UNIT 6 ALTERNATOR (SYNCHRONOUS GENERATOR)

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6.1 INTRODUCTION

In India, almost all generating stations produce electricity by using alternators. Alternators consists of a dc heteropolar field system as in a dc machine and a three phase armature winding whose coil arrangement is quite different from that of a d.c. machine. In this unit, first we will consider the constructional features and EMF equation of alternator. After that we discuss the armature reaction and various reactances in alternator. You will also consider the methods to find out voltage regulation and phasors. Finally, we will describe the synchronization of alternators.

Objectives

After studying this unit, you should be able to

- give an elementary description of constructional features and principle of operation,
- give a qualitative account of EMF induced,
- explain armature reaction and synchronous reactance,
- describe the methods to find voltage regulation, and
- explain the synchronization.

6.2 ALTERNATOR

6.2.1 Construction of Alternator

Synchronous machine is consists of two parts, one is stator and another is rotor.

Stator

The stator or armature is an iron ring, formed of laminations of silicon steel with slots in periphery to contains armature conductors. These slots may be open, semi-closed and closed according to speed and size of machine. Open slots are most commonly used because the coil can be freely wound and insulated properly. These slots provide the facility of removal and replacement of defective coils. The semi-closed slots are used to provide better performance over open slots. The totally closed slots are rarely used.

Rotor

The magnetic field required for the generation of AC voltage is provided by rotating magnetic field similar are DC generator. The field system is placed on a rotating shaft, which rotates within the armature conductors or stator. The field system contains electromagnets which are excited by pilot or main excitors. Generally main excitors are used but for very large machines the pilot excitor is also used. These excitors are DC generators.

A synchronous generator is an electromechanical device which converts mechanical energy (usually provided by steam, water or gas turbine as the 'prime-mover') into electrical energy in the form of three-phase (usually) AC quantities. It works on the principle of Faraday's Law of Electromagnetic Induction. Synchronous Generators are known as Alternator. The term 'Synchronous Generator' usually refers to a machine in a Power Station connected to a large interconnected power system.

Electromechanical energy conversion takes place whenever a change in flux is associated with mechanical motion. EMF is generated in a coil when there is a relative movement between the coil and the magnetic field. Alternating emf is generated if the change in flux-linkage of the coil is cyclic. Since electromechanical energy conversion requires relative motion between the field and armature winding, either of these could be placed on the stator or rotor. Because of practical convenience, field windings are normally placed on the Rotor and the Stator serves as the seats of induced emf, (i.e. the armature winding will be on Stator) in almost all Synchronous machines.

Alternators are classified according to their pole construction as :

(a) Salient pole-type

(b) Smooth cylindrical pole-type or Round rotor construction.

The cylindrical or round rotor consists of a steel forging with slots to carry the field winding. It has inherent mechanical strength and is, therefore, used for two-pole or four-pole synchronous generators driven by steam turbines which require a high-speed for optimum efficiency. Such machines have less diameter and more axial length and are rated upto 1 GVA (Giga Volt-Ampere). They employ modern cooling techniques (water-cooled stator conductors, hydrogen atmosphere etc.) and are called as Turbo-Alternators.

The Salient Pole construction is suitable for slower machines since many pole-pieces can be accommodated. Hydro synchronous generators (or Hydro-alternators) are driven by water turbines with optimum speeds in the range of 250 rpm, which requires twelve pole pairs $\left(\because N_s = \frac{120f}{p}\right)$. Since rating is approximately proportional to speed, the low-speed machines are physically large and expensive. Salient Pole Machines have more diameter and less axial length. Now, with this background, let us discuss 'Principle' first.

6.2.2 Working Principle

Figure 6.1(a) shows two magnetic poles 'N' and 'S' of a two-pole simple alternator having a loop of conductors AB and CD placed in between the magnetic poles. The loop ends are connected to two SLIP-RINGS and the conductors are rotated in a clockwise direction by some external means, thereby creating a relative motion between the flux and the conductors.

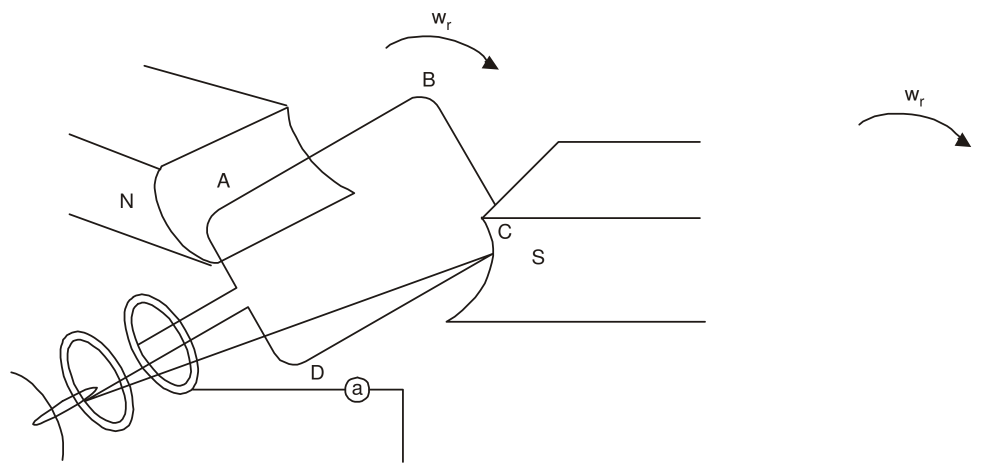


Figure 6.1(a) : Simple Illustration of emf Generation

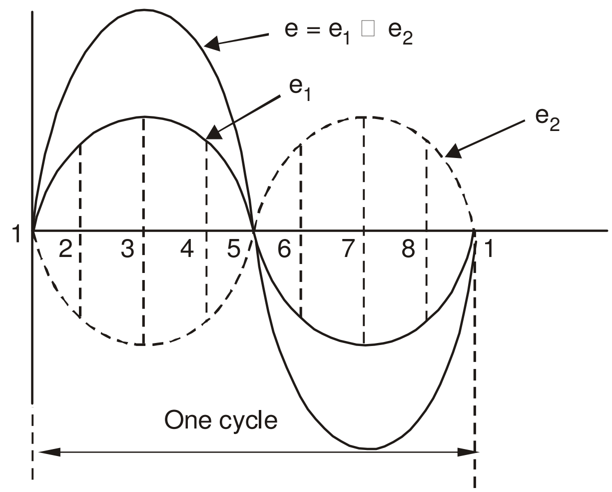


Figure 6.1(b) : Plot of emf with Respect to Time

[**Note :** For simplicity in explanation of the principle, the field-poles have been considered to be the stationary member (stator) and just a single-armature coil as the rotor.]

At position 1, the conductor is moving in the same direction as that of the lines of flux and hence there is no change in flux-linkage and so the emf induced is zero as plotted in Figure 6.1(b). When the conductor moves to position number 2, it experiences some change in the flux-linkage, thereby producing some emf.

At position number 3, the rate of change of flux-linkage is maximum and hence the emf induced is maximum. At position number 4, the emf induced is exactly same as that produced at position number 2. In the fifth position, the motion of conductor and flux are parallel, thereby resulting in zero emf.

When coming to position number 6, since the direction of motion now becomes upward, Fleming's Right Hand Rule yields an opposite emf. which becomes maximum at seventh position and then decreases at position 8 finally coming back to position 1 where the induced emf is zero.

As both conductors are connected to slip rings, if we plot a graph for the values of emf with respect to time, we will obtain a sine wave of Figure 6.1(b). The bold line represents the waveform of emf for conductor AB and the dotted line for conductor DC. The emfs thus obtained will have the magnitude continuously changing with time and the direction periodically changing after a fixed interval of time. Such emf is known as alternating emf and the resulting currentis termed Alternating Current. Since AB and DC are series connected with DC reversed in connection, the voltage across slip rings is also sinusoidal.

In Alternator, we are having a large number of conductors which are systematically placed over the armature to obtain a smooth curve. **In actual construction, the armature conductors (source of emf) form the stationary part (stator) and the field windings (for producing flux) are placed on the rotating part (rotor)**. The main reason is to have less sparking because field current magnitude is negligible as compared to Generator's output current and so heavy currents at sliding contacts are avoided.

6.2.3 EMF Equation

Let Z' = No. of conductors per pole $\left(\text{i.e. } \frac{Z}{P}\right)$ here P is no. of poles

N' = No. of turns per pole $\left(\text{i.e. } \frac{Z'}{2}\right)$

e = Instantaneous e.m.f. (Volts)

E' = R.M.S. value of e.m.f. induced (neglecting effect of distribution and coil throw) (Volts)

E = Value of e.m.f. (r.m.s.) induced in an Alternator considering the factors of distribution and coil throw) (Volts)

E_{ph} = Induced e.m.f. per phase (neglecting those two effects) (Volts).

Referring to Figure 6.1(a) and Figure 6.1(c), we find that AB and CD both are associated with flux $\frac{\phi}{2}$ and since they form one coil $ABCD$, so we can regard the flux associated with one coil as the flux per pole ϕ (weber)

$$\text{E.M.F. (instantaneous)} = -\frac{d\phi}{dt} = -N'\frac{d\phi}{dt} \text{ and } \phi = \phi_m \sin \omega t$$

$$e = +N'\frac{d}{dt}(\phi_m \sin \omega t) \qquad ; \text{ neglecting the direction consideration}$$

$$= \left(\frac{Z'}{2}\right).\omega\phi_m \cos \omega t$$

$$= \frac{Z'}{2}.\omega\Phi \cos \alpha \qquad ; \text{ where } \alpha = \omega t \text{ and } \Phi = \phi_m. \qquad \ldots (6.1)$$

R.M.S. value of this voltage

$$E' = \frac{Z'}{2}.\omega.\Phi\left[\frac{1}{\pi}\int_{-\pi/2}^{\pi/2} \cos^2\alpha \, d\alpha\right]^{1/2}$$

$$= \frac{Z'}{2}.2\pi f.\Phi\left[\frac{1}{2\pi}\int_{-\pi/2}^{\pi/2} (1+\cos 2\alpha)\, d\alpha\right]^{1/2}$$

$$= Z'.\pi f.\Phi\left[\frac{1}{2\pi}\left\{\frac{\pi}{2} - \frac{-\pi}{2} + 0\right\}\right]^{1/2}$$

$$= 2.93 fZ'\Phi \text{ (Volts)} \qquad \ldots (6.2)$$

Hence, if there are Z_{ph} conductors in series per phase, the induced emf per phase is

$$E_{ph} = 2.22 \; f \, Z_{ph} \, \Phi \text{ (Volts)} \qquad \ldots (6.3)$$

If there are N_{ph} turns per phase, then

$$E_{ph} = 4.44 \; f \, N_{ph} \, \Phi \text{ (Volts)} \qquad \text{. . . (6.4)}$$

This gives the emf generated per phase in an Alternator and is similar to that giving the emf of a transformer winding. The value of f can be found out by $N = \frac{120f}{P}$; knowing the r.p.m. and number of poles.

In practice, there are two major corrections to be made to the simplify expression of emf (given by Eq. 6.4).

Effect of Distribution

With a distributed winding, the emf induced in the various coils constituting a group of coils are not in phase and so the total emf is the vector sum of all such emf's. Hence, its value is less than that due to a concentrated winding. A factor K_d (which is less than unity) is therefore, introduced in the expression of emf.

$$K_d = \frac{\sin\left(\frac{m\psi}{2}\right)}{m \sin(\psi/2)}$$

where m = no. of sections or no. of slots per pole per phase (SPP)

and ψ = slot angle $= \frac{180^o}{\text{slots per pole}}$

In the Figure 6.2, value of m is 4.

i.e. S/P/P = 4 or S/P/3 = 4

or S/P = 3 × 4 = 12

$$\therefore \quad \psi = \frac{180^o}{\text{S/P}} = \frac{180^o}{12} = 15^o$$

$$E_g = E_c \, . \, K_d$$

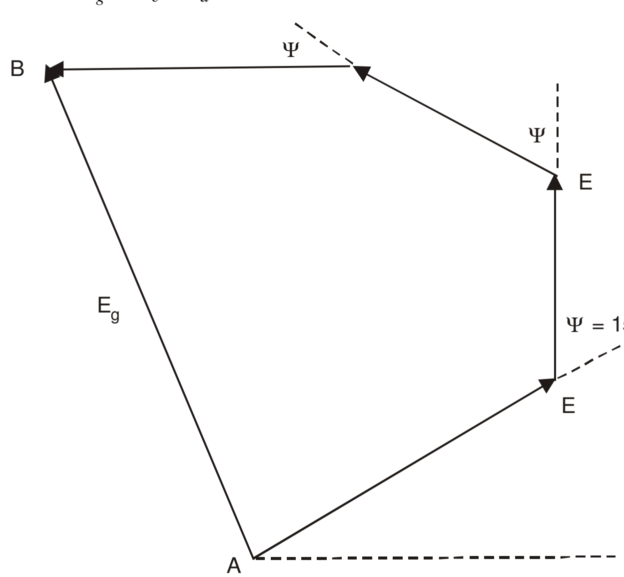


Figure 6.2

Here E_g = Emf per group

E_c = Emf per coil = $4.44 \, f \, N_{ph} \, \Phi$

K_d = Distribution factor or Breadth factor

∴ Eq. (6.4) now becomes

$$E = E_g = K_d\, E_c = 4.44\, K_d\, f\, N_{ph}\, \Phi \text{ (Volts)} \qquad \ldots (6.5)$$

Effect of Coil Throw (i.e. Pitch Factor)

To reduce weight of copper, the stator winding is constructed with a coil width less than the pole-pitch.

(For a 3-phase, 2 pole structure if the two conductors forming a coil are physically (mechanical angle) located at less than 180° and for a 3-phase,
4 pole structure if the mechanical angle is less than 90° and so on. Note here that if the electrical radian is less than π, it is always a short-pitched coil).

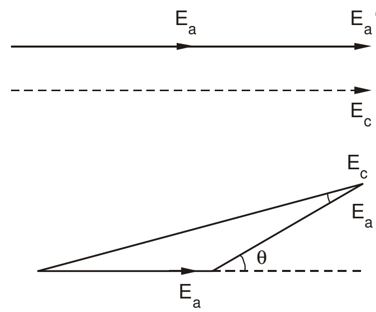


Figure 6.3

Though the emf magnitude reduces and it is undesirable but the advantages of short-pitching or chording overweighs the effect of reduced emf and so it is generally resorted to in Alternators. Advantages of short-pitched coils :

(a) It reduces harmonics in the voltage waveform.

(b) It gives a saving in the amount of copper in the overhang.

So, a pitch factor, K_p is introduced in the expression for emf; $K_p < 1$. The K_p can be calculated as

$$K_p = \cos\frac{\alpha}{2}$$

here α is a angle in electrical degree i.e. α = 180° – coil span is electrical degree.

Final emf expression becomes

$$E = 4.44\, K_d\, K_p\, f\, N_{ph}\, \Phi \qquad \ldots (6.6)$$

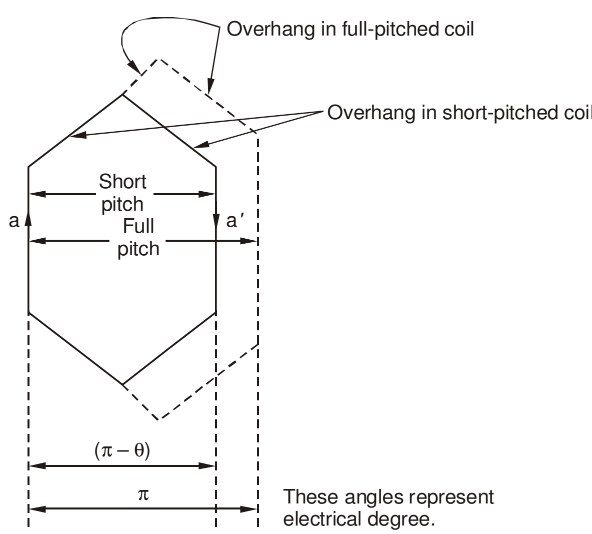


Figure 6.4 : Short-Pitched Coil

Example 6.1

A 3-phase, 16-pole synchronous generator has a star-connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.04 wb and the speed is 375 rpm. Find the frequency and phase emf and line emf. The total turns/phase may be assumed to be series connected.

Solution

$$N = \frac{120f}{P} \Rightarrow f = \frac{PN}{120} \text{ (Hz.)}$$

$$\therefore \quad f = \frac{16 \times 375}{120} = 50 \text{ Hz.}$$

$$Z = \text{No. of slots} \times \text{Conductors per slot}$$

$$= 144 \times 10 = 1440$$

Total no. of turns = $\frac{1440}{2} = 720$.

Total no. of turns per phase, $N_{ph} = \frac{720}{3} = 240$.

Phase emf, $E = 4.44\, K_d\, K_p\, f\, N_{ph}\, \Phi$ (Volts)

$f = 50$ Hz, $N_{ph} = 240$, $\Phi = 0.04$ wb.

$$K_d \text{ (Distribution Factor)} = \frac{\sin\left(\frac{m\psi}{2}\right)}{m \sin(\psi/2)}; \quad K_p = 1$$

m is *S/P/P* (slot per pole per phase)

$$\therefore \quad m = \frac{\text{no. of slots}}{\text{no. of poles} \times \text{no. of phase}} = \frac{144}{16 \times 3} = 3.$$

$$\psi = \text{Slot angle} = \frac{180°}{\text{Slots per pole}}$$

$$= \frac{180°}{(144/16)} = 20°$$

$$\therefore \quad K_d = \frac{\sin\left(\frac{3 \times 20^o}{2}\right)}{3 \times \sin\left(\frac{20^o}{2}\right)} = 0.96$$

Phase e.m.f. = $4.44\, K_d\, K_p\, f\, N\, \Phi$

$$E_{ph} = 4.44 \times 0.96 \times 1 \times 50 \times 240 \times 0.04$$

$$= 2046 \text{ Volt}$$

Since the winding is star connected,

so line voltage = $\sqrt{3}$ × Phase Voltage

$$V_L = \sqrt{3}\, V_{ph} \text{ for Y-connection}$$

$$\therefore \quad E_L = \sqrt{3} \times 2046 = 3543.7 \text{ Volt}$$

Example 6.2

A 3-phase, 16-pole alternator has a star-connected winding with 144 slots and 10 conductors per slot. The chording is by one slot. The flux per pole is 0.03 webers sinusoidally distributed and the speed is 375 rpm. Find the frequency, phase voltage and line voltage.

Solution

Given $P = 16$, $\phi = 0.03$ webers, $N = 375$ rpm

Conductors per phase $Z = \dfrac{\text{No. of slots} \times \text{conductors/slot}}{\text{No. of phases}}$

or $$Z = \frac{144 \times 10}{3} = 480$$

No. of slots per pole per phase $m = \dfrac{144}{16 \times 3} = 3$

No. of slots per pole $= \dfrac{144}{16} = 9$

$\therefore$ $$\psi = \frac{180}{9} = 20°$$

Distribution factor $$K_d = \frac{\sin \frac{m\psi}{2}}{m \sin \frac{\psi}{2}} = \frac{\sin\left(\frac{3 \times 20^o}{2}\right)}{3 \sin\left(\frac{20^o}{2}\right)}$$

or $$K_d = \frac{\sin 30^o}{3 \sin 10^o} = 0.959795$$

The coil is short chorded by 1 slot

$\therefore$ $$\alpha = \frac{1}{9} \times 180^o = 20°$$

Pitch factor $$K_p = \cos \frac{\alpha}{2} = \cos \frac{20^o}{2} = 0.9848$$

Frequency $$f = \frac{N_P}{120} = 375 \times \frac{16}{120} = 50 \text{ Hz}$$

$\therefore$ E.M.F. induced per phase $E = 4.44\, K_d\, K_p\, \phi f T$

or $$E = 4.44 \times 0.959795 \times 0.98 \times 0.03 \times 50 \times \frac{480}{2} = 1503.5 \text{ volts}$$

The generator is star connected

$$\text{Line voltage} = \sqrt{3} \times 1503.5$$
$$= 2604.14 \text{ Volts.}$$

SAQ 1

(a) The stator of a 12 pole, 600 rpm alternator has single layer winding with 12 slots per pole wound with full pitch coils of 40 turns each. The flux per pole is 0.029 weber and the current per conductor is 45 amperes. Assuming sinusoidal flux distribution, calculate the kVA output of the stator with single-phase and 3-phase connections.

(b) A 4-pole, 50 Hz star-connected alternator has a flux per pole of 0.12 wb. It has 4 slots per pole per phase, conductors per slot being 4. If the winding coil span is 150°, find the emf.

6.3 PERFORMANCE OF ALTERNATOR

6.3.1 Armature Reaction

Magnetic fluxes in alternators

There are three main fluxes associated with an alternator:

(a) Main useful flux linked with both field & armature winding.

(b) Leakage flux linked only with armature winding.

(c) Leakage flux linked only with field winding.

The useful flux which links with both windings, is due to combined mmf of the armature winding and field winding. When the armature winding of an alternator carries current then an mmf sets in armature. This armature mmf reacts with field mmf producing the resultant flux, which differs from flux of field winding alone.

The effect of armature reaction depends on nature of load (power factor of load). At no load condition, the armature has no reaction due to absence of armature flux. When armature delivers current at unity power factor load, then the resultant flux is displaced along the air gap towards the trailing pole tip. Under this condition, armature reaction has distorting effect on mmf wave as shown in Figure 6.5 at zero lagging power factor loads the armature current is lagging by 90° with armature voltage. Under this condition, the position of armature conductor when inducing maximum emf is the centre line of field mmf. Since there is no distortion but the two mmf are in opposition, the armature reaction is now purely demagnetizing as shown in Figure 6.6.

Now at zero leading power factor, the armature current leads armature voltage by 90°. Under this condition, the mmf of armature as well as the field winding are in same phase and additive. The armature mmf has magnetizing effect due to leading armature current as shown in Figure 6.7.

Armature reaction at :

(a) Unity Power Factor

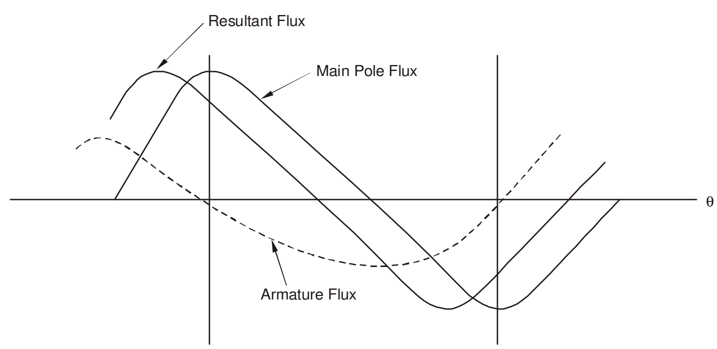


Figure 6.5 : Distorting Effect of Armature Reaction

(b) Zero Power Factor Leading

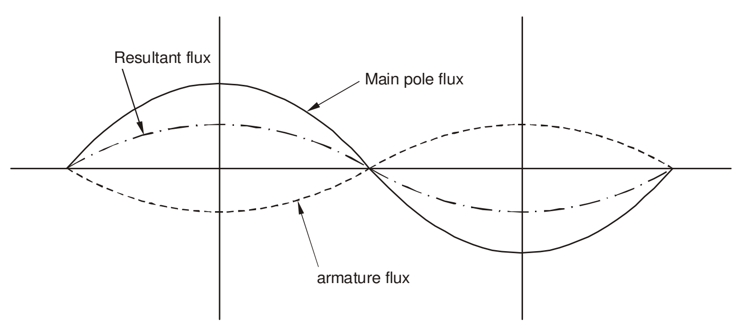


Figure 6.6 : Demagnetizing Effect of Armature Reaction

(c) Zero Power Factor Lagging

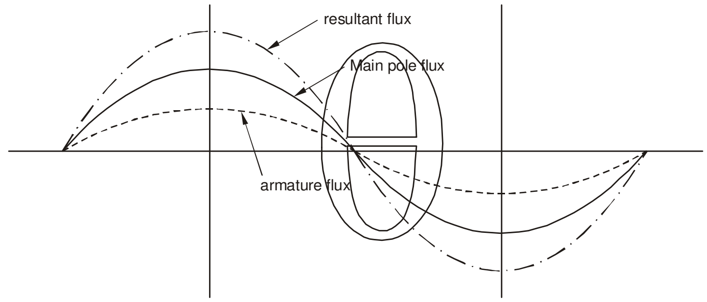


Figure 6.7 : Magnetizing Effect of Armature Reaction

6.3.2 Synchronous Reactance and its Determination

Open Circuit Characteristic (O.C.C.)

The open-circuit characteristic or magnetization curve is really the B-H curve of the complete magnetic circuit of the alternator, although the knee of the curve is not so well pronounced as in the case of an iron circuit without any air gap. Indeed, in large turbo-alternators, where the air gap is relatively long, the curve shows a gradual bend without any obvious knee at all. It is determined by inserting resistance in the field circuit and measuring corresponding value of terminal voltage and field current. Figure 6.8 illustrates a typical example.

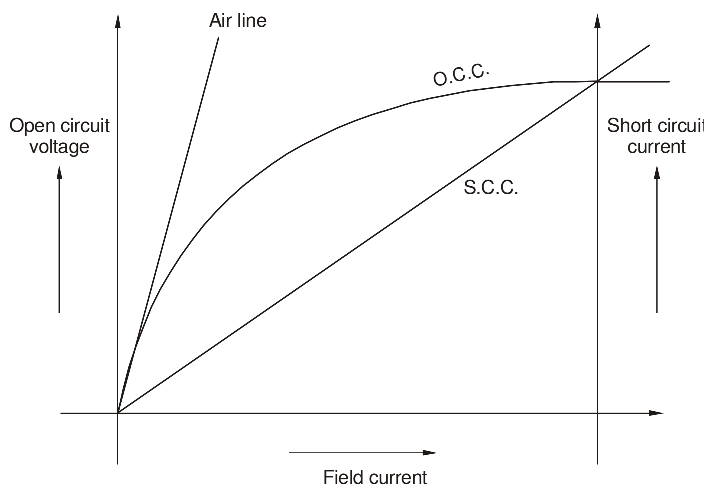


Figure 6.8 : O.C.C. and S.C.C. of an Alternator

The major portion of the exciting ampere-turns are required to force the flux across the air gap, the reluctance of which is assumed to be constant. A straight line called the air line can therefore be drawn as shown, dividing the excitation for any voltage into two portions,

(a) that required to force the flux across the air gap, and

(b) that required to force it through the remainder of the magnetic circuit. The shorter the air gap, the steeper is the air line.

Short Circuit Characteristic (S.C.C.)

The short-circuit characteristic, as its name implies, refers to the behaviour of the alternator when its armature is short-circuited or at negligible terminal voltage. In a single-phase machine the armature terminals are short-circuited through an ammeter, but in a three-phase machine all three phases must be short-circuited. An ammeter is connected in series with each armature terminal, the three remaining ammeter terminals being short-circuited.

The machine is run at related speed and field current is increased gradually to I_{f_2} free armature current reaches rated value.

The armature short-circuit current and the field current are found to be proportional to each other over a wide range, as shown in Figure 6.8, so that the short-circuit characteristic is a straight line. Under short-circuit conditions the armature current is almost 90° out of phase with the voltage, and the armature mmf has a direct demagnetizing action on the field. The resultant ampere – turns inducing the armature emf are, therefore, very small and is equal to the difference between the field and the armature ampere – turns. This results in low mmf in the magnetic circuit, which remains in unsaturated condition and hence the small value of induced emf increases linearly with field current. This small induced armature emf is equal to the voltage drop in the winding itself, since the terminal voltage is zero by assumption. It is the voltage required to circulate the short-circuit current through the armature windings. The armature resistance is usually small compared with the reactance.

Short-Circuit Ratio

The short-circuit ratio is defined as the ratio of the field current required to give rated volts on open circuit to that required to circulate full-load current with the armature short-circuited.

$$\text{Short-circuit ratio} = \frac{OA}{OB} = \frac{I_{f_1}}{I_{f_2}} .$$

Synchronous Reactance

The synchronous reactance is an equivalent reactance the effects of which are supposed to reproduce the combined effects of both the armature leakage reactance and the armature reaction. The alternator is supposed to have no armature reaction at all, but is supposed to possess an armature reactance in excess of its true leakage reactance. When the synchronous reactance is combined vectorially with the armature resistance, a quantity called the synchronous impedance is obtained.

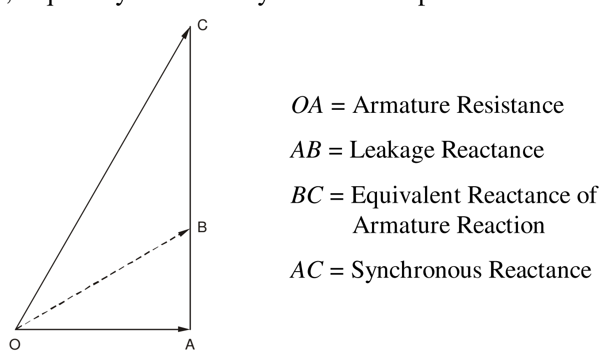


Figure 6.9

The synchronous impedance (or synchronous reactance) can be calculated from the open-circuit and short-circuit characteristics. When short-circuited, the armature is supposed to generate exactly the same e.m.f., and since the terminal voltage is zero, all this e.m.f. is supposed to be consumed in circulating the short-circuit current through the synchronous impedance of the armature. The ratio of the open-circuit voltage to the short-circuit current gives the synchronous impedance.

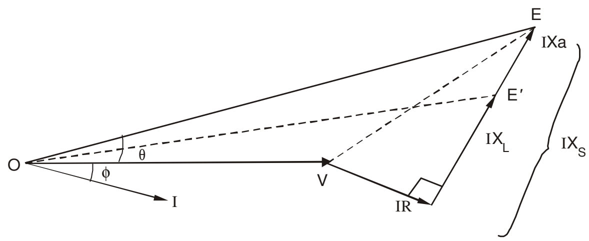


Figure 6.10 : Voltage Phasor Diagram for an Alternator at Lagging at Load

The effects of armature reaction are now replaced by the introduction of the equivalent reactance X_a, causing a further voltage drop, IX_a. The exciting current must now be sufficient to induce a voltage *OE*, this being the voltage obtained when the load current is thrown off. When the load is applied, the same exciting current induces only the smaller e.m.f., E', since the armature reaction has the effect of weakening the field. The synchronous reactance is equal to

$$X_s = X_l + X_a$$

When the synchronous reactance is obtained from the short-circuit characteristic in the above manner, the alternator is operating on the straight line (unsaturated) part of the open-circuit characteristic, and the synchronous reactance obtained in this way is called the unsaturated synchronous reactance. The angle between internal voltage *E* and terminal voltage *V* is called load angle or torque angle.

Example 6.3

Find the synchronous impedance, synchronous reactance the terminal voltage when full load is thrown off, of a 250 amp, 6600 volts, 0.8 p.f. alternator, in which a given field current produces an armature current of 250 amp on short circuit and a generated e.m.f. of 1500 volts on open circuit. The armature resistance is 2 Ω.

Solution

$$\text{Synchronous impedance } Z_s = \frac{\text{Open circuit volts}}{\text{Corresponding S.C. current}}$$

or $$Z_s = \frac{\left(1500/\sqrt{3}\right)}{250} \quad \text{(The alternator is assumed to be star connected)}$$

or $$Z_s = 3.464\,\Omega$$

$$\text{Synchronous reactance } X_s = \sqrt{Z_s^2 - R_a^2} = \sqrt{(3.464)^2 - (2)^2}$$

$$= 2.828\ \Omega$$

Assuming the load to be lagging, the voltage/phase at no load is given by

$$V_0 = V_t + I.Z_s = V_t + |I|(\cos\phi - j\sin\phi)\,(R + IX_s)$$

$$= \frac{6600}{\sqrt{3}} + 250(0.8 - j0.6)(2 + j2.828)$$

$$= \frac{6600}{\sqrt{3}} + (250\angle{-36.87°})\,(3.464\angle{54.73°})$$

$$\text{Line voltage} = \frac{6600}{\sqrt{3}} \times \sqrt{3} + 250 \times 3.464 \times \sqrt{3}\ \angle{17.86°}$$

$$= 6600 + 1500\angle{17.86°}$$

$$= 6600 + 1427.7 + j\,460.04$$

$$= 8027.7 + j\,460.04$$

$$= 8040.87\angle{3.28°}$$

when the full load is thrown off, the terminal voltage rises to 8040.87 volts.

SAQ 2

Neglecting armature resistance find the synchronous impedance in ohms of a 1000 kVA, 2000 V, 50 Hz, 3 phase generator having the following open circuit test figures :

Open circuit terminal emf %	35	90	100	110	120	128
Excitation %	25	80	100	125	160	200

An excitation of 80% was required for full load on short-circuit.

6.3.3 Voltage Regulation

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine. The numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged

$$\text{Voltage Regulation} = \frac{E - V}{V} \times 100\% .$$

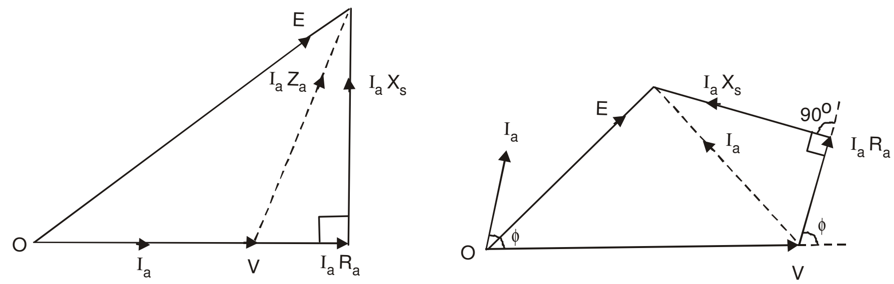
Here E is voltage across open terminals of stator (at no load) and V is voltage across terminals at full load. E is also called internal voltage. Now we shall study various methods for calculating voltage regulation.

EMF Method

Calculation of Regulation from Synchronous Reactance

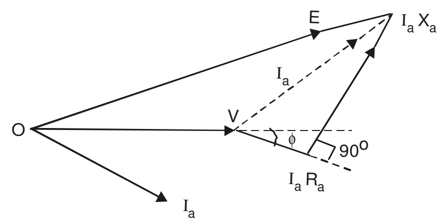
The synchronous impedance triangle must first be obtained from the open-circuit and short-circuit characteristics, as already explained, after which the regulation is derived by the aid of the vector diagrams shown in Figure 6.9. Let OV be the terminal voltage (or phase voltage in the case of a three-phase alternator), and let OI_a represent full-load current. The voltage-drop triangle, obtained from the armature resistance and synchronous reactance, is then erected in position, the synchronous reactance voltage-drop vector being at right angles to the current vector. The induced voltage is then given by OE, and the % regulation by $\frac{OE - OV}{OV} \times 100$ percent. Conversely, if the open-circuit voltage OE is known, the value of OV can be ascertained by striking an arc with E as centre and $OE \times \left(\frac{\%\ \text{Regulation}}{\%\ \text{Regluation} + 100} \right)$ as radius. The point where the arc cuts the OE vector determines the position of the point V.

The construction can be carried out for any phase angle, and also for any value, of the current. Figures 6.11(a) and (b) illustrate cases of lagging and leading armature currents respectively. It will be observed that a lagging current causes a greater voltage rise on throwing off the load than does a current at unity power factor, while a leading current brings about a reduced voltage rise. In fact, if the current be made to lead by a sufficient angle, the voltage on no-load may actually be lower than the voltage on load.



$$E=\sqrt{(V+I_a R_a)^2+(I_a X_s)^2} \qquad E=\sqrt{(V\cos\phi+I_a R_a)^2+(V\sin\phi+I_a X_s)^2}$$

(a)



$$E=\sqrt{(V\cos\phi+I_a R_a)^2+(V\sin\phi-I_a X_s)^2}$$

Figure 6.11(b)

In general, the voltage rises calculated by this method are higher than the true ones obtained by direct test, unless the correct value of the saturated synchronous reactance is used.

Example 6.4

A 3-phase star connected alternator is rated at 100 kVA. On a short-circuit a field current of 50 amp gives the full load current. The e.m.f. generated on open circuit with the same field current is 1575 V/phase. Calculate the voltage regulation at (a) 0.8 power factor lagging, and (b) 0.8 power factor leading. Assume armature resistance is 1.5Ω.

Solution

Let the rated terminal voltage of the alternator

V = 1575 volts per phase

$\therefore$ Full load current $I=\dfrac{1000\times10^{3}}{3\times1575}=211.64$ amp

Synchronous impedance

$$Z_s=\frac{\text{o.c. voltage}}{\text{s.c. current}}\ \text{for same field excitation}$$

0r $\quad Z_s=\dfrac{1575}{211.64}=7.442\,\Omega$

$$X_s=\sqrt{(Z_s)^2-R_a^2}=\sqrt{(7.442)^2-(1.5)^2}=7.289\,\Omega$$

(a) At lagging power factor, the no. load voltage E_0 is given by the equation

$$E_0=\sqrt{(V\cos\phi+IR_a)^2+(V\sin\phi+IX_s)^2}$$

$$=\sqrt{(1575\times0.8+211.64\times1.5)^2+(1575\times0.6+211.64\times7.289)^2}=2945.63$$

$\therefore$ % Regulation = $\dfrac{2945.63-1575}{1575}\times100=87.02\%$

(b) At leading power factor, the no. load voltage E_0 is given by the equation

$$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_s)^2}$$

$$= \sqrt{(1575\times0.8 + 211.64\times15)^2 + (1575\times0.6 - 211.64\times7.289)^2}$$

$$= 1686.878$$

$$\therefore \quad \%\ \text{Regulation} = \frac{1686.878 - 1575}{1575}\times100 = 7.1\%$$

SAQ 3

A 3-phase star-connected synchronous generator is rated at 1.5 MVA, 11 kV. The armature effective resistance and synchronous reactance are 1.2 Ω and 25 Ω respectively per phase. Calculate the percentage voltage regulation for a load of 1.4375 MVA at (a) 0.8 pf lagging and (b) 0.8 pf leading. Also find out the pf at which the regulation becomes zero.

The Magnetomotive Force (MMF) Method

This method is based on the MMF calculation or no. of ampere turns required to produced flux which gives Rated Voltage at Open Circuit and Rated Current at Short Circuit. From open circuit characteristic field current If_1 gives rated voltage V and If_2 to cause the short circuit current which is equal to Full Load Current.

For Unity Power Factor If_2 balanced impedance drop in addition to armature reaction. But R_a is very small when compared to X_L, so If_2 has an angle with If_1 approximate 90°. We can find If which gives related voltage at full load by adding If_2 and If_1 at 90° as shown in Figure 6.12.

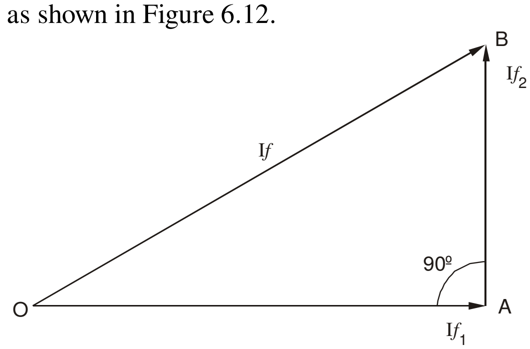
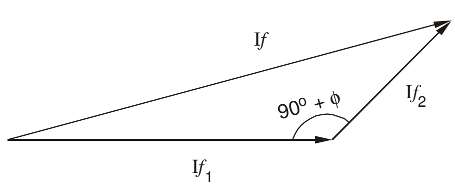
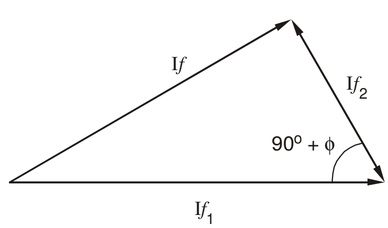


Figure 6.12

If load power factor is cos ϕ lagging or leading, then If_1 gives voltage $V + IR_a\cos\phi$ in place of V. So we add If_2 at an angle $90^\circ \pm \phi$ (+ ve sign for lagging load and − ve sign for leading load) as shown in Figure 6.13. The value of internal voltage E_0 at this resultant I_f, required for rated terminal voltage and rated current, can be found from the OCC.



(a)



(b)

Figure 6.13

Then Percentage Voltage Regulation can be determined by

$$\% \ VR = \frac{E_0 - V}{V} \times 100$$

Zero Power Factor Method

This method is also known as Potier Method. This method is based on separation of reactances due to leakage flux and due to armature reaction flux.

To find Voltage Regulation, we calculate armature resistance and draw *OCC* and *SCC*. A port from these, we draw a curve between terminal voltage and excitation while the machine is being run on synchronous speed at Zero Power Factor lagging load. This zero power factor curve appears like *OCC* but shifted by a factor IX_L vertically and horizontally by armature reaction mmf.

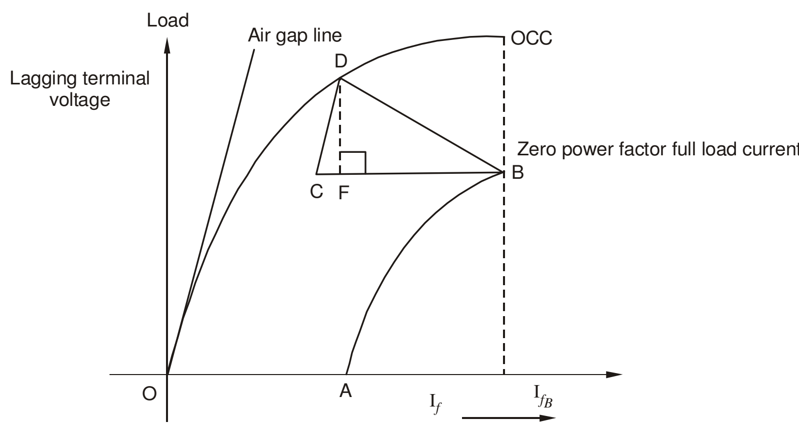


Figure 6.14 : O.C.C., P.F.C. and Potier Triangle

Point *B* on *ZPF* curve corresponds to I_{FB} at which full load current flows in the armature. Draw *CB* parallel and equal to *OA*, *CD* is parallel to our gap line. Draw a perpendicular to *CB* from *D* at *F*. Triangle *BDF* known as Potier triangle. In triangle *BDF*, length *BF* represents armature reaction excitation and *DF* represents leakage reactance drop. The Potier reactance is

$$X_{\text{Potier}} = \frac{DF \text{ (Voltage per phase)}}{\text{Zero power factor per phase}}$$

Now, we draw phasor diagram for determination of voltage regulation as shown in Figure 6.15.

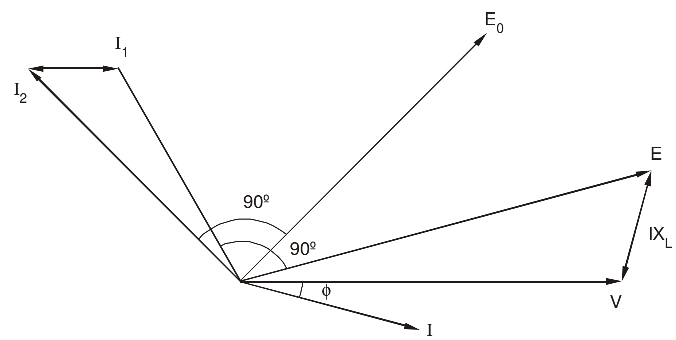


Figure 6.15 : Phasor Diagram

Now, voltage regulation can be obtained

$$\% \ VR = \frac{E_0 - V}{V} \times 100$$

Example 6.5

The data obtained on 100 kVA, 1100 V, 3-phase alternator is : DC resistance test, *E* between line = 6 V dc, *I* in lines = 10 A dc. Open circuit test, field current = 12.5 A dc, line voltage = 420 V ac. Short circuit test, field current = 12.5 A, line current = rated value, calculate the voltage regulation of alternator at 0.8 pf lagging.

Solution

Assume alternator to be star-connected, as usually

$$\text{Phase voltage, } V_p = \frac{1100}{\sqrt{3}} = 635.1 \text{ A}$$

$$\text{Full load phase current, } I_p = I_L = \frac{100 \times 1000}{\sqrt{3} \times 1100} = 52.5 \text{ V}$$

$$\text{Armature dc resistance per phase, } R_{dc} = \frac{E_{dc}}{2 \times I_{dc}} = \frac{6}{2 \times 10} = 0.3 \Omega$$

($\because$ dc voltage is connected across two phases)

Armature effective ac resistance per phase, $R_a = 1.667 \times 0.3 = 0.5\ \Omega$

(assuming 66.7% of dc resistance for skin effect)

Synchronous impedance per phase,

$$Z_s = \frac{OC \text{ voltage per phase}}{SC \text{current per phase}} \text{ for same excitation}$$

$$= \frac{\frac{420}{\sqrt{3}}}{52.5} = 4.62\ \Omega$$

$$\text{Synchronous reactance per phase, } X_s = \sqrt{(4.62)^2 - (0.5)^2} = 4.59 \Omega$$

At 0.8 lagging power factor, $\cos \phi = 0.8$ and $\sin \phi = 0.6$

Open circuit voltage per phase,

$$E_{op} = \sqrt{(V_p \cos \phi + I_p R_A)^2 + (V_p \sin \phi + I_p X_s)^2}$$

$$= \sqrt{(635.1 \times 0.8 + 52.5 \times 0.5)^2 + (635.1 \times 0.6 + 52.5 \times 4.59)^2}$$

$$= 820 \text{ V}$$

$$\text{Percentage regulation} = \frac{820 - 635.1}{635.1} \times 100$$

$$= 29.11\%$$

SAQ 4

A 3-phase, star-connected alternator is rated at 1600 kVA, 13500 V. The armature resistance and synchronous reactance are 1.5 Ω and 30 Ω respectively per phase. Calculate the percentage regulation for a load of 1280 kW at 0.8 leading power factor.

6.4 SYNCHRONIZING OF ALTERNATORS

Synchronizing

The operation of paralleling two alternators is known as synchronizing, and certain conditions must be fulfilled before this can be effected. The incoming machine must have its voltage and frequency equal to that of the bus bars and, should be in same phase with bus bar voltage. The instruments or apparatus for determining when these conditions are fulfilled are called synchroscopes. Synchronizing can be done with the help of (i) dark lamp method or (ii) by using synchroscope.

Synchronizing by Three Dark Lamp Method

The simplest method of synchronizing is by means of three lamps connected across the ends of paralleling switch, as shown in Figure 6.16(a). If the conditions for synchronizing are fulfilled there is no voltage across the lamps and the switch may be closed. The speed of the incoming machine must be adjusted as closely as possible so that the lamps light up and die down at a very low frequency. The alternator may then be switched in at the middle of the period of darkness, which must be judged by the speed at which the light is varying. By arranging three lamps across the poles of the main switch as in the case of machine *B* it is possible to synchronize with lamps dark. A better arrangement is to cross connect two of the lamps as given in machine *C*. Suppose that the voltage sequence *ABC* refers to the bus bars and A' B' C' to the incoming machine *C*. Then the instantaneous voltage across the three lamps in the case of machine *C* are given by the vectors AB', $A'B$, and CC'. Now both vector diagrams are rotating in space, but they will only have the same angular velocities if the incoming machine is too slow. Then diagram A' B' C' will rotate more slowly than *ABC*. So that at the instant represented AB' is increasing, A' B' is decreasing, and CC' is increasing.

If the incoming machine is too fast, the *AB'* is decreasing *A'B* is increasing, and CC' is decreasing. Hence, if the three lamps are placed in a ring a wave of light will travel in a clockwise or counter-clockwise direction round the ring according as the incoming machine is fast or slow. This arrangement therefore indicates whether the speed must be decreased or increased. The switch is closed when the changes in light are very slow and at the instant the lamp connected directly across one phase is dark. Lamp synchronizers are only suitable for small low voltage machines.

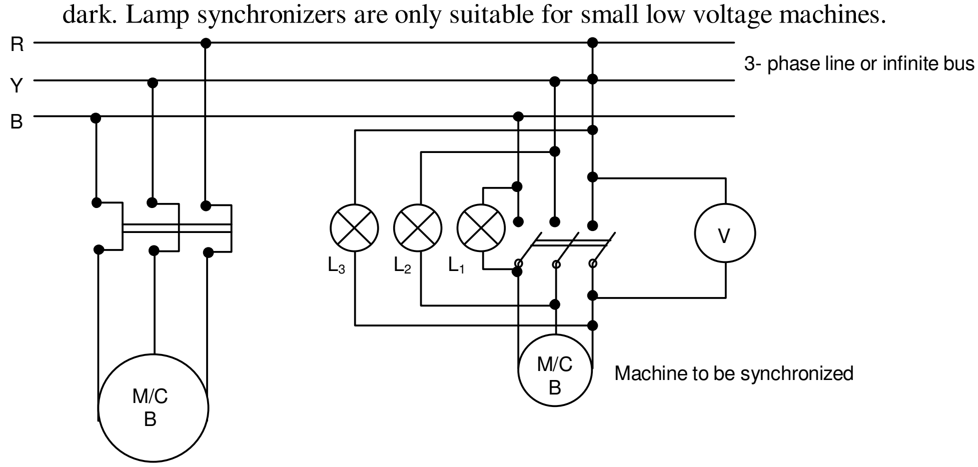


Figure 6.16(a) : Illustration of Method of Synchronizing

Synchroscopes

Synchronizing by means of lamps is not very exact, as a considerable amount of judgement is called for in the operator, and in large machines even a small phase difference causes a certain amount of jerk to the machines. For large machines a rotary synchroscope is almost invariably used. This synchroscope which is based on the rotating field principle consists of a small motor with both field and rotor wound two-phase. The stator is supplied by a pressure transformer connected to two of the main bus bars, while the rotor is supplied through a pressure transformer connected to a corresponding pair of terminals on the incoming machine. Two phase current is obtained from the phase across which the instrument is connected by a split phase device.

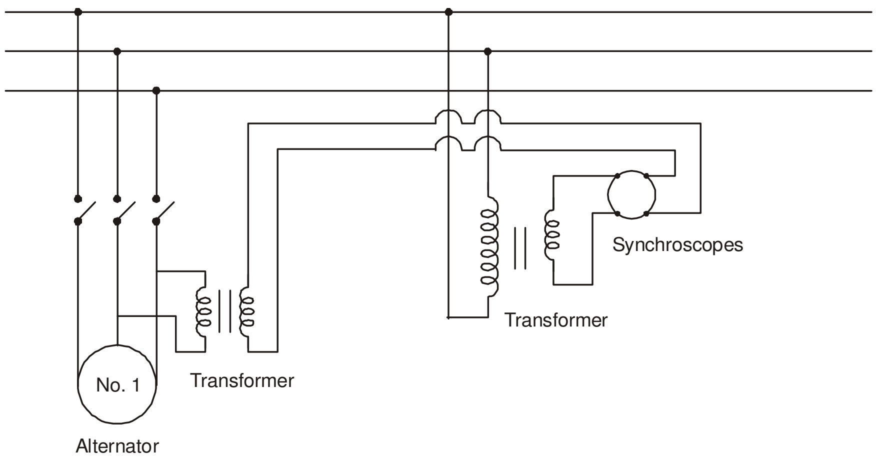


Figure 6.16(b) : Method of Synchronizing by Synchronoscope

One rotor, phase *A* is in series with a non-inductive resistance *R*, and the other. *B* is in series with an inductive coil *C*. The two then being connected in parallel. The phase difference so produced in the currents through the two rotor coils causes the rotor to set up a rotating magnetic field. Now if the incoming machine has the same frequency as the bus-bars, the two field will travel at the same speed, and therefore, the rotor will exhibit no tendency to move. If the incoming machine is not running at the correct speed, then the rotor will tend to rotate at a speed equal to the difference in the speeds of the rotating fields set up by its rotor and stator. Thus it will tend to rotate in one direction if the incoming machine is too slow, and in the opposite direction if too fast.

In practice, it is usual to perform the synchronizing on a pair of auxiliary bars, called synchronizing bars. The rotor of the synchroscope is connected permanently to these bars, and the incoming machine switched to these bars during synchronizing. In this way, one synchroscope can be used for a group of alternators. The arrangement of synchronizing bars and switch gear.

6.4.1 Synchronizing Current

If two alternators generating exactly the same emf are perfectly synchronized, there is no resultant emf acting on the local circuit consisting of their two armatures connected in parallel. No current circulates between the two and no power is transferred from one to the other. Under this condition emf of alternator 1, i.e. E_1 is equal to and in phase opposition to emf of alternator 2, i.e. E'_2 as shown in the Figure 6.17.

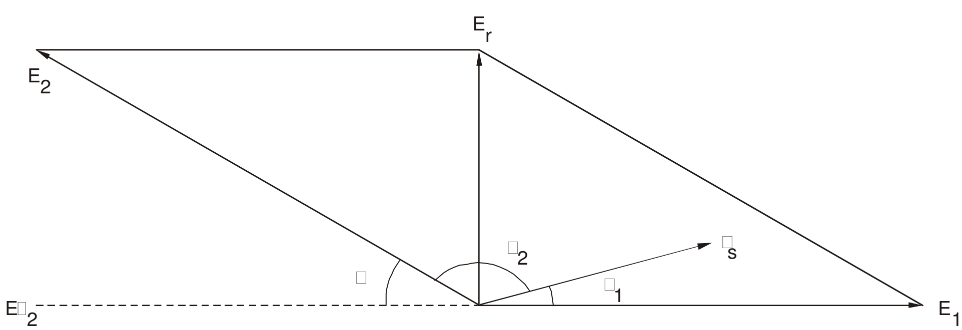


Figure 6.17 : E_2 Falling Back

There is, apparently, no force tending to keep them in synchronism, but as soon as the conditions are disturbed a synchronizing force is developed, tending to keep the whole system stable. Suppose one alternator falls behind a little in phase by and angle θ. The two alternator emfs now produce a resultant voltage and this acts on the local circuit consisting of the two armature windings and the joining connections. In alternators, the synchronous reactance is large compared with the resistance, so that the resultant circulating current I_s is very nearly in quadrature with the resultant emf E_r acting on the circuit. Figure 6.17 represents a single phase case, where E_1 and E_2 represent the two induced emfs, the latter having fallen back slightly in phase. The resultant emf, E_r, is almost in quadrature with both the emfs, and gives rise to a current, I_s, lagging behind E_r by an angle approximating to a right angle. It is, thus, seen that E_1 and I_s are almost in phase. The first alternator is generating a power $E_1 I_s \cos \phi_1$, which is positive, while the second one is generating a power $E_2 I_s \cos \phi_2$, which is negative, since $\cos \phi_2$ is negative. In other words, the first alternator is supplying the second with power, the difference between the two amounts of power represents the copper losses occasioned by the current I_s flowing through the circuit which possesses resistance. This power output of the first alternator tends to retard it, while the power input to the second one tends to accelerate it fill such a time that E_1 and E_2 are again in phase opposition and the machines once again work in perfect synchronism. So, the action helps to keep both machines in stable synchronism. The current, I_s, is called the synchronizing current.

Synchronizing Power

Suppose that one alternator has fallen behind its ideal position by an electrical angle θ, measured in radians. This corresponds to an actual geometrical angle of $\frac{2\theta}{p} = \psi$, where p is the number of poles. Since E_1 and E_2 are assumed equal and θ is very small E_r is very nearly equal to θE_1. Moreover, since E_r is practically in quadrature with E_1 and I_s may be assumed to be in phase with E_1 as a first approximation. The synchronizing power may, therefore, be taken as $E_1 I_s = \frac{\theta E_1^2}{X}$, since $I_s = \frac{E_r}{X} = \frac{\theta E_1}{X}$, where X is the sum of synchronous reactance of both armatures, the resistance being neglected. When one alternator is considered as running on a set of bus bars the power capacity of which is very large compared with its own, the combined reactance of the others sets connected to the bus bars is negligible, so that in this case X is the synchronous reactance of the one alternator under consideration. If $I_x = \frac{E}{X}$ is the steady short-circuit current of this alternator, then the synchronizing power may be written $\frac{\theta E^2}{X} = E I_x \theta$, although the current I_x does not actually flow.

In an m-phase case the synchronizing power becomes $P_s = m E I_x \theta$ watts, E and I_x now being the phase values.

Alternators with a large ratio of reactance to resistance are superior from a synchronizing point of view to those which have a smaller ratio, as then the synchronizing current I_s cannot be considered as being in phase with E_1. Thus, while reactance is bad from a regulation point of view, it is good for synchronizing purposes. It is also good from the point of view of self-protection in the even of a fault.

6.4.2 Effect of Voltage

Inequality of Voltage

Suppose the alternators are running exactly in phase, but their induced e.m.f.s are not quite equal. Considering the local circuit, their e.m.f.s are now in exact phase opposition, as shown in Figure 6.18, but they set up a resultant voltage E_r, now in phase with E_1, assumed to be the greater of the two. The synchronizing current, I_s, now lags by almost 90° behind E_1, so that the synchronizing power, $E_1 I_s \cos \phi_1$ is relatively small, and the synchronizing torque per ampere is also very small. This lagging current, however, exerts a demagnetizing effect upon the alternator generating E_1, so that the effect is to reduce its induced e.m.f. Again, the other machine is, so far as this action is concerned, operating as a synchronous motor, taking a current leading by approximately 90°. The effect of this is to strengthen its field and so raise its voltage. The two effects combine to lesson the inequality in the two voltages, and thus tend towards stability.

Inequality of voltage is, however, objectionable, since it given rise to synchronizing currents that have a very large reactive component.

Effect of Change of Excitation

A change in the excitation of an alternator running in parallel with other affects only its KVA output; it does not affect the KW output. A change in the excitation, thus, affects only the power factor of its output.

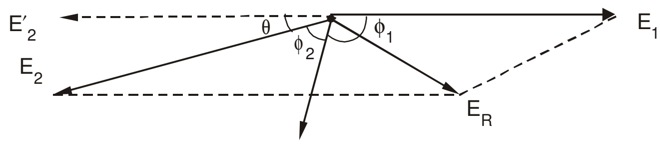


Figure 6.18

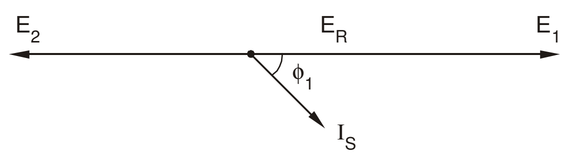


Figure 6.19 : Change in Excitation

Let two similar alternators of the same rating be operating in parallel, receiving equal power inputs from their prime movers. Neglecting losses, their kW outputs are therefore equal. If their excitations are the same, they induce the same emf, and since they are in parallel their terminal voltages are also the same.

When delivering a total load of I amperes at a power-factor of $\cos \phi$, each alternator delivers half the total current and $I_1 = I_2 = \frac{1}{2} I$. Since their induced emfs are the same, there is no resultant emf acting around the local circuit formed by their two armature windings, so that the synchronizing current, I_s, is zero. Since the armature resistance is neglected, the vector difference between $E_1 = E_2$ and V is equal to $I_1 X_{S_1} = I_2 X_{S_2}$, this vector leading the current I by 90°, where X_{S_1} and X_{S_2} are the synchronous reactances of the two alternators respectively.

Now examine the effect of reducing the excitation of the second alternator. E_2 is therefore reduced as shown in Figure 6.19. This reduces the terminal voltage slightly, so let the excitation of the first alternator be increased so as to bring the terminal voltage back to its original value. Since the two alternator inputs are unchanged and losses are neglected, the two kW outputs are the same as before. The current I_2 is changed due to the change in E_2, but the active components of both I_1 and I_2 remain unaltered.

It will be observed that there is a small change in the load angles of the two alternators, this angle being slightly increased in the case of the weakly excited alternator and slightly decreased in the case of the strongly excited alternator.
It will also be observed that $I_1 + I_2 = I$, the total load current.

Load Sharing

When several alternators are required to run in parallel, it probably happens that their rated outputs differ. In such cases it is usual to divide the total load between them in such a way that each alternator takes the load in the same proportion of its rated load in total rated outputs. The total load is not divided equally. Alternatively, it may be desired to run one large alternator permanently on full load, the fluctuations in load being borne by one or more of the others.

Effect of Change of Input Torque

The amount of power output delivered by an alternator running in parallel with others is governed solely by the power input received from its prime mover.

If two alternators only are operating in parallel the increase in power input may be accompanied by a minute increase in their speeds, causing a proportional rise in frequency. This can be corrected by reducing the power input to the other alternator, until the frequency is brought back to its original value. In practice, when load is transferred from one alternator to another, the power input to the alternator required to take additional load is increased, the power input to the other alternator being simultaneously decreased. In this way, the change in power output can be effected without measurable change in the frequency.

The effect of increasing the input to one prime mover is, thus, seen to make its alternator take an increased share of the load, the other being relieved to a corresponding extent. The final power-factors are also altered, since the ratio of the reactive components of the load has also been changed.

The power-factors of the two alternators can be brought back to their original values, if desired, by adjusting the excitations of alternators.

Example 6.6

Two alternators operating in parallel supply a total load of 40 mW at p.f. = 0.8 lagging, and the load on one machine is 20 mW at 0.9 p.f. lagging. What is the load on the other machine and at what p.f. it is operating.

Solution

Total load

$$= 40 \text{ mW at p.f. } 0.8 = 40/0.8 = 50 \text{ mVA}$$

Since, $\cos\phi = 0.8$, $\sin\phi = 0.6$

$\therefore$ total load $= 50 \times 0.8 - j\,50 \times 0.6 = 40 - j\,30$

Load on one machine is 20 mW at 0.9 p.f.

$$= 20/0.9 = 22.2 \text{ mVA}$$

$$= 22.2 \times 0.9 - j\,22.2 \times 0.435$$

$$= (20 - j\,9.65)$$

Load on the other machine

$$= (40 - j\,30) - (20 - j\,9.65) = 20 - j\,20.35$$

$$= \sqrt{20^2 + 20.35^2} = 28.5 \text{ kVA}$$

$$\tan\phi = \frac{20.35}{20},\ \phi = 45°30',\ \cos\phi = 0.7$$

Hence load on second machine is 28.5 kVA lagging at p.f. 0.7.

SAQ 5

Two alternators running in parallel supply the following four load simultaneously :

(a) 100 kW at unity p.f.

(b) 152 kW at 0.8 lagging

(c) 144 kW at 0.9 leading

(d) 153 kW at 0.9 lagging

If the load on one machine is adjusted to 250 kW at 0.93 lagging. Calculate the load and p.f. of the other machine.

Example 6.7

Consider a 10,000 kVA, 3-phase, star-connected 11,000 V, 2-pole turbo-generator. The various losses in this generator are as follows :

Open circuit core loss at 11,000 V	90 kW
Windage and friction loss	50 kW
Armature copper loss at Short-circuit load of 525 A	220 kW
Field winding resistance	3 Ω
Field current	175 A

Ignoring the change in field current, compute the efficiency at

(a) rated load 0.8 pf leading

(b) half-rated load 0.9 pf lagging.

Solution

Phase current, $I_L = \frac{10000 \times 1000}{\sqrt{3} \times 11000} = 525 \text{ A}$

Friction and windage loss = 50 kW

core loss = 90 kW

Armature copper loss = 220 kW being given at full-load current of 525 A.

Field copper loss $= \frac{I_f^2 R_f}{1000} = \frac{(175)^2 \times 3}{1000} = 91.875 \text{ kW}$

(a) At full load 0.8 pf (lead)

Output = Rated KVA × pf = 10000 × 0.8 = 8000 kW

Total losses = 50 + 90 + 220 + 91.875 = 451.875 kW

Efficiency,

$$\eta = \frac{\text{Output}}{\text{Output} + \text{losses}} \times 100 = \frac{8000}{8000 + 451.875} \times 100 = 94.65\%$$

(b) At half load 0.9 pf (lag)

$$\text{Output} = \frac{1}{2} \times 10000 \times 0.9 = 4500 \text{ kW}$$

$$\text{Armature copper loss } = \left(\frac{1}{2}\right)^2 \times 220 = 55 \text{ kW}$$

Total losses = 50 + 90 + 55 + 91.875 = 286.875 kW

$$\text{Efficiency, } \eta = \frac{4500}{4500 + 286.875} \times 100 = 94\% .$$

6.5 THREE PHASE ROTATING MAGNETIC FIELD

We know the principle of emf induced in stator winding conductors discussed earlier. When a balanced three phase supply is given to a balanced three phase winding, a rotating magnetic field will be developed. For better understanding, we discuss the generation of 3-phase EMF with the help of phasor diagram shown in Figure 6.20.

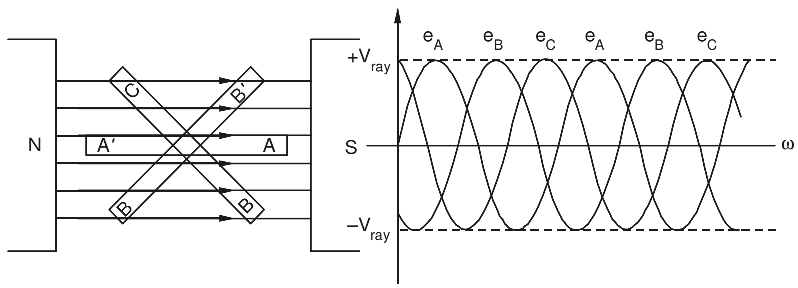


Figure 6.20 : Three Phase Rotating Magnetic Field

As shown in figure three coils, AA', BB', CC' which are placed at 120° to each other, are rotated at ω angular velocity in a magnetic field. The waveform of emf induced in three conductors is shown in figure. The position of maximum emf induced in conductors of the coil is changing with time.

When a 3-phase supply is connected across stator of synchronous motor or induction motor, then a rotating flux ϕ_R is produced in stator which rotates in clockwise direction at synchronous speed

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

Here, P is no. of poles and f is supply frequency.

The sequence of maximum emf shown in Figure 6.20 is generally *RYB*. If we interchanged the position of two phases then sequence will change, hence the direction of rotation of rotating magnetic field will reverse.

$$e_{\dot{A}} \text{ or } e_{AA_1} = E_m \sin wt$$

$$e_{\dot{B}} \text{ or } e_{BB_1} = E_m \sin \left(wt - \frac{2\pi}{3} \right)$$

$$= E_m \sin (wt - 120^{\circ})$$

$$e_C \text{ or } e_{CC_1} = E_m \sin \left(wt - \frac{4\pi}{3} \right)$$

$$= E_m \sin (wt - 240^{\circ})$$

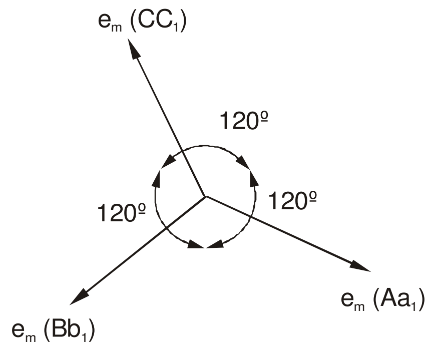


Figure 6.21 : Phasor Diagram of Three Phase AC Supply

6.6 SUMMARY

In this unit you learn how to calculate the induced emf in alternators. You understood armature reaction and different reactances. Also, you were introduced the synchronous impedance and methods to calculate voltage regulation in alternators. Finally, synchronisation of alternators was considered.

6.7 ANSWERS TO SAQs

SAQ 1

(a) Given number of poles $P = 12$

Speed $N = 600$ rpm

Frequency $f = \frac{NP}{120} = \frac{600 \times 10}{120} = 50$ Hz

(i) Single phase connections :

Angular displacement between slots β

$$= \frac{180°}{\text{No. of slots/pole}}$$

or $$\beta = \frac{180}{12} = 15°$$

No. of slots per pole per phase $= m = \frac{12}{1} = 12$

Distribution factor $$K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin \frac{12 \times 15^o}{2}}{12 \sin \frac{15o}{2}}$$

or $$K_d = \frac{\sin 90°}{12 \sin 7.5°} = 0.63844$$

Number of turns per phase = T = No. of slots per phase × turns in each coil

or $$T = (12 \times 12) \times 40 = 5760$$

The coils are full pitch

Pitch factor $K_p = 1$

EMF induced per phase

$$E = 4.44\ K_p\ K_d\ f\ \phi\ T \text{ volts}$$

or $E = 4.44 \times 1 \times 0.63844 \times 50 \times 0.029 \times 5760$

$= 23675.193$ volts

kVA output $= E \times I \times 10^{-3} = 23675.193 \times 45 \times 10^{-3}$

$= 1065.38$ kVA

(ii) Three phase connections:

Angular displacement between slots β

$$= \frac{180°}{\text{No. of slots/pole}}$$

or $\beta = \frac{180°}{12} = 15°$

No. of slots per pole per phase $m = \frac{12}{3} = 4$

Distribution factor $K_d = \frac{\sin \frac{m\beta}{2}}{m \sin \frac{\beta}{2}} = \frac{\sin \frac{4 \times 15^o}{2}}{4 \sin \frac{15^o}{2}}$

or $K_d = \frac{\sin 30°}{4 \sin 7.5°} = 0.95766$

Pitch factor $K_p = 1$

No. of turns per phase

T = No. of slots per phase $\times$ coil turns

$$= \frac{12 \times 12}{3} \times 40 = 1920$$

EMF induced per phase

$$E = 4.44\ K_p\ K_d\ f\ \phi\ T \text{ volts}$$

$E = 4.44 \times 1 \times 0.95766 \times 50 \times 0.029 \times 1920$

$= 11837.60$ volts

kVA output $= 3 \times E \times I \times 10^{-3}$

$= 3 \times 11837.60 \times 45 \times 10^{-3}$

$= 1598.07$ kVA

(b) Here, $\phi = 0.12$ Wb, $m = 4$, $\psi = \frac{180^o}{4 \times 3} = 15^o$, $\alpha = 180^o - 150^o = 30^o$,

$f = 250$ Hz

$$K_d = \frac{\sin\left(\frac{4 \times 15^o}{2}\right)}{4\ \sin\left(\frac{15^o}{2}\right)} = 0.95766$$

$$K_p = \cos \frac{30^o}{2} = \cos 15^o = 0.9659$$

$$E_{ph} = 4.44 \times 0.95766 \times 0.9659 \times 50 \times 0.12 \times \frac{4 \times 4 \times 3 \times 4}{2} = 2365.64 \text{ Volts}$$

$$K_L = \sqrt{3}\ E_{ph} = \sqrt{3} \times 2365.64 = 4097.4 \text{ Volts}$$

SAQ 2

Terminal rated voltage $= \frac{2000}{\sqrt{3}}$ volts per phase

Full load current $= \frac{1000 \times 1000}{\sqrt{3} \times 2000} = \frac{500}{\sqrt{3}}$ amps

Under short circuit condition 80% excitation produces 100% armature current. The current corresponding to 100% excitation can be calculated by assuming the short-circuit characteristic to be a straight line.

$\therefore$ S.C. current at 100% excitation $= \frac{100}{80} \times \frac{500}{\sqrt{3}}$

$$= 1.25 \times \frac{500}{\sqrt{3}} \text{ amps}$$

Synchronous impedance $Z_s = \frac{\text{E.M.F. induced at 100\% excitation}}{\text{Short circuit current at same excitation}}$

or $$Z_s = \frac{2000/\sqrt{3}}{1.25 \times 500/\sqrt{3}} = \frac{2000}{\sqrt{3}} \times \frac{\sqrt{3}}{1.25 \times 500} = 3.2 \Omega$$

SAQ 3

(a) $E_0 = \sqrt{(V \cos \phi + I\ R_a)^2 + (V \sin \phi + I\ X_s)^2}$,

Here, $I = \frac{1.4375 \times 10^3}{\sqrt{3} \times 11} = 75.5 \text{ A}$

$$= \sqrt{(6351 \times 0.8 + 75.5 \times 1.2)^2 + (6351 \times 0.6 + 75.5 \times 25)^2}$$

and $V = \frac{1100}{\sqrt{3}} = 6351 \text{ V}$

$$= 7695 \text{ V}$$

$\therefore$ $\% \text{ Regulation} = \frac{7695 - 6351}{6351} \times 100 = 21.16\%$

(b) $E_0 = \sqrt{(6351 \times 0.8 + 75.5 \times 1.2)^2 + (6351 \times 0.6 - 75.5 \times 25)^2} = 5517 \text{ V}$

$$\% \text{ Regulation} = \frac{5517 - 6351}{6351} = -13.13\%$$

(c) % Regulation is zero when $= \frac{E_0 - V}{V} = 0 \Rightarrow E_0 = V$

or, $\sqrt{(V \cos \phi + I R_a)^2 + (V \sin \phi \pm I X_s)^2} = V$

or, $(V \cos \phi + I R_a)^2 + (V \sin \phi \pm I X_s)^2 = V^2$

or,

$$V^2 \cos^2 \phi + I^2 R_a^2 + 2 R_a V I \cos\phi + V^2 \sin^2 \phi + I^2 X_s^2 \pm 2 X_s V I \sin\phi = V^2$$

or, $$V^2 (\cos^2 \phi + \sin^2 \phi) + I (R^2 + X_s^2) + 2 V I (R_a \cos\phi \pm X_s \sin\phi) = V^2$$

or, $$R_a \cos \phi \pm X_s \sin \phi = \frac{- I (R_a^2 + X_s^2)}{2V}$$

or, $$r \sin \theta \cos \phi \pm r \cos \theta \sin \phi = \frac{- I r^2}{2V}$$

or, $$\sin (\theta \pm \phi) = \frac{- I r}{2V} = \frac{- 75.5 \times 25.03}{2 \times 6351} = - 0.1488$$

Let $R_a = r \sin \theta$,

$$r = \sqrt{R_a^2 + X_s^2}$$

$$= \sqrt{1.2^2 + 25^2}$$

$$= 25.03$$

$$X_s = r \cos \phi$$

$$\theta = \tan^{-1} \frac{R_a}{X_s}$$

$$= \tan^{-1} \frac{1.2}{25}$$

$$= 2.750$$

or, $\theta \pm \phi = \sin^{-1} (- 0.1488) = - 8.56$ (+ for logging load and – for loading load and ϕ is always + ve) with fusion, i.e. – logging load

$$\phi = - 8.56^{\circ} - \theta = - 8.56^{\circ} - 2.75^{\circ} = - 11.31^{\circ}$$

Since ϕ is – ve, this cannot be the solution and hence load cannot be inductive.

With – ve sign, i.e. loading load

$$\phi = \theta + 8.56^{\circ} = 2.75^{\circ} + 8.56^{\circ} = 11.31^{\circ}$$

Thus, pf of the load is $\cos \phi = \cos 11.31^{\circ} = 0.98$ (leading)

SAQ 4

Here, $$I = \frac{1280 \times 10^3}{\sqrt{3} \times 13500 \times 0.8} = 68.43 \text{ A}$$

$$E_0 = \sqrt{(V \cos \phi + I R_a)^2 + (V \sin \phi - I X_s)^2}$$

$$= \sqrt{13500 \times 0.8 + 68.43 \times 1.5)^2 + (13500 \times 0.6 - 68.43 \times 30)^2}$$

$$= 12467 \text{ V}$$

$$\% \text{ Regulation} = \frac{E_0 - V}{V} \times 100 = \frac{12467 - 13500}{13500} \times 100 = - 7.65\%$$

SAQ 5

$$S_{L1} = 100,\ S_{L2}\ \sin j\ \frac{152}{0.8}\ \sin\ (\cos^{-1}\ 0.8) = 152 -\ j\ 114$$

$$S_{L3} = 144 +\ j\ \frac{144}{0.9}\ \sin\ (\cos^{-1}\ 0.9) = 144 +\ j\ 69.74$$

Total load $S_L = S_{L1} + S_{L2} + S_{L3} + S_{L4} = 549 -\ j\ 118.36$

Load supplied by generator 1

$$S_{G1} = 250 -\ j\ \frac{250}{0.93}\ \sin\ (\cos^{-1}\ 0.93) = 250 -\ j\ 98.81$$

$\therefore$ Balance load supplied by generator 2

$$S_{G2} = S_L - S_{G1} = (549 - 250) -\ j\ (118.36 - 98.81) = 299 -\ j\ 19.55$$

$$= 299.64\ \angle -3.74^{o}$$

$$\cos\phi = \cos\ (-3.74^{o}) = 0.9978 \quad \text{(lagging)}$$

Thus, generator 2 supplies 299 kW or 299.64 kVA at 0.9978 lagging pf.