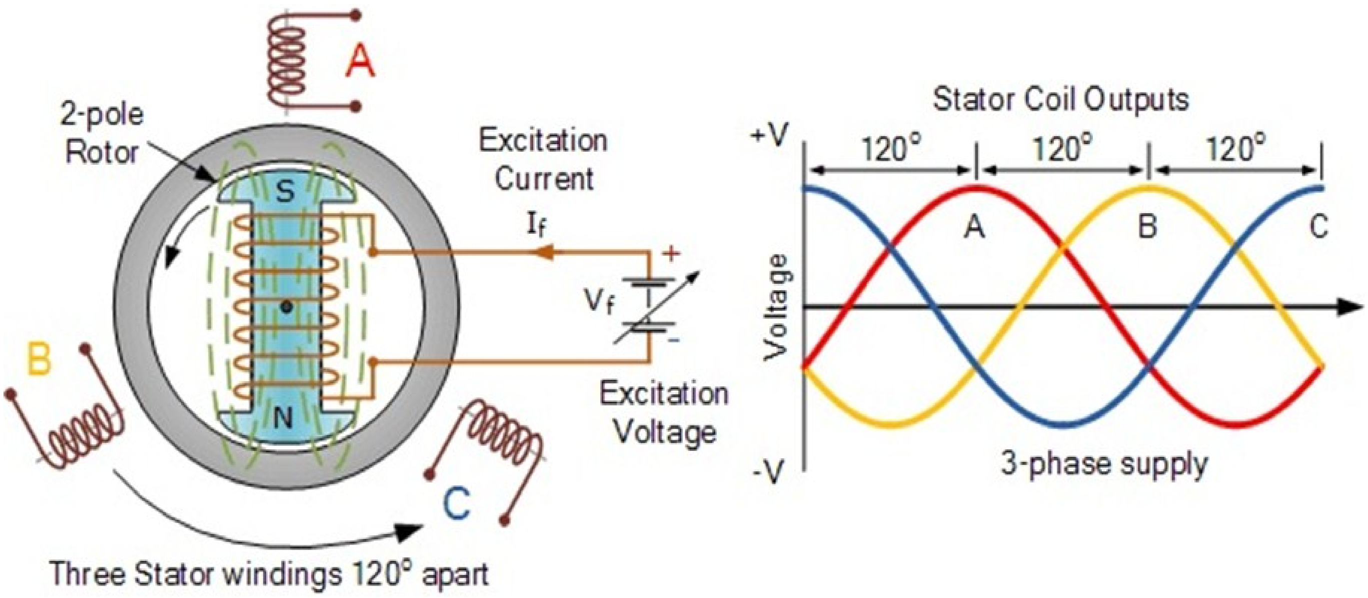
OPERATION & CHARACTERISTICS OF SYNCHRONOUS GENERATOR

The machine which produces 3-phase electrical power from mechanical power is called an alternator or synchronous generator. Alternators are the primary source of all the electrical energy we consume. These machines are the largest energy converters found in the world.

Alternator Operation :

Synchronous generators also are called alternators. In synchronous generator rotor's winding is supplied by a DC power source, generating a magnetic field. When rotor rotates in synchronous speed, a sinusoidal AC voltage is induced in each stator's phase winding. This is the principle of electromagnetic induction.



The value of induced voltage phase A of stator is:

$$E_A = V \cdot \sin(\omega t) \qquad (1)$$

Being that (V) is amplitude voltage, (w) is angular speed ,and(t) is time. While voltages in B and C phases respectively are.

$$E_B = V \cdot \sin(\omega t - 120°) \qquad (2)$$

$$E_C = V \cdot \sin(\omega t + 120°) \qquad (3)$$

The r.m.s of induced e.m.f.'s in each phase of an alternator is calculated according to equation (4), whrer T is number of turns per phase , Φp is flux per pole ,k_p and k_d, the pitch factor and the distribution factor.

$$E_{r.m.s.} = 4.44\ k_p\ k_d\ f\ T\ \Phi_p \quad \text{volts per phase} \qquad (4)$$

If the alternator is star connected, the alternator line voltage is,

$$E_L = \sqrt{3}\ (E_{r.m.s.} \text{ per phase}). \qquad (5)$$

Armature Synchronous Reactance :

When the current pass through the stator conductors the flux is set up, and a portion of this flux does not cross the air gap but completes the path inside the stator as shown in Fig. 1. This flux is known as **leakage flux**,

The magnitude of the leakage inductance in practical units,henrys,

is given by the general equation :

L = (Flux in webers per amperes**) * (**No. turns**)** henrys

And leakage reactance per phase,

$$X_l = \omega L = 2\pi f L \quad \text{ohms/ph}$$

X_l causes a voltage drop in alternator terminal voltage and this drop is equal to an e.m.f. set up by the leakage flux. Also, there is another source causes voltage drop , that is due to armature reaction which can be represented by a fictitious reactance X_a.

The summation of both reactances leads to the per phase synchronous reactance of armature winding Xs .

$$X_l + X_a = Xs$$

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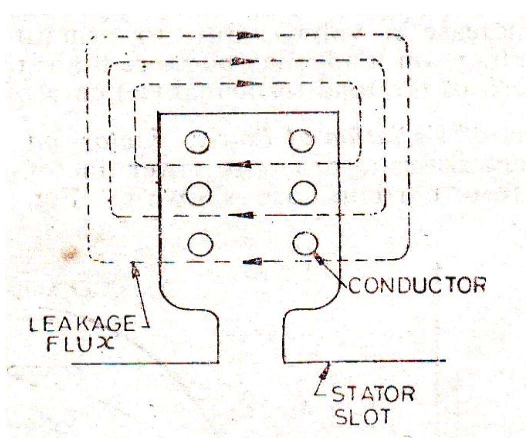

Fig 1

Synchronous Generator Characteristics :

(i) *Magnetisation curve*:

A plot of the exciting current versus terminal voltage of alternator is known as the magnetisation curve. This magnetisation curve is obtained by passing different values of currents in exciting windings, thereby giving, correspondingly different values of terminal voltage. The **no load magnetisation curve** is shown in Fig.2-I] ,which has the same general shape as ***B-H*** curve of armature steel.

The **full load magnetisation characteristics** with unity power factor and with 0.8 lagging power factor have been shown at (II) and (III) in Fig.2.

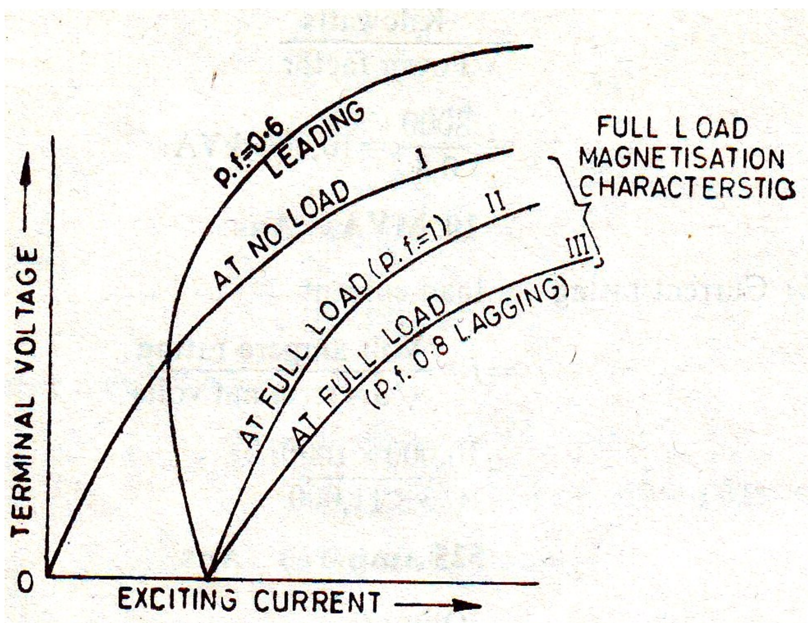

Fig. 2 Magnetization curves for alternator at different loading conditions

(ii) *Load characteristics* :

If the speed and exciting current remain constant, the terminal voltage of the alternator changes with the load currents. **The plot between the terminal voltage and the load (or armature) current of an alternator is known as load characteristics.** An increase in the armature (or load) currents make the terminal voltage drops. This has been shown in Fig. 3. The drop in terminal voltage is attributed to many reasons but primarily because of the following:

(a) Resistance and reactance of the armature (or stator) winding.

(b) Armature reaction.

The resistance and reactance of the armature winding causes the drop in generated e.m.f. (voltage) ,whereas the armature reaction weakens the magnetic field and thereby decreases the generated e.m.f. (voltage).

The magnitude of the effect of armature reaction depends upon, the power factor of load i.e. angle of lag or lead of the stator (armature) current. In case of a unity power factor of load, each phase of alternator when connected to the load takes a current which is in phase with its generated voltage. But the magnetic field is strengthened, instead of weakening, if the load (or armature) current, is leading. In the above case, when the power factor is leading, the drop in voltage due to resistance and reactance of stator winding may be less than the increase in voltage due to armature reaction. Thus the terminal voltage on load may be more than that at no-load, if the angle of lead of the load (or armature) current is sufficient.

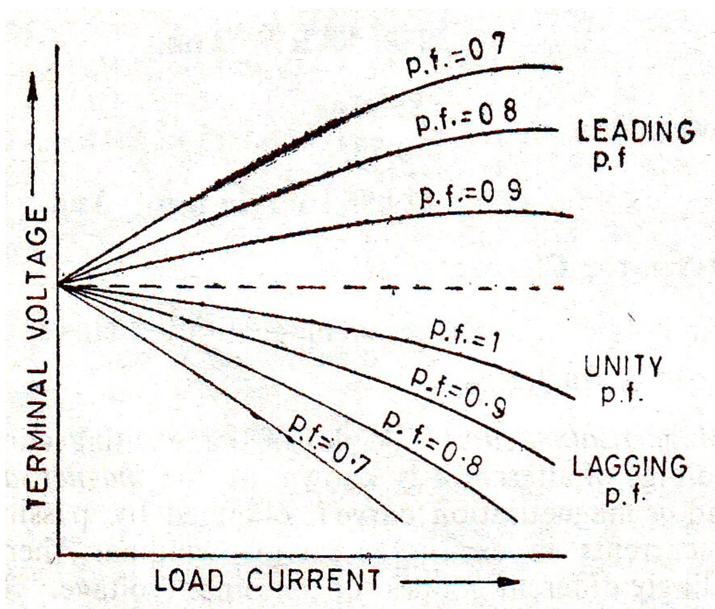

Fig. 3. Load Characteristic of alternator

(iii) Effect of variation of power factor on terminal voltage :

The load characteristics at different power factors with leading and lagging armature currents are shown in Fig. 4. If the load, current and excitation are kept constant, the terminal voltage falls on changing the power factor from leading to lagging one.This effect is because of the armature flux helping the main flux, in case p.f. is leading, hence generating more e.m,f. and the armature flux, opposing the main flux, in case the p.f. is lagging, hence generating less e.m.f., Therefore, the terminal voltage at lagging power factor decreases from that on leading p.f. because of decrease in generated e.m.f.

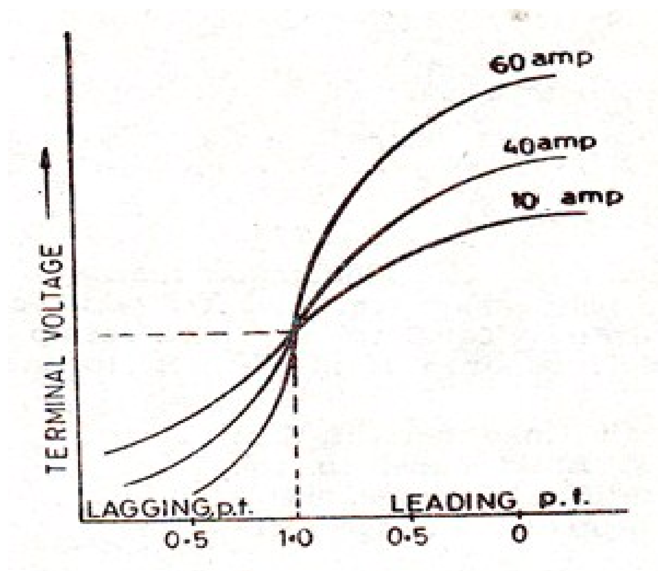

Fig. 4

Performance Of A Round-Rotor Synchronous Generator :

If the generator operates at a terminal voltage $\mathbf{V}_t$, while supplying a load corresponding to an armature current $\mathbf{I_a}$, then

$$\mathbf{E_o = V_t + I_a (R_a + \mathit{j}\, X_S)} \qquad (1)$$

The angle between $\mathbf{E_o}$ and $\mathbf{V_t}$ is defined as the power angle, $\boldsymbol{\delta}$. Notice that the power angle, $\boldsymbol{\delta}$, is not the same as the power factor angle, $\boldsymbol{\varphi}$. To justify this definition, we consider Fig. 5, from which we obtain

$$\mathbf{I_a X_S \cos\varphi = E_o \sin\delta} \qquad (2)$$

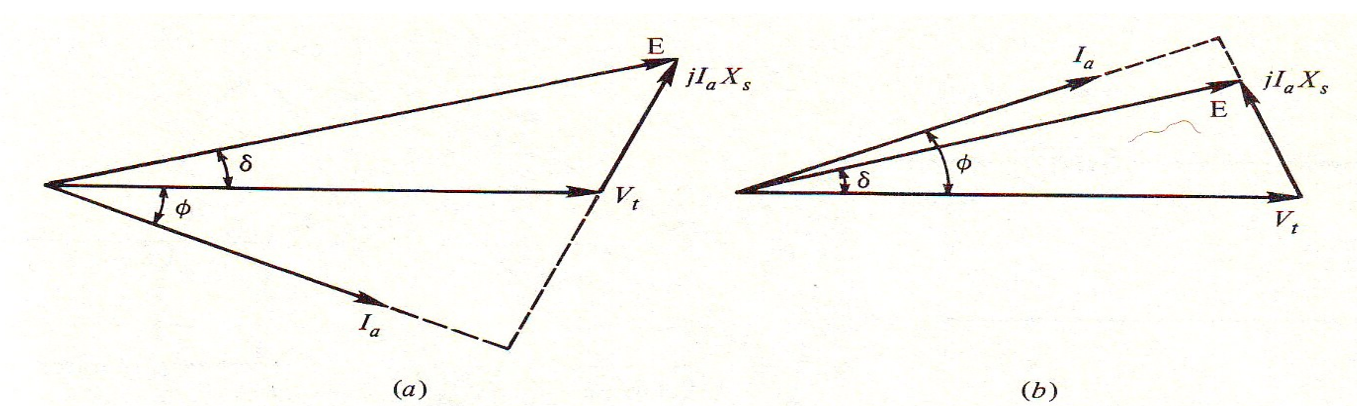

Fig. 5 Phasor diagram of round rotor generator (a) lag p.f (b) lead p.f

Now, from the approximate equivalent circuit (assuming that $\mathbf{X_S} >> \mathbf{R_a}$) as shown in Fig 6-a,

the **power delivered by the generator = power developed,**

$$\mathbf{P_d = V_t\, I_a \cos\varphi} \qquad (3)$$

$$\mathbf{P_d = (E_o\, V_t / X_S) \sin\delta} \quad \text{per phase} \qquad (4)$$

$$\mathbf{P_d = 3(E_o\, V_t / X_S) \sin\delta} \quad \text{for three phases} \qquad (5)$$

Which shows that the internal power of the machine is porportional to **sin δ**,
Equation (5) is often said to represent the **power-angle characteristic** of a round rotor synchronous machine.
Fig. 6-b shows that for a negative **δ**, the machine will operate as a motor.

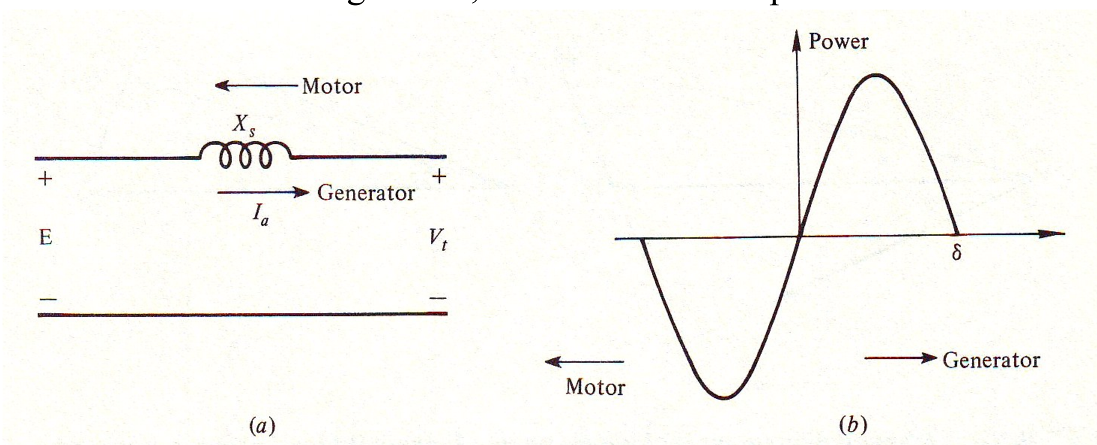

Fig 6 : (a) an approximate equivalent circuit of synchronous machine
(b) power-angle characteristics of a round-rotor synchronous machine

<u>Performance Of A Salient-Pole Synchronous Generator :</u>

Because of saliency, the reactance measured at the terminals of a salient-rotor machine will vary as a function of the rotor position. This is not so in a round-rotor machine. Thus a simple definition of the synchronous reactance for a salient-rotor machine is not immediately forthcoming. To overcome this difficulty, we use the two-reaction theory proposed by "**Andre Blondel**". The theory proposes to resolve the given armature mmf's into two mutually perpendicular components, with one located along the axis of the rotor salient pole, known as the direct (or **d**)axis and with the other in quadrature and known as the quadrature (or **q**)axis. Correspondingly, we may define the d-axis and q-axis synchronous reactances, $\mathbf{X_d}$ and $\mathbf{X_q}$ for a salient-pole synchronous machine. Thus, for generator operation, we draw the phasor diagram of Fig. 7 . Notice that $\mathbf{I_a}$ has been resolved into its **d-** and **q-**axis (fictitious) components, $\mathbf{I_d}$ and $\mathbf{I_q}$ With the help of this phasor diagram, we obtain

$$I_d = I_a \sin(\delta + \varphi) \qquad (1)$$

$$I_q = I_a \cos(\delta + \varphi) \qquad (2)$$

$$V_t \sin\delta = I_q X_q = I_a X_q \cos(\delta + \varphi) \qquad (3)$$

From these we get

$$P_d = 3 (E_o V_t / X_d) \sin\delta + 3 (V_t^2 / 2) [1/X_q - 1/X_d] \sin 2\delta \qquad (4)$$

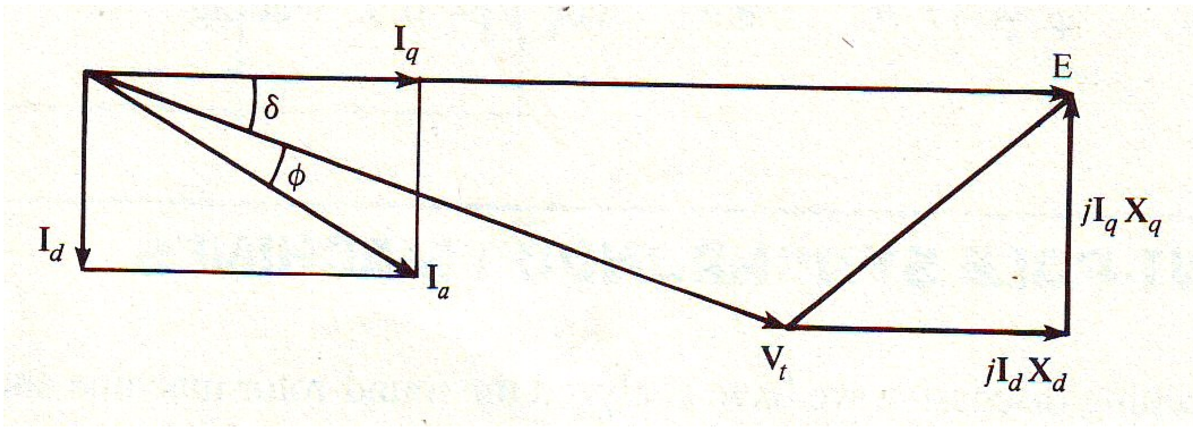

Fig. 7 Phasor Diagram of a Salient-Pole Generator

In fact, the phasor diagram depicts the complete performance characteristics of the machine.
We use Fig. 7 to drive the power-angle characteristics of a salient-pole generator.

$$P_d = 3 (E_o V_t / X_d) \sin\delta + (V_t^2 / 2) [1/X_q - 1/X_d] \sin 2\delta \qquad (5)$$

Equation (5)can also be established for a salient-pole motor (δ<0), the graph of above equation is given in Fig. 8. Observe that for $\mathbf{X_d} = \mathbf{X_q} = \mathbf{X_S}$, reduces to the round-rotor equation.

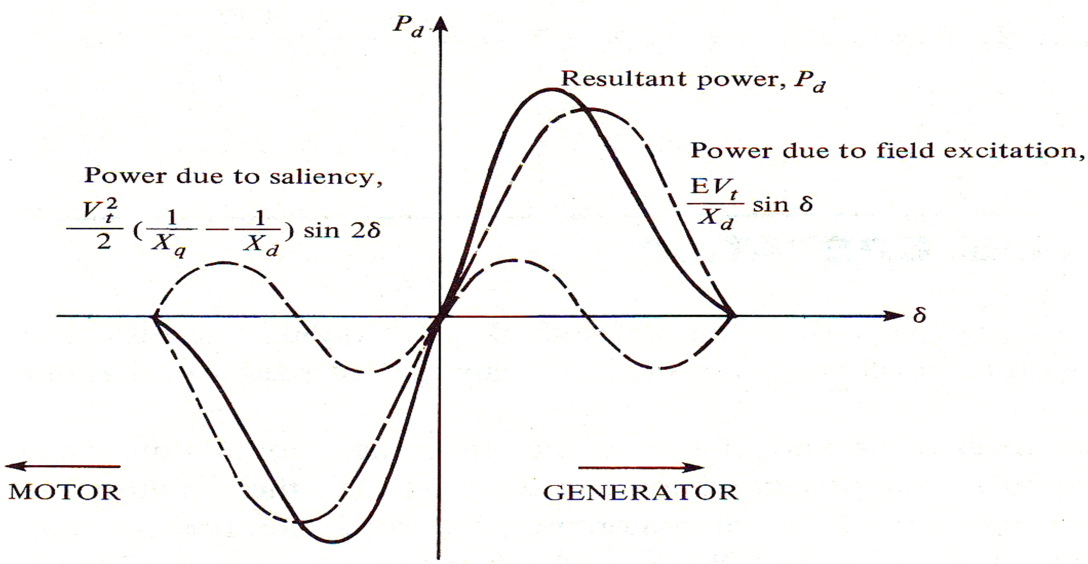

Fig. 8 Power-angle characteristic of salient-pole machine