed- voltage inductance coefficients

L- Inductance matrix

The above equation can be schematically represented by the following figure

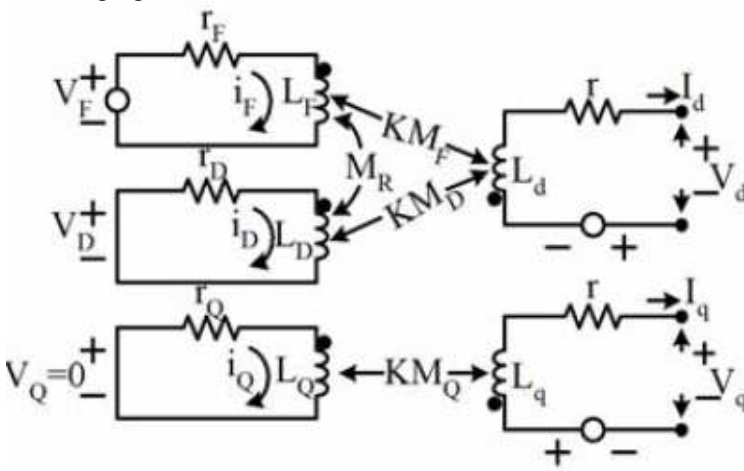


Figure 2.2 Equivalent d-q axis circuit

In the above figure, speed voltage terms represent the controlled sources.

Three phase power is given by:

$$P_{3\phi}(t) = i_d v_d + i_q v_q$$

Note: The power output is invariant under park's Transformation.

Torque equation in d-q axis is given by

$$T_E = \frac{\partial P}{\partial w} = i_d \lambda_q - i_q \lambda_d$$

Here state space analysis is based on current formulation because it has an advantage of offering simple relations between the

voltages  $v_d$  and  $v_q$  and the state variables.

Now incorporating the state variables  $\delta$  and  $w$  in the state space equation gives the overall system state space equation as given by

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{w} \\ \dot{\delta} \end{bmatrix}_{7 \times 1} = \begin{bmatrix} -L^{-1}(R + wN)_{3 \times 3} & & & & & & \\ & 0 & 0 & & & & \\ & 0 & 0 & & & & \\ \frac{L_d i_q}{3T_j} & -\frac{kM_f i_f}{3T_j} & -\frac{kM_D i_D}{3T_j} & -\frac{L_q i_d}{3T_j} & -\frac{kM_Q i_Q}{3T_j} & -\frac{D}{3T_j} & \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}_{7 \times 7} \begin{bmatrix} i_d \\ i_q \\ w \\ \delta \end{bmatrix}_{7 \times 1} + \begin{bmatrix} -L^{-1}v_{3 \times 1} \\ T_m \\ \frac{1}{3T_j} \\ -1 \end{bmatrix}_{7 \times 1}$$

Now we have set of load equations for each machine in the form given by

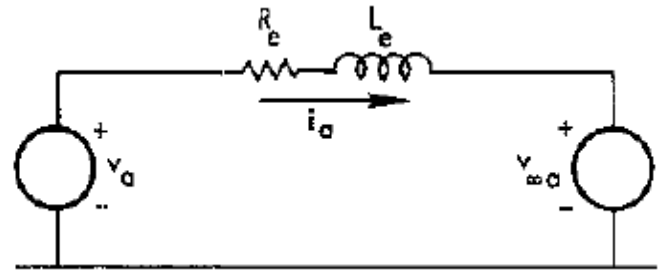
$$\dot{x} = f(x, v, T_m)$$

Let us assume that  $v_F$  and  $T_m$  are known. But the above equation does not completely describe the synchronous machine

because there are 2 auxiliary variables  $v_d$  and  $v_q$ . For writing additional equations for those variables we need to know the terminal conditions of the machine. Terminal voltage of synchronous machine is controlled by excitation system. For simple illustration, load constraint can be satisfied by one machine-infinite bus system.[3]

### 2.1 One machine-Infinite bus system

Below figure represents the synchronous machine connected to infinite bus through a transmission line having resistance  $R_s$  and inductance  $L_s$  whose voltages and current only for one phase are shown with an assumption of no mutual coupling between phases.



We can write KVL equation as

$$v_{abc} = v_{xabc} + R_s U i_{abc} + L_s U \dot{i}_{abc}$$

The above equation after transforming to 0-d-q frame of reference by park's transformation we get

$$v_{0dq} = P v_{abc} = v_x \sqrt{3} \begin{bmatrix} 0 \\ -\sin(\delta - \alpha) \\ \cos(\delta - \alpha) \end{bmatrix} + R_s i_{0dq} + L_s \dot{i}_{0dq} - w L_s \begin{bmatrix} 0 \\ -i_q \\ i_d \end{bmatrix}$$

Where  $\delta = w$

It can be observed that above equation have two nonlinearities: one due to speed voltage term and other due to trigonometric functions in the first term. Linearizing the above equation about

an equilibrium point ( $\delta_0, w_0, i_{q0}, i_{d0}$ ) we get:

$$v_{d\Delta} = -\sqrt{3}v_{xc} \cos(\delta_0 - \alpha) \delta_\Delta + R_s i_{d\Delta} + w_0 L_s \dot{i}_{q\Delta} + i_{q0} L_s w_\Delta + L_s i_{d\Delta}$$

$$v_{q\Delta} = -\sqrt{3}v_{xc} \sin(\delta_0 - \alpha) \delta_\Delta + R_s i_{q\Delta} - w_0 L_s \dot{i}_{d\Delta} - i_{d0} L_s w_\Delta + L_s \dot{i}_{q\Delta}$$

For small displacements, the above equations can be written as:

$$v = -Kx - M\dot{x}$$

Matrices M and K represents the synchronous machine constants, transmission line constants, and infinite bus voltage.

The above equation in state space representation is given by

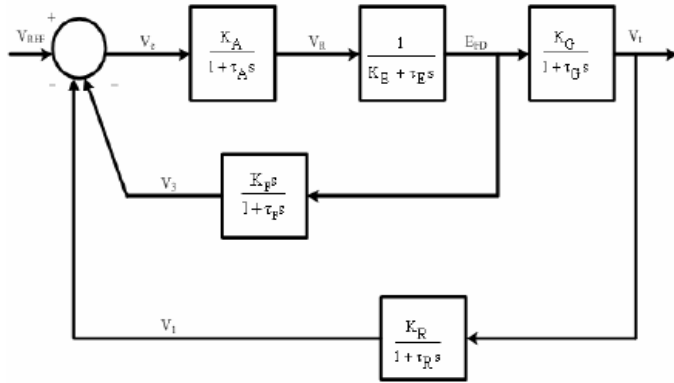
$$\dot{x} = -M^{-1}Kx - M^{-1}v \quad [3]$$

### 2.2 Buck-Boost Excitation system

A power system is nearly a constant voltage source and is made so because of system component design and close voltage control. This means that Thevenin's impedance seen looking in

to source is very small. Fast excitation helps keep this impedance small during disturbances and contributes to system stability by allowing the required transfer of power even during disturbances. Therefore excitation system is of significant importance in the power system.

Given below is the block diagram for the buck-boost excitation system with compensation. This compensation makes the root locus bend near  $j\omega$  axis crossing in order to improve stability substantially.



From the block diagram, the equations of excitation system which controls the generated EMF of generator are given by:

$$\begin{aligned} \dot{v}_1 &= \left(\frac{k_R}{\tau_R}\right) v_i - \left(\frac{1}{\tau_R}\right) v_1 \\ \dot{v}_3 &= \left(\frac{k_F}{\tau_F}\right) E_{FD} - \left(\frac{1}{\tau_F}\right) v_3 \\ \dot{v}_R &= \left(\frac{k_A}{\tau_A}\right) v_e - \left(\frac{1}{\tau_A}\right) v_R \\ E'_{FD} &= \left(\frac{1}{\tau_E}\right) v_R - \left(\frac{S_E + k_E}{\tau_E}\right) E_{FD} \\ v_e &= V_{REF} + v_2 - v_1 - v_3 \end{aligned}$$

Using the above data state space matrix was constructed. Characteristic Matrix A was constructed and it was observed that the roots have negative real parts which indicate that system is stable. Then terminal voltage and machine currents were calculated from state space equations and corresponding plots are plotted. Analysis of the current plots show that they consist of Fundamental frequency component which is symmetrical with respect to the time axis and its superposition on the dc component gave an unsymmetrical waveform. The degree of asymmetry depends upon the point of the voltage cycle at which the short circuit takes place. Field current has dc and ac components with ac component decaying. Ac component of field current consists of fundamental as well as second harmonic but its second harmonic is relatively small.[3]

### III. SYNCHRONOUS MACHINES

Rotating machine that rotate at a speed fixed by the supply frequency and number of poles are called Synchronous

machine. The speed of synchronous is given by

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

where  $f$  = frequency of supply,  $P$  = Number of poles. There are two types of synchronous machines

- (i) Rotating armature type (ii) Rotating field type

### 3.1 Advantages of Rotating field

Most alternators have the rotating field and stationary armature. The rotating field type alternator has following advantages over the rotating armature type alternator.

A stationary armature have is more easy to to insulate for high voltage. This generated voltage may be as high as 33 KV (33000 Volt).

The armature-winding can brace better mechanically against high electromagnetic forces due to large short circuit current when the armature windings are in the stator.

The armature winding, being stationary are not subject to vibration and stresses due to centrifugal forces.

The rotating field is supplied with direct current. Usually the field voltage is in between 100 to 500 V, which is easily fed to rotating field with the help of slip rings.

The output current can be taken directly from fixed terminals on the stationary armature without using slip rings and brushes etc.

The weight of the armature windings is substantially greater than the windings of the poles. The size of machine is therefore reduced.

Rotating field is comparatively light and can be constructed for high-speed rotation.

The armature of large alternators are forced cooled with circulating gas or liquids so stationary armatures are easy to cool.

### 3.2 Stator Construction

The stator has various parts such as frame, stator core, stator winding and cooling arrangement. The frame may be of cast iron for small size machines and welded steel type for large size machines. In order to reduce Hysteresis and eddy current losses, the stator core is assembled with high grade silicon steel laminations.

### 3.3 Rotor Construction

#### 3.3.1 Salient Pole Rotor:

The salient poles are made of thick steel laminations riveted together and fixed to rotor by a dove tail joints. The pole faces are usually provided with slots for damper winding. These dampers are useful to prevent rotor oscillations during sudden changes in load. The pole faces are so shaped that the radial air gap length increases from the pole center to the pole tips so that the flux distribution over armature is sinusoidal. The ends of the field windings are connected to a dc source through slip rings carrying brushes. The salient pole field structure has following special features [4]:

- a) They have large diameter and short axial length.
- b) The pole shoes cover about 2/3 of pole pitch.
- c) They are suitable for low speed operation (100 to 375 rpm). So they are used in hydraulic turbines.

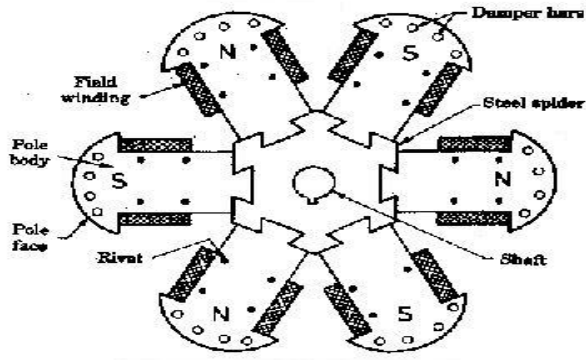


Figure 3.1 Salient pole Rotor

**3.3.2 Cylindrical Rotor:** Cylindrical rotors are used in very high speed alternators driven by steam turbines in thermal power plants. To reduce the peripheral velocity, the diameter of the rotor is reduced and axial length is increased. Such rotors have two or four poles. The cylindrical rotors are made from solid forgings of high-grade steel. In about two third of rotor periphery, slots are cut at regular intervals and parallel to the shaft. Due to long axial length and small diameter limits the centrifugal forces and has greater mechanical strength. So this type of construction is suitable for high-speed operation. Cylindrical rotors has following special features:

- a) They are of small diameter and very long axial length.
- b) Less windage losses.
- c) High operating speed (3000 rpm)
- d) Robust construction and noiseless operation.

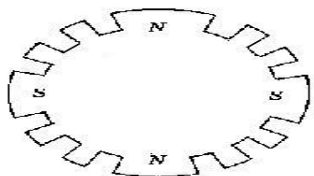


Figure 3.2 Cylindrical Rotor

**3.3 Production of Rotating Magnetic Field:** A rotating magnetic field is a field which is constant in magnitude but axis of direction rotates in space.

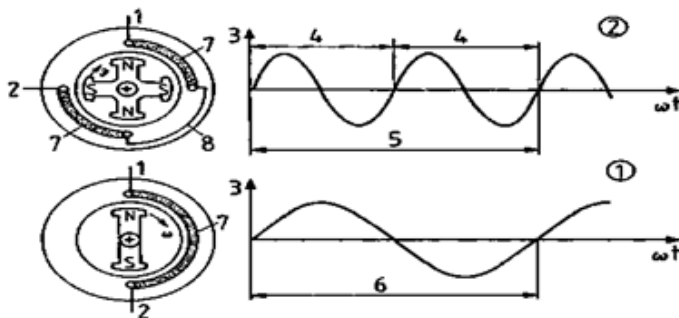


Figure 3.3 Interdependence of pole pair number and frequency in a synchronous machine

(1) Two-pole generator, (2) Four-pole generator

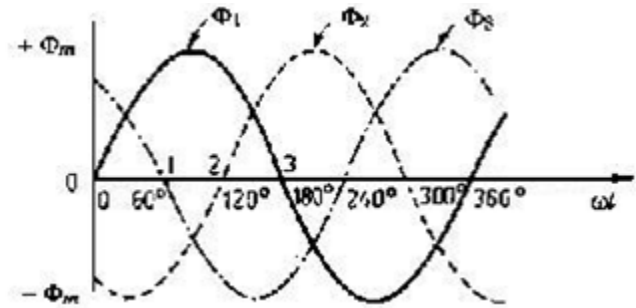
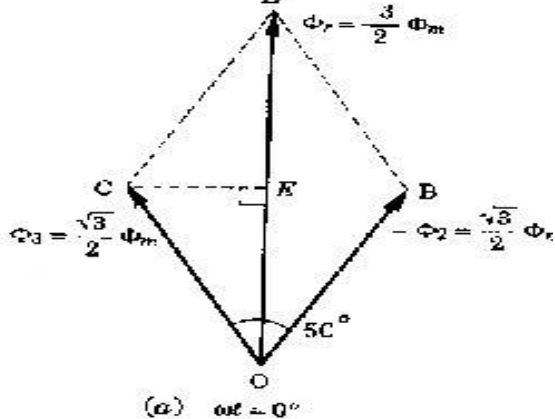


Figure 3.4 Waveform of fluxes produced by the three coils.

The maximum value of the flux due to the three phases is  $\phi_m$ . The resultant flux  $\phi_r$  at any instant is equal to the phasor sum of the fluxes due to three phases. We shall determine the value of  $\phi_r$  at four instants 60° apart corresponding to points 0,1,2,3 in fig. (b).



(i) When  $\omega t = 0$

$$\phi_1 = \phi_m \sin \omega t = \phi_m \sin 0 = 0$$

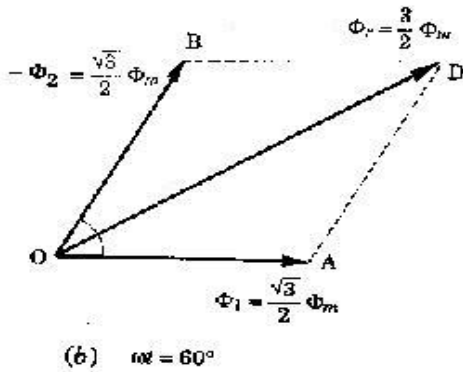
$$\phi_2 = \phi_m \sin(\omega t - 120^\circ) = \phi_m \sin(-120^\circ) = -\frac{\sqrt{3}}{2} \phi_m$$

$$\phi_3 = \phi_m \sin(\omega t + 120^\circ) = \phi_m \sin(120^\circ) = \frac{\sqrt{3}}{2} \phi_m$$

$\phi_2$  is shown by OB,  $\phi_3$  along OC. The resultant flux  $\phi_r$  is the phasor sum of OB and OC. Thus  $\phi_r$  is equal to phasor OD

$$\phi_r = OD = 2 OC \cos 30^\circ = 2 * \frac{\sqrt{3}}{2} \phi_m \frac{\sqrt{3}}{2} = \frac{3}{2} \phi_m$$

(ii) When  $\omega t = 60^\circ$



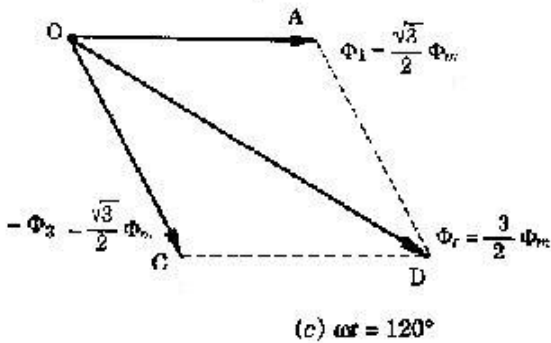
$$\phi_1 = \phi_m \sin 60^\circ = \frac{\sqrt{3}}{2} \phi_m$$

$$\phi_2 = \phi_m \sin(60^\circ - 120^\circ) = \phi_m \sin(-60^\circ) = -\frac{\sqrt{3}}{2} \phi_m$$

$$\phi_3 = \phi_m \sin(60^\circ + 120^\circ) = \phi_m \sin(180^\circ) = 0$$

$$\phi_r = OD = 2 OA \cos 30^\circ = 2 * \frac{\sqrt{3}}{2} \phi_m * \frac{\sqrt{3}}{2} = \frac{3}{2} \phi_m$$

(iii) When  $\omega t = 120^\circ$



$$\phi_1 = \phi_m \sin 120^\circ = \frac{\sqrt{3}}{2} \phi_m$$

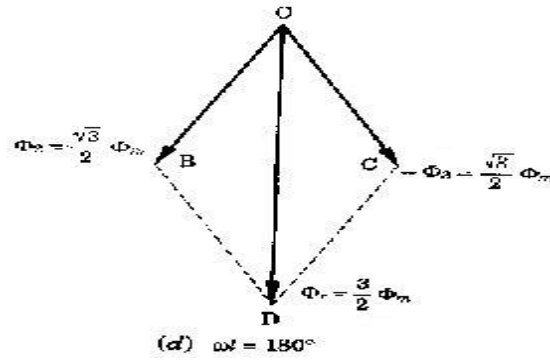
$$\phi_2 = \phi_m \sin(120^\circ - 120^\circ) = \phi_m \sin(0^\circ) = 0$$

$$\phi_3 = \phi_m \sin(120^\circ + 120^\circ) = \phi_m \sin(240^\circ) = -\frac{\sqrt{3}}{2} \phi_m$$

$$\phi_r = OD = 2 OA \cos 30^\circ = 2 * \frac{\sqrt{3}}{2} \phi_m * \frac{\sqrt{3}}{2} = \frac{3}{2} \phi_m$$

(iv) When  $\omega t = 180^\circ$

$$\phi_1 = \phi_m \sin 180^\circ = 0$$



$$\phi_2 = \phi_m \sin(180^\circ - 120^\circ) = \phi_m \sin(60^\circ) = \frac{\sqrt{3}}{2} \phi_m$$

$$\phi_3 = \phi_m \sin(180^\circ + 120^\circ) = \phi_m \sin(300^\circ) = -\frac{\sqrt{3}}{2} \phi_m$$

$$\phi_r = OD = 2 OB \cos 30^\circ = 2 * \frac{\sqrt{3}}{2} \phi_m * \frac{\sqrt{3}}{2} = \frac{3}{2} \phi_m$$

$$\phi_r = \frac{3}{2} \phi_m$$

It is seen that the resultant flux is constant in magnitude but changing in direction.

#### IV. SYNCHRONOUS MOTOR

In the synchronous motor the field structure is energized by direct current, whereas the armature winding is connected to a 3φ AC supply. Such a machine requires two sources one is DC to excite the field and other is AC for driving the armature.

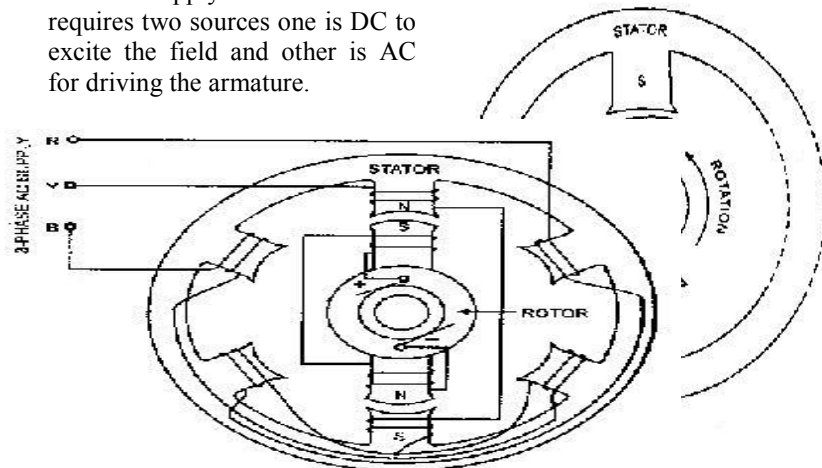
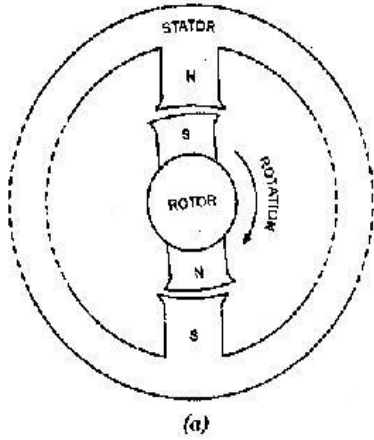


Figure 4.1 Three Phase Synchronous Motor

A synchronous motor may have either a revolving armature or a revolving field, but the revolving field construction is more common. The essential parts of a 3 phase synchronous motor are (1) Laminated stator core with 3 phase armature winding (2) Rotating field structure with damper winding and slip rings (3) Brushes and brush holders (4) Two ends shields to house the bearings that support the rotor shaft. Damper windings are also used for starting.

4.1 Principle of operation of Synchronous motor:- Figure shows a 3 phase, two pole synchronous machine. The rotor has two poles and stator has two poles per phase. As motor is excited from DC supply, so the poles of the rotor retains the same polarity throughout but the polarity of stator poles changes as it is connected to an AC supply.

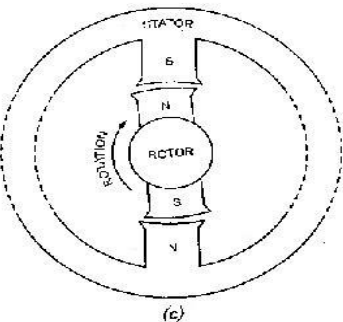


Initially the rotor is stationary as shown in fig. (a). At this instant of the rotor S-pole is attracted to the stator N pole and therefore, the rotor tends to rotate in clockwise direction. After half time period  $\left(\frac{T}{2} \text{ Sec}\right)$  the polarity of stator pole is reversed but polarity of rotor poles remains same.

At this instant S-pole is repelled by the stator S-pole as shown in fig.(b). Thus the torque acting on the rotor of synchronous motor is of pulsating nature not unidirectional. Due to inertia rotor will not move in any direction. **So the synchronous motors have no self starting torque or synchronous motors are not self starting.**

Now consider the rotor is rotating in clockwise direction by some external means. The rotor S-poles is attracted to stator N-pole and torque act on rotor in clockwise direction. After half a time period the polarity of stator pole is reversed. But if the rotor is rotated at such a speed by some external means at starting moment that rotor S-pole advances by a pole pitch so that it is again under the influence of stator N-pole as shown in fig. (c). The torque acting on the rotor will again in clockwise direction. Hence a continuous torque will be obtained. Hence to obtain a continuous torque it is necessary that the rotor rotates at such a speed that it moves through a distance equal to pole pitch in half

the time period i.e.  $\frac{T}{2}$  or  $\frac{1}{2f}$  seconds. If there are P poles the complete revolution should take  $\frac{P}{2f} * 60$  revolution per minute. Hence to obtain continuous torque the rotor should rotate at synchronous



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

speed i.e.

**4.2 Effect of Load on Synchronous Motor:** All the electric motors, whether DC or AC act as generator at the same time they are motoring. This is true because an emf is always induced and opposes the applied voltage. The opposing induced emf limits the armature current. In case of synchronous motors the speed is remains constant irrespective magnitude of load. Since the synchronous motor has no self-starting torque therefore first it is driven by some external means and is synchronized with the supply. At the instant of synchronizing the induced emf across the stator of motor is equal to the applied line voltage V but opposite in the direction. After synchronizing the external means is removed and the motor tends to slow down. There is no change in speed. There is a little shift in relative position of two poles, which continue to rotate at synchronous speed. The rotor poles fall back a little relative to stator pole. The angular displacement between the rotor and stator pole is known as delta and it is denoted by  $\delta$ . The applied voltage and induced emf are no longer in direct opposition since induced emf at this instant lags behind the induced emf at the synchronizing instant by an angle  $\delta_0$ .

$$I_0 = \frac{E_R}{Z_S}$$

The resultant voltage ER causes a current  $I_0$  to flow in the stator winding, where  $Z_S$  is the synchronous impedance per phase of the armature circuit.  $I_0$  lags ER by an angle  $\theta$ , called

$$\theta + \tan^{-1} \frac{X_S}{R_e}$$

the internal angle where  $X_S$  and  $R_e$  being the stator synchronous reactance and effective resistance respectively. Hence on no load motor draws power equal to  $V I_0 \cos \phi_0$  from the supply mains. Now when the motor is loaded, it shows down momentarily to adjust itself to the change in loading conditions, so the poles falls back a little more relative to the stator pole. Now the torque angle increases with the increase in load. Due to increase in load angle  $\delta$ , the resultant voltage ER across the armature circuit increases so the current drawn from supply increases. Thus a synchronous motor is able to supply increased mechanical load, not by reduction in speed, but by shift in relative position of rotor and rotating magnetic field. If the load is increased to a very high value the rotor will pull out of synchronism, after which it will come to stand still.

**4.3 Effect of Varying Excitation On Armature Current And Power Factor:**

The change in field excitation neither affects the speed of motor nor the output of motor. It only affects the power factor. The operation of a synchronous motor at a constant supply voltage demands nearly constant flux. When DC excitation is weak, the flux produced by it is weak and needs strengthen, so stator draws current lagging behind the supply voltage by 90°, so the input current results in low lagging power factor as shown in fig (b). If the excitation increases up to 100%, the magnetizing current drawn from supply is reduced and power factor improves as shown in fig (a). If the excitation further increased such that

power factor becomes unity, the stator draws only energy or active component and DC field circuit supply all the current necessary to magnetizing the rotor. Further increase in excitation the field produced by it becomes stronger than it is required and needs demagnetizing. The motor draws the leading current so as to demagnetize the main field. In this condition machine behaves like **"Synchronous Condenser"**.

**Advantages of Damper Winding:** When the motor is over loaded it does not stop. It continues running as a squirrel cage induction motor. When the speed falls below synchronism due to over loading an emf is induced in damper winding. Due to this emf a torque is produced which keep motor running.

**Disadvantages:** Since damper winding resistance is low so at the time of starting it takes large current from supply mains.

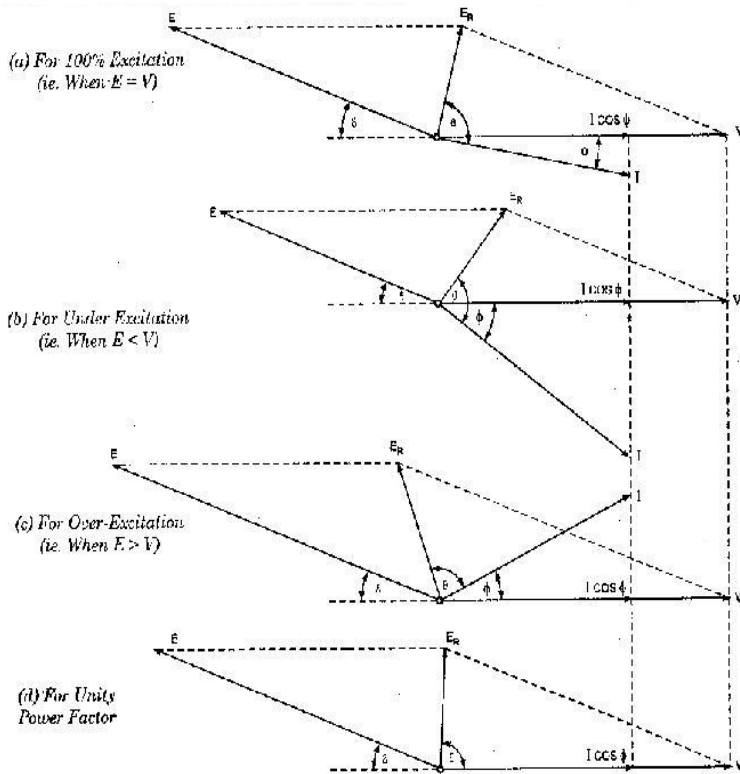


Figure 4.2 Effect of Varying Excitation on Armature Current and Power Factor

**4.4 Merit and Demerits of Synchronous Motors**

**Merits:**

- i. Power factor can easily be controlled.
- ii. The speed is constant and independent of load.
- iii. These motors can be constructed with wider air gap than induction motors.
- iv. These motors usually operate at higher efficiency.

**Demerits:**

- i. Cost per KW is higher than induction motor.
- ii. It requires DC excitation.

- iii. Synchronous motors are not self-starting, additional arrangements are used to make it self-starting.
- iv. It has tendency to hunt.
- v. It cannot be used for variable speed jobs as there is no possibility of speed adjustment.
- vi. It may fall out of synchronism and stop when over loaded.

**4.5 Applications of Synchronous Motors:**

Synchronous motors are mainly used in constant speed applications. 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 fans, mainline traction, servo drivers etc. The synchronous motors behaves like variable inductor or variable capacitor, it is used in power transmission systems to regulate the power factor.

**V. RESULTS**

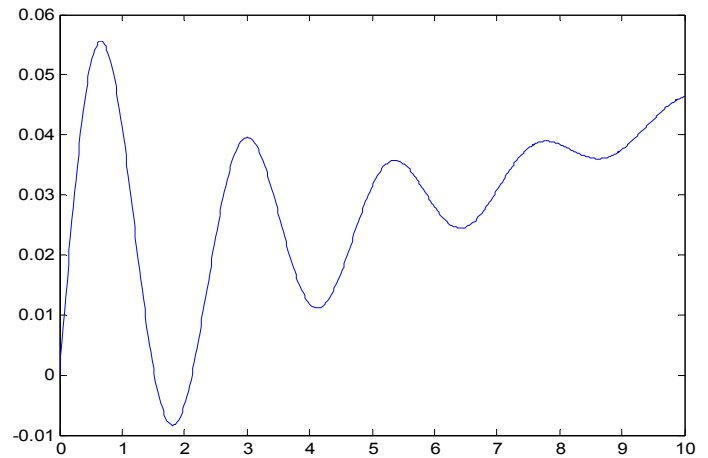


Figure 5.1: Output Field current

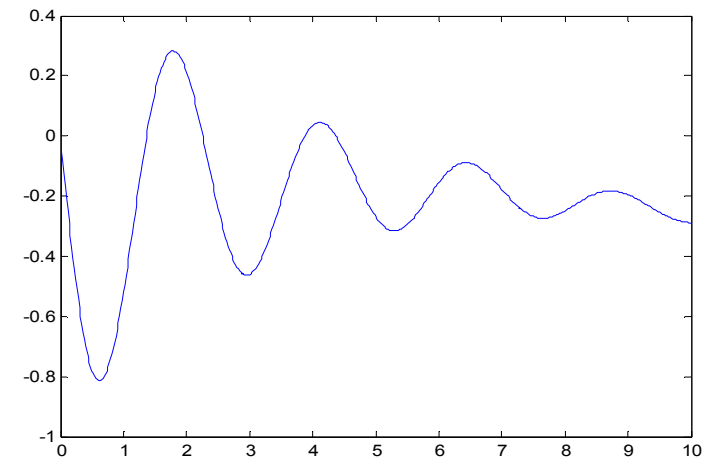
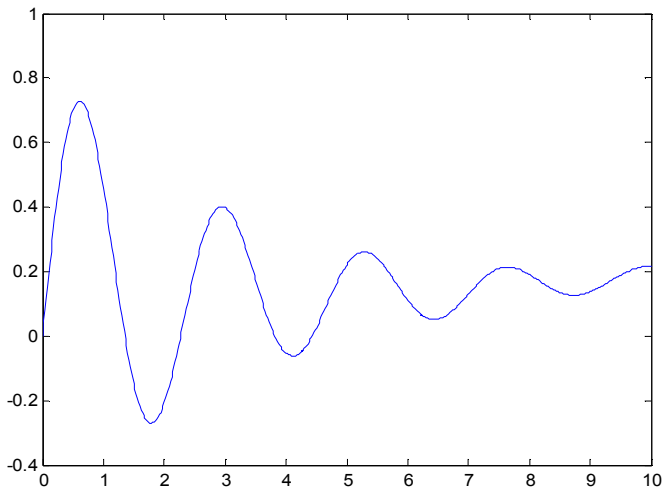
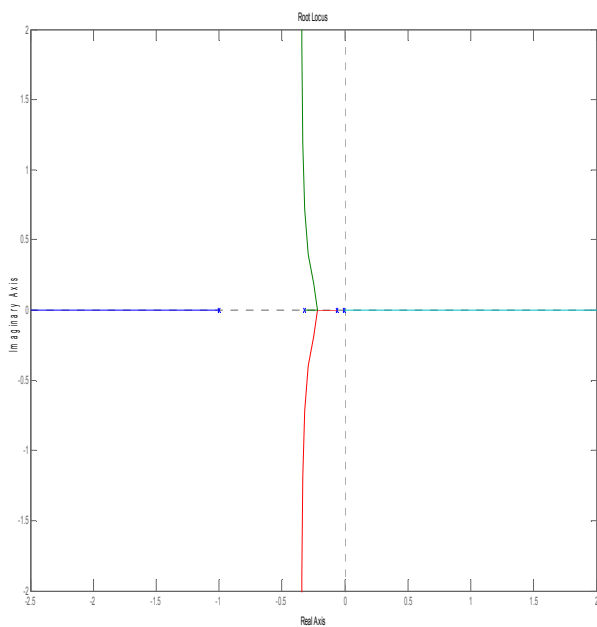


Figure 5.2: d-axis stator current

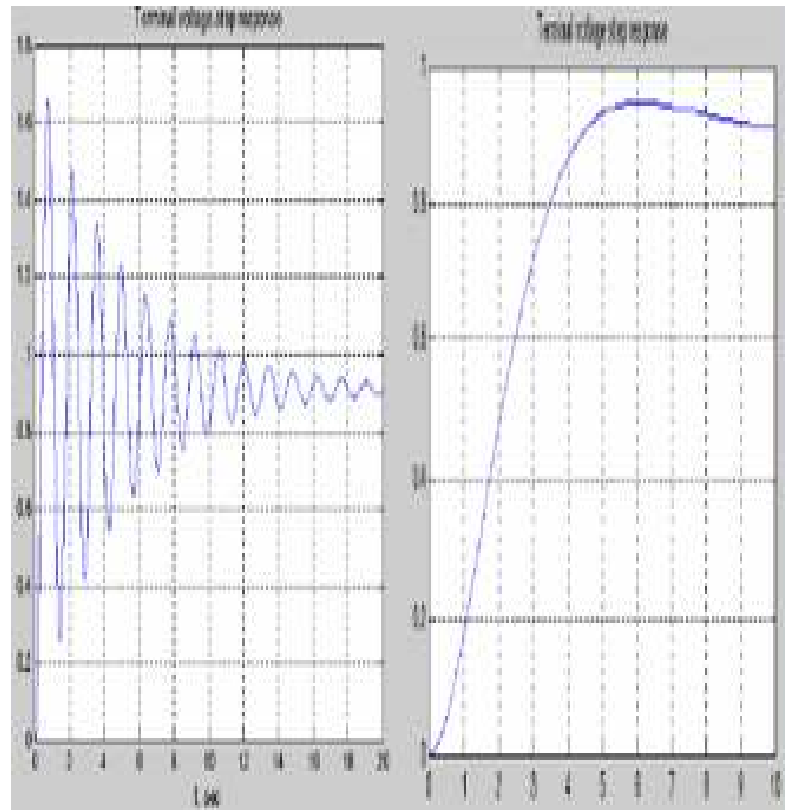




**Figure 5.3: d-axis damper current**



**Figure 5.4 Root Locus**



**Figure 5.5: Step response of Terminal Voltage**

- (a) Without stabilizer feedback**
- (b) With stabilizer feedback**

VI. 6. CONCLUSIONS

A mathematical model of synchronous machine with buck-boost excitation system has been developed. Sample data has been taken from [1] in order to perform the required numerical calculations for state space representation. In the project important concepts such as per unit system, park's transformation, one machine-infinite bus system, state space modeling, Linearization, buck-boost excitation system. Using MATLAB, the transient and control performance of overall system is studied. Eigen value method for close loop system and Root locus plots for open loop system have been used to determine the steady state power system stability. For load change observed, exciter has stabilizing effect due to its ability to maintain flux linkages and voltage nearly constant. The simulation results indicated that response is highly oscillatory with a large overshoot and long settling time. And also it was observed that there is a tradeoff between steady state error and satisfactory transient response.

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