UNIT – V
Regulation and Parallel Operation of Alternator

Objectives:

- To determine the voltage regulation of an alternator using MMF and ZPF methods.
- To synchronize the alternators with infinite bus bars.
- To analyze the power angle characteristics of alternators.
- To interpret the parallel operation of alternators with change in excitation and mechanical power input.

Syllabus:

Voltage regulation of an alternator , EMF method for calculation of voltage regulation ,Voltage regulation by M.M.F method – Z.P.F Characteristic – Voltage regulation by Z.P.F Method – Synchronization – Conditions for synchronization – Methods of synchronizing alternators with infinite bus bars, dark lamp method, synchroscope method – Power angle characteristics of synchronous machines – Synchronizing power – Synchronizing torque – Parallel operation of synchronous generator – Load sharing – Effect of change of excitation, effect of change of mechanical power input

Outcomes:

Students will be able to

- determine the voltage regulation of alternator by MMF and ZPF methods
- analyze the methods of synchronizing alternators with bus bars.
- demonstrate the concepts of synchronizing power and synchronizing torque.
- illustrate the effect of change in excitation and mechanical input during parallel operation of alternators.

Determination of Voltage Regulation by EMF method (Synchronous Impedance Method):

The synchronous impedance of the alternator changes as load condition changes. O.C.C. and S.C.C. can be used to determine Z_s for any load and load p.f. conditions.

In short circuit test, external load impedance is zero. The short circuit armature current is circulated against the impedance of the armature winding which is Z_s. The voltage responsible for driving this short circuit current is internally induced e.m.f. This can be shown in the equivalent circuit drawn in the Fig. 5.1.

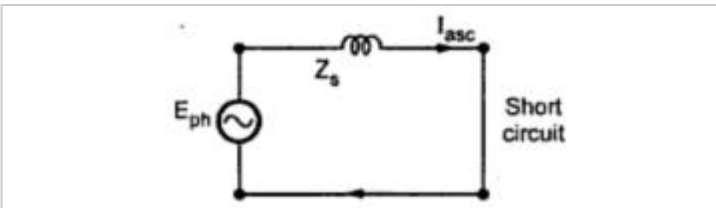


Fig. 5.1 Equivalent circuit on short circuit

From the equivalent circuit we can write,

$$Z_s = \frac{E_{ph}}{I_{asc}}$$

Now value of I_{asc} is known, which can observed on the alternator. But internally induced e.m.f. cannot be observed under short circuit condition. The voltmeter connected will read zero which is voltage across short circuit. To determine Z_s it is necessary to determine value of E which is driving I_{asc} against Z_s.

Now internally induced e.m.f. is proportional to the flux i.e. field current I_f.

$$\mathbf{E_{ph}} \ \alpha \ \mathbf{\Phi} \ \alpha \ \mathbf{I_f} \qquad \text{...... from e.m.f. equation}$$

So if the terminal of the alternator are opened without disturbing I_f which was present at the time of short circuited condition, internally induced e.m.f. will remain same as E_{ph}. But now current will be zero. Under this condition equivalent circuit will become as shown in the Fig.5.2.

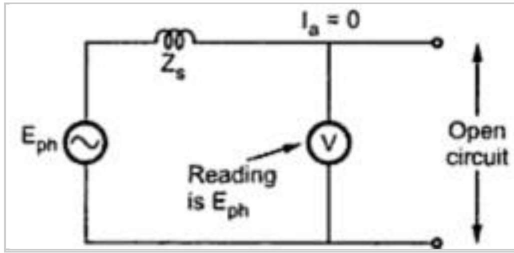


Fig 5.2

It is clear now from the equivalent circuit that as $I_a = 0$ the voltmeter reading $(V_{oc})_{ph}$ will be equal to internally induced e.m.f. (E_{ph}).

$$\therefore \quad \boxed{E_{ph} = (V_{oc})_{ph} \text{ on open circuit}}$$

This is what we are interested in obtaining to calculate value of Z_s. So expression for Z_s can be modified as,

$$Z_s = \left.\frac{(V_{oc})_{ph}}{(I_{asc})_{ph}}\right|_{\text{for same } I_f}$$

$$\text{Thus in general,} \quad \boxed{Z_s = \left.\frac{\text{Phase e.m.f. on open circuit}}{\text{Phase current on short circuit}}\right|_{\text{For same excitation current}}}$$

So O.C.C. and S.C.C. can be used effectively to calculate Z_s.

The value of Z_s is different for different values of I_f as the graph of O.C.C. is non linear in nature.

So suppose Z_s at full load is required then,

I_{asc} = full load current.

From S.C.C. determine I_f required to drive this full load short circuit I_a. This is equal to 'OA', as shown in the Fig.5.2.

Now for this value of I_f, $(V_{oc})_{ph}$ can be obtained from O.C.C. Extend line from point A, till it meets O.C.C. at point C. The corresponding $(V_{oc})_{ph}$ value is available at point D.

$$(V_{oc})_{ph} = OD$$
$$\text{While } (I_{asc})_{ph} = OE$$

$$\therefore \quad Z_s \text{ at full load} = \left.\frac{(V_{oc})_{ph}}{\text{Full load } (I_{asc})_{ph}}\right|_{\text{same } I_f \text{ (same excitation)}}$$

$$= \left.\frac{OD}{OE}\right|_{\text{same } I_f = OA}$$

at full load

General steps to determine Z_s at any load condition are :

i) Determine the value of $(I_{asc})_{ph}$ for corresponding load condition. This can be determined from known full load current of the alternator. For half load, it is half of the full load value and so on.

ii) S.C.C. gives relation between $(I_{asc})_{ph}$ and I_f. So for $(I_{asc})_{ph}$ required, determine the corresponding value of I_f from S.C.C.

iii) Now for this same value of I_f, extend the line on O.C.C. to get the value of $(V_{oc})_{ph}$. This is $(V_{oc})_{ph}$ for same I_f, required to drive the selected $(I_{asc})_{ph}$.

iv) The ratio of $(V_{oc})_{ph}$ and $(I_{asc})_{ph}$, for the same excitation gives the value of Z_s at any load conditions.

Regulation Calculations:

From O.C.C. and S.C.C., Z_s can be determined for any load condition.

The armature resistance per phase (R_a) can be measured by different methods. One of the method is applying d.c. known voltage across the two terminals and measuring current. So value of R_a per phase is known.

Now $$Z_s = \sqrt{(R_a)^2 + (X_s)^2}$$

$$\therefore \quad \boxed{X_s = \sqrt{(Z_s)^2 - (R_a)^2} \ \Omega/\text{ph}}$$

So synchronous reactance per phase can be determined.

No load induced e.m.f. per phase, E_{ph} can be determined by the mathematical expression derived earlier.

$$\boxed{E_{ph} = \sqrt{(V_{ph} \cos\phi + I_a R_a)^2 + (V_{ph} \sin\phi \pm I_a X_s)^2}}$$

where V_{ph} = Phase value of rated voltage

I_a = Phase value of current depending on the load condition

$\cos\Phi$ = p.f. of load

Positive sign for lagging power factor while negative sign for leading power factor, R_a and X_s values are known from the various tests performed.

The regulation then can be determined by using formula,

$$\% \text{ Regulation} = \frac{E_{ph} - V_{ph}}{V_{ph}} \times 100$$

Advantages of Synchronous Impedance Method:

The main advantages of this method is the value of synchronous impedance Z_s for any load condition can be calculated. Hence regulation of the alternator at any load condition and load power factor can be determined. Actual load need not be connected to the alternator and hence method can be used for very high capacity alternators.

Drawbacks of EMF or Synchronous Impedance method:

1) Syn. Impedance is not constant. In linear portion only it is constant. Above the knee of OCC, syn. Impedance decreases. Zs below saturation is larger than under saturation. Thus we don't take the effect of saturation. This the greatest source of error in this method.
2) The flux under test conditions is not same as under load conditions. In SCC, armature reaction is almost demagnetising. Thus, the OC voltage is greater than the SC voltage.The Zs obtained is too large.
3) This method assumes that the reluctance to the armature flux is constant. This is true only for a cylindrical rotor, not for a salient pole machine. So, this method is suitable only for cylindrical rotor alternators.

   As, Zs obtained is more in this method, the regulation obtained is higher than the actual. That is why this method is called pessimistic method.

Voltage regulation by MMF method:

In the emf method all the mmfs were transformed into their corresponding emfs. In the mmf method, the reverse procedure is adopted, each emf is replaced by and equivalent mmf provided all the assumptions of emf method are invoked here.

The voltage equation of a synchronous machine, working as an alternator is

$$\overline{E}_f = \overline{V}_t + \overline{I}_a r_a + j\,\overline{I}_a X_s$$

For using mmf method the above equation must now be converted to a new equation involving mmfs only. Division of emfs in volts by –jK gives the corresponding mmf. So the mmf equation as follows.

$$\frac{\overline{E}_f}{-jK} = \frac{\overline{V}_t + \overline{I}_a\, r_a}{-jK} + \frac{j\,\overline{I}_a\,(x_{al} + X_{ar})}{-jK}$$

$$\frac{\overline{E}_f}{-jK} = \frac{\overline{E}'}{-jK} - \frac{\overline{I}_a\, x_{al}}{K} - \frac{\overline{I}_a\, X_{ar}}{K}$$

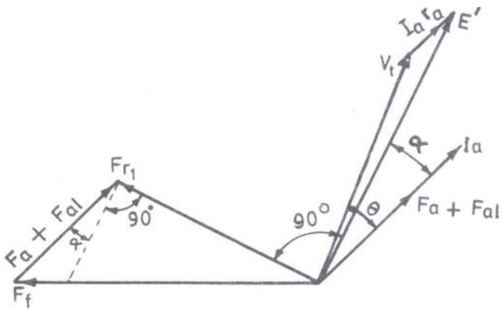


Fig. 5.3 Phasor diagram for mmf method.

From above equation

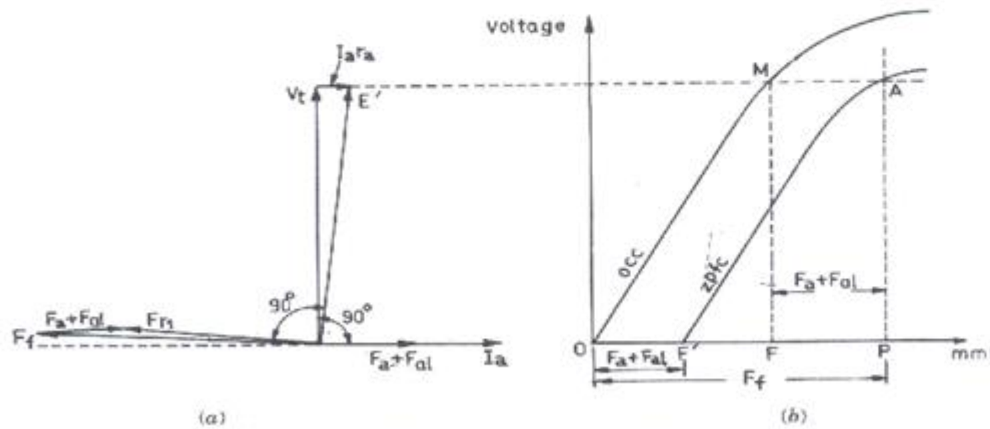
$\frac{\overline{E}_f}{-jK} = \overline{F}_f$ and similarly let $\frac{\overline{E}'}{-jK}$ be equal to $\overline{F}_{r1}$.

The armature reactance drop IaXar is transformed into mmf Fa. Similarly IaXal can be transformed into equivalent mmf Fal. Introducing these changes,

$$\overline{F}_f = \overline{F}_{r1} - (\overline{F}_{al} + \overline{F}_a)$$

It is seen from fig. 3.2 that α is the angle by which Ia lags E' and between the normal line to Fr1 and Fa+Fal.

For a purely reactive load the phasor diagram of fig 5.3 gets modified to that shown in Fig. 5.4



(a) Alternator phasor diagram for purely reactive load ; m.m.f. method (b) Determination of $(F_a + F_{al})$ by m.m.f. method.

Fig 5.4

Terminal voltage is nearly the same as E'. The OCC is again assumed to represent the relation between E' and mmf Fr1. In Fig 5.4 OP=Ff is any field excitation, from which PF = Fa+Fal has been deducted to give the resultant mmf Fr1 = OF. This mmf Fr1 induces 90 degrees lagging emf E' equal to Vt = FM=PA. Here zpfc is seen to be shifted horizontally to the right of OCC by an amount equal to Fa+Fal. Thus Fa+Fal can be obtained by measuring the horizontal displacement between OCC and zpfc, such as MA=OF'. Therefore Fa+Fal is the mmf or field current, required to circulate full load armature current under short circuit test.

Hence, in order to obtain voltage regulation by mmf method:

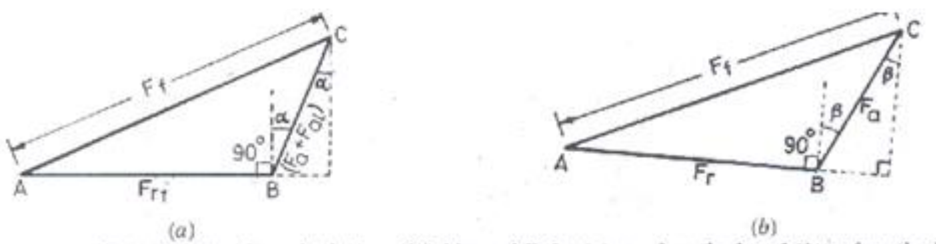
(i) Plot OCC and SCC

(ii) Find $\overline{E}' = \overline{V}_t + \overline{I}_a r_a$ and obtain the corresponding value of F_{r1} from O.C.C.

(iii) Find $(F_a + F_{al})$ from S.C.C.

Calculate Ff = Fr1+Fa+Fal .

Field mmf Ff can also be obtained from fig 5.5



Pertaining to the calculation of field mmf F_f for (a) mmf method and (b) zpf method

Fig 5.5

$$F_f = \sqrt{(AB + BC \sin \alpha)^2 + (BC \cos \alpha)^2}$$

Now, corresponding to field mmf Ff, obtain Ef from OCC and thus the voltage regulation of alternator.

This method is called optimistic method because it gives regulation lesser than the actual. The reason for this is that the excitation to overcome armature reaction is determined on unsaturated part of the saturated curve.

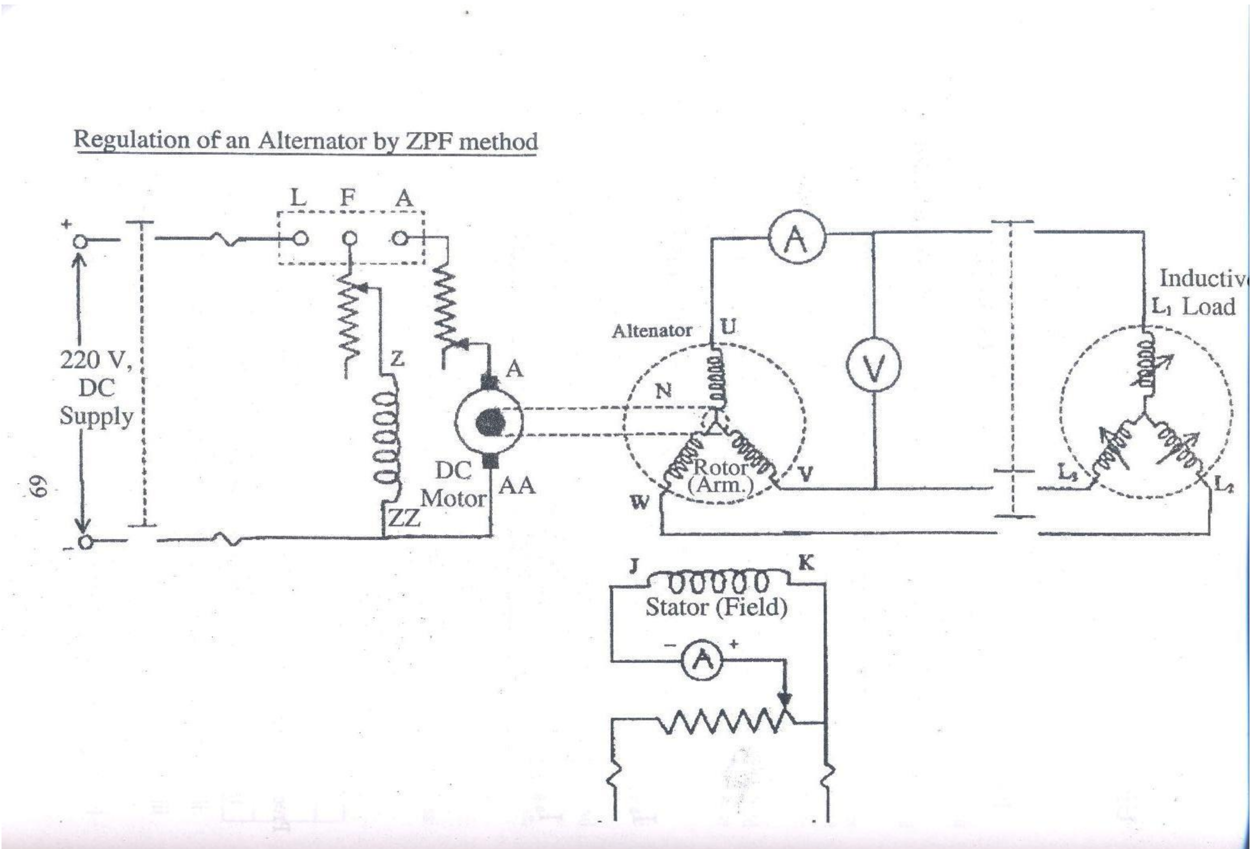
Zero power-factor characteristic and Potier Triangle:

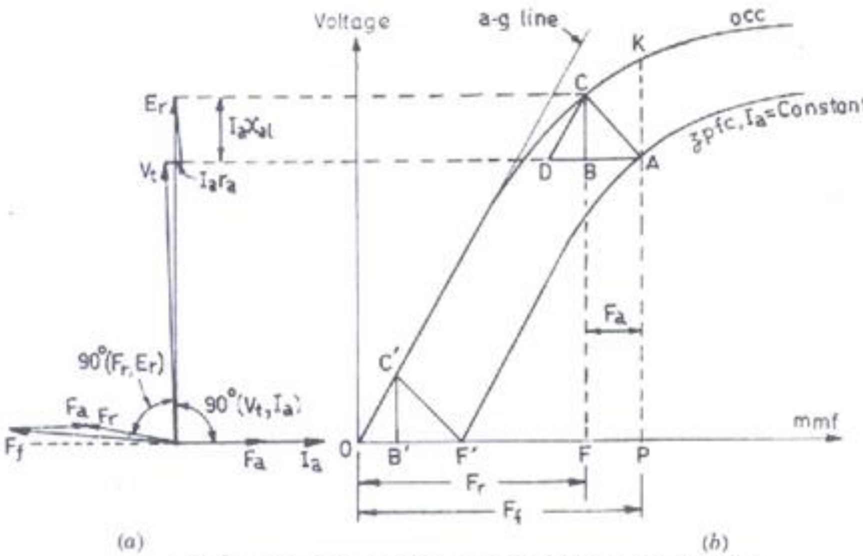
Zero power factor characteristic (z.p.f.c) of an alternator is a plot between armature terminal voltage and its field current for constant values of armature current and speed. Z.p.f.c. in conjunction with OCC is usefull in obtaining the armature leakage reactance X_{al} and armature reaction mmf F_a. For an alternator zpfc is obtained as follows:

(i) The synchronous machine is run at rated synchronous speed by a prime mover.

(ii) A purely inductive load is connected across armature terminals and field current is increased till full load armature current is flowing.

(iii) The load is varied in steps and the field current at each step is adjusted to maintain full load armature current. The plot of armature terminal voltage and field current recorded at each step gives zpfc at full armature current.





(a) General phasor diagram of cylindrical-rotor alternator at zero power-factor over-excited. (b) O.C.C., z.p.f.c. and Potier triangle.

Fig 5.6

The phasor diagram under zero power factor over excited conditions is shown in fig.5.6 (a). From this fig it can be seen that terminal voltage Vt and airgap voltage Er, are nearly in phase and are therefore related by the simple algebraic equation

$$V_t = E_r - I_a x_{al}$$

The resultant mmf Fr and the field mmf Ff are also very nearly in phase and are related by simple algebraic equation

$$F_f = F_r + F_a$$

Assume that OCC gives the exact relation between airgap voltage Er and the resultant mmf Fr under load. Also assume armature leakage reactance to be constant.

The OCC and zpfc are shown in Fig. 5.6 [b]. For field excitation Ff or field current If, equal to OP, the open circuit voltage is PK. With the field excitation and speed remaining unchanged, the armature terminals are connected to a purely inductive load such that full load armature current flows. An examination of Fig 5.6 reveals that under zero power factor load, the net excitation is OF, which is less than OP by Fa. According to the resultant mmf OF, the airgap voltage is Er is FC and if CB = IaXal is subtracted from Er = FC, the terminal voltage FB=PA=Vt is obtained. Since zpfc is a plot between the terminal voltage and field current If or Ff, which has not changed from its no load value of OP, the point A lies on zpfc. The triangle ABC so obtained is called the Potier triangle, where CB= IaXal and BA=Fa. Thus from the Potier triangle, the armature leakage reactance Xal and armature reaction mmf Fa can be determined.

If the armature resistance is assumed zero and the armature current is kept constant, then the size of potier triangle ABC remains constant and can be shifted parallel to itself with its corner C remaining on the OCC and its corner A, tracing the zpfc. Thus the zpfc has the same shape as the OCC and is shifted vertically downward by an amount equal to IaXal and horizontally to the right by an amount equal to the armature reaction mmf Fa or the field current equivalent to armature reaction mmf.

The point F' on the zpfc corresponds to the zero terminal voltage and can there be obtained by performing SC test. So here OF' is the field current required to circulate the short circuit current equal to the armature current at which the point A is determined in the zero power factor test.

Now draw a horizontal line AD, parallel and equal to F'O. Through the point D, draw a straight line parallel to airgap line, intersecting the OCC at C. Draw CB perpendicular to AD. Then ABC is the Potier triangle from which

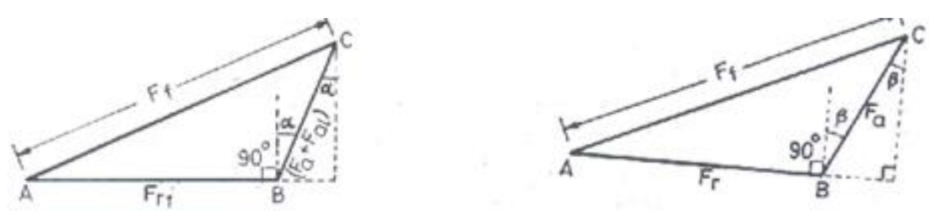
$$BC = I_a x_{al}$$
$$AB = F_a$$

Zero Power Factor Method:

This is also called general method of obtaining voltage regulation. In the emf method, the phasor diagram involving voltages is used, whereas in mmf method, the phasor diagram involving mmfs is used. For the zpf method, the emfs are handled as voltages and the mmfs as field ampere turns or field amperes.

First of all determine the airgap voltage Er by the relation

$$\overline{E}_r = \overline{V}_t + \overline{I}_a\,(r_a + jx_{al})$$



Pertaining to the calculation of field mmf F_f for (a) mmf method and (b) zpf method.

Fig 5.7

According to the magnitude of Er, obtain Fr from OCC. Field mmf Ff can be obtained by referring to figure 5.7(b) where mmf components are drawn by taking Fr horizontal. So, in this figure, AB = Fr, BC = Fa and angle β is the angle between Er and Ia. Then AC = Ff can be calculated as

$$F_f = \sqrt{(AB + BC\sin\beta)^2 + (BC\cos\beta)^2}$$

Corresponding to Ff, excitation voltage Ef is obtained from OCC and then the voltage regulation is obtained. Zpfc method requires OCC and zpfc and gives quite accurate results.

The regulation obtained by EMF and MMF methods is based on the total syn. reactance (sum of reactance due to arm. leakage flux and arm. reaction effect). In ZPF method, regulation is based on the separation of reactances due to arm. leakage and arm. reaction flux; it is more accurate.

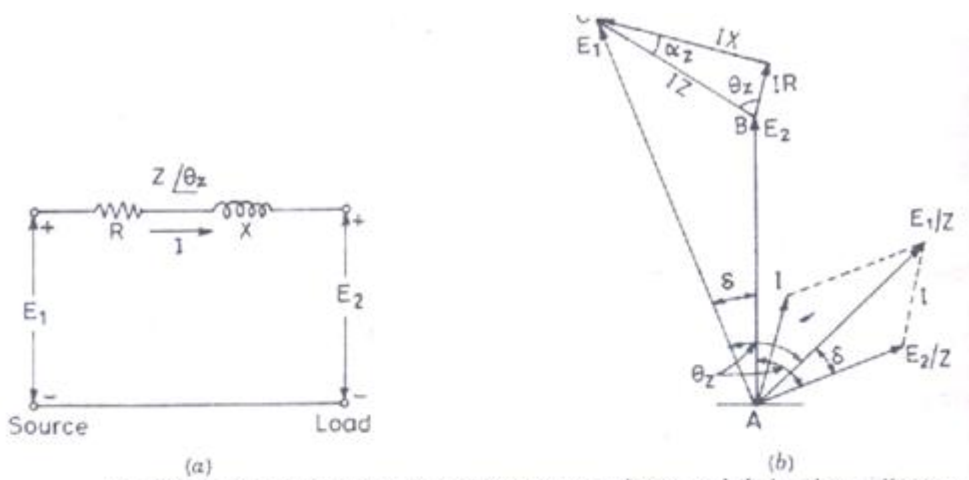
Power flow through an Inductive Impedance:

A more general problem of power flow through an inductive impedance is considered here, since the problems associated with the steady state power flow in many systems, can be studied with its help. Fig. 5.8 shows two ac voltage sources E1, E2 interconnected through impedance $Z\angle\theta_z$.

With current I flowing from E1 to E2, the phasor diagram as shown in fig. 5.8 (b). from which

$$\overline{E}_1 = \overline{E}_2 + \overline{I}\,\overline{Z}$$

$$\overline{I} = \frac{\overline{E}_1 - \overline{E}_2}{\overline{Z}} = \frac{\overline{E}_1}{\overline{Z}} - \frac{\overline{E}_2}{\overline{Z}}$$



(a) Circuit for inductive impedance between two voltages and (b) its phasor diagram.

Fig 5.8

Here impedance angle is given by

$$\theta_z = \tan^{-1}\left(\frac{X}{R}\right).$$

It is seen from Fig5.8 (b) that $\alpha_z + \theta_z = 90°$

The power P1 at the source end E1 of the impedance Z is given by

P1 = E1 (Component of I in phase with E1).

From Fig. 5.8 (b), the component of I in phase with E1 is seen to be

$$\left[\frac{E_1}{Z}\cos\theta_z - \frac{E_2}{Z}\cos(\delta + \theta_z)\right].$$

$$P_1 = E_1\left[\frac{E_1}{Z}\cos\theta_z - \frac{E_2}{Z}\cos(\delta + \theta_z)\right]$$

$$= \frac{E_1^2}{Z}\cos\theta_z - \frac{E_1E_2}{Z}\cos(\delta + \theta_z)$$

$$\cos\theta_z = \frac{R}{Z},$$

if $\theta_z = (90 - \alpha_z)$ is substituted, we get

$$P_1 = \frac{E_1^2 R}{Z^2} - \frac{E_1E_2}{Z}[\cos\{(\delta - \alpha_z) + 90°\}]$$

$$= \frac{E_1 E_2}{Z}\sin(\delta - \alpha_z) + \frac{E_1^2 R}{Z^2}$$

The power P2 at the load end E2 and flowing through the impedance Z, is given by

P2 = E2 (Component of I in phase with E2).

From Fig. 5.8(b), the component of I in phase with E2 is

$$\left[\frac{E_1}{Z}\cos(\theta_z - \delta) - \frac{E_2}{Z}\cos\theta_z\right]$$

$$P_2 = \frac{E_2E_1}{Z}\cos(\theta_z - \delta) - \frac{E_2^2}{Z}\cos\theta_z$$

$$= \frac{E_2 E_1}{Z}\cos[90 - (\alpha_z + \delta)] - \frac{E_2^2}{Z}\cos\theta_z$$

$$= \frac{E_2 E_1}{Z}\sin(\delta + \alpha_z) - \frac{E_2^2}{Z^2}R$$

The power flow in a cylindrical rotor synchronous machine is special case of the above more general problem of power flow through an inductive impedance this is because the equivalent circuit of this machine is identical with the circuit of fig.5.8

Thus, for studying the power flow in a cylindrical rotor alternator,

$$E_1 = E_f, E_2 = V_t,$$
$$Z = Z_s = r_a + jX_s.$$

Power input to generator is

$$P_{ig} = \frac{E_f V_t}{Z_s} \sin(\delta - \alpha_z) + \frac{E_f^2}{Z_s^2} r_a$$

Power output of generator is

$$P_{og} = \frac{E_f V_t}{Z_s} \sin(\delta + \alpha_z) - \frac{V_t^2}{Z_s^2} r_a$$

The difference between input and output must be equal to ohmic loss. This can be proved as follows

$$P_{ig} - P_{og} = \frac{E_f V_t}{Z_s} [\sin\delta\cos\alpha_z - \cos\delta\sin\alpha_z - \sin\delta\cos\alpha_z - \cos\delta\sin\alpha_z] + (E_f^2 + V_t^2)\frac{r_a}{Z_s^2}$$

$$= \frac{r_a}{Z_s^2}(E_f^2 + V_t^2) - \frac{2E_f V_t}{Z_s}\cos\delta\sin\alpha_z$$

$$= \frac{r_a}{Z_s^2}(E_f^2 + V_t^2) - \frac{2E_f V_t}{Z_s}\cdot\frac{r_a}{Z_s}\cdot\cos\delta$$

$$= \frac{r_a}{Z_s^2}[E_f^2 + V_t^2 - 2E_f V_t \cos\delta].$$

From triangle ABC of fig5.8(b) and with appropriate changes

$$(AC)^2 + (AB)^2 - 2(AC)(AB)\cos\delta = (BC)^2$$

or $$E_f^2 + V_t^2 - 2E_f V_t \cos\delta = I_a^2 Z_s^2$$

$\therefore$ $$P_{ig} - P_{og} = \frac{r_a}{Z_s^2}(I_a^2 Z_s^2) = I_a^2 r_a = \text{ohmic loss}.$$

Similarly, $$P_{im} - P_{om} = I_a^2 r_a.$$

Generally armature resistance is negligible and this makes

$$\alpha_z = 0$$

$$Z_s = X_s.$$

with these changes

$$P_{ig} = P_{og} = P_{im} = P_{om} = P \text{ (say)}$$

$$= \frac{E_f V_t}{X_s}\sin\delta$$

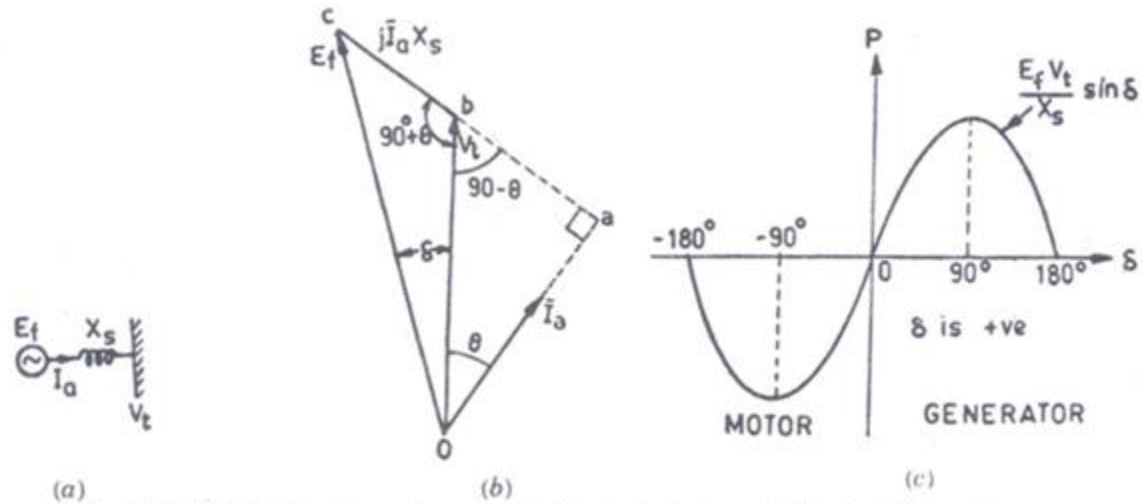
Power angle characteristics of Synchronous machines:

In this article, the power expressions are derived in terms of power angle, from the phasor diagrams of cylindrical rotor and salient pole machines. The power flow through a non salient pole synchronous machine is already discussed in previous article and the present derivation merely supplements the previous analysis.

Armature resistance of synchronous machines are usually small, these are, therefore, neglected in this article.

Cylindrical rotor synchronous machine:

Consider that the synchronous machine is acting as a generator and is feeding power to an infinite bus of constant voltage Vt, as shown in single line diagram of fig. 5.9 (a). Its phasor diagram for a lagging power factor with zero armature resistance is shown.



. Cylindrical-rotor alternator connected to infinite bus, (a) its single line diagram (b) its phasor diagram for a lagging power factor and (c) its power angle characteristic.

Fig 5.9

The per phase power delivered to the infinite bus is given by

$$P = V_t I_a \cos \theta$$

$\angle oba = 90 - \theta$ and $\angle obc = 180 - (90 - \theta) = 90 + \theta$.

$$\frac{bc}{\sin \angle boc} = \frac{oc}{\sin \angle obc}$$

or
$$\frac{X_s I_a}{\sin \delta} = \frac{E_f}{\sin (90 + \theta)}$$

or
$$X_s I_a \sin (90 + \theta) = E_f \sin \delta$$

or
$$X_s I_a \cos \theta = E_f \sin \delta$$

or
$$I_a \cos \theta = \frac{E_f}{X_s} \sin \delta.$$

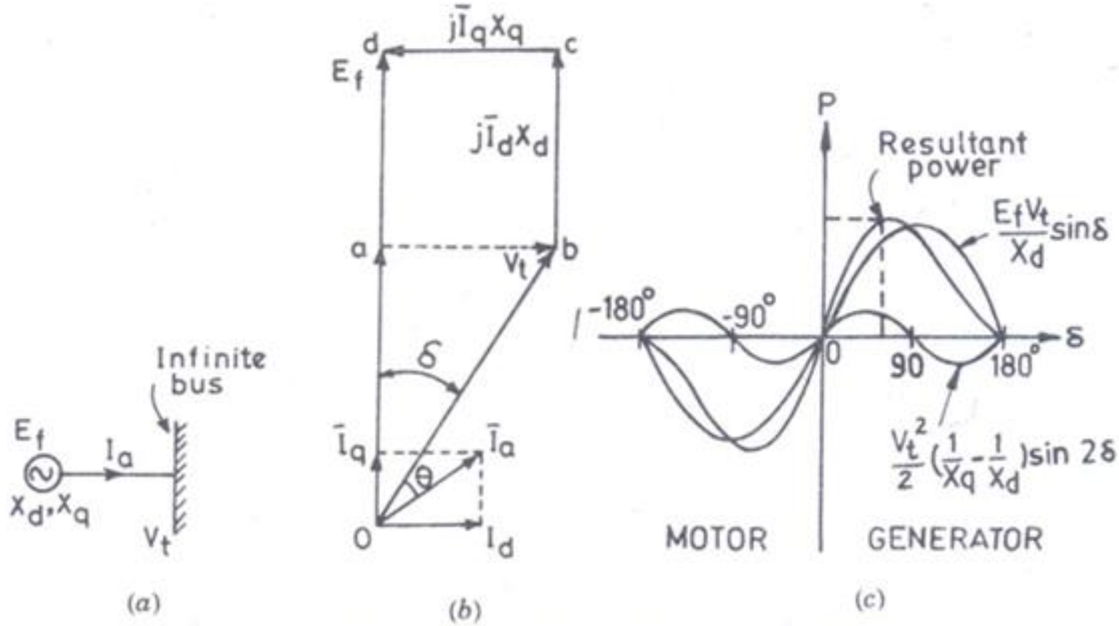
$$P = \frac{E_f V_t}{X_s} \sin \delta$$

With the help of the above equation, the variation of power with power angle is plotted in fig.5.9 (c). This power versus load angle curve has a sinusoidal shape and is usually called the power angle characteristics of cylindrical rotor synchronous machine.

Salient pole synchronous machine:

Consider that the synchronous machine acting as a generator, is connected to an infinite bus shown in fig.5.10. Its phasor diagram for a lagging power factor load and with zero armature resistance is shown in fig. 5.10. The components of Vt in phase with Id and Iq are $V_t \sin \delta$ and $V_t \cos \delta$ respectively.. Since these two components of Vt are in phase with Id and Iq, the per phase power delivered to the bus is

$$P = I_d\,(V_t \sin \delta) + I_q\,(V_t \cos \delta) \qquad \ldots($$



. Salient pole synchronous generator (a) single line diagram (b) phasor diagram for a lagging p.f. and (c) power-angle characteristic.

Fig 5.10

From fig.

$$, V_t \sin \delta = ab = dc = I_q X_q$$

$$I_q = \frac{V_t \sin \delta}{X_q}$$

$$V_t \cos \delta = oa = od - ad = od - bc = E_f - I_d X_d$$

$$I_d = \frac{E_f - V_t \cos \delta}{X_d}$$

Substituting values of Id and Iq and simplifying, we get

$$P = \frac{E_f V_t}{X_d} \sin \delta + \frac{V_t^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta$$

The power versus load angle characteristics of a salient pole machine is shown in fig. 5.10 (c).The total power consists of a fundamental component and a second harmonic component. The first term is identical with that obtained for a cylindrical rotor machine. This component of power is called the electromagnetic power, because its existence depends on both the armature winding (with Vt) and the field winding (with If). The second term exists even when the field current is zero i.e. Ef is zero. This second component of power is present because the armature reaction flux has a tendency to pass through the field structure along minimum reluctance path i.e. along the field pole axis or d axis.

Synchronizing power and Synchronizing torque:

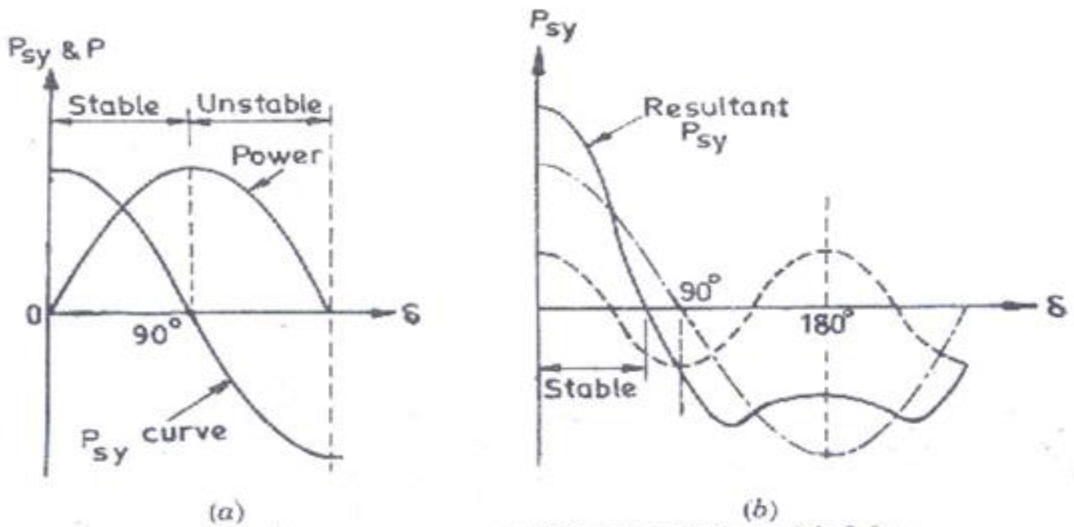
The rate at which synchronous power P varies with load angle is called the synchronizing power coefficient Psy. It is also known as stiffness of coupling, rigidity factor or stability factor. For a cylindrical rotor machine,

$$P_{sy} = \frac{dP}{d\delta} = \frac{E_f V_t}{X_s} \cos \delta$$

For a salient pole machine,

$$P_{sy} = \frac{dP}{d\delta} = \frac{E_f V_t}{X_d} \cos \delta + V_t^2 \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \cos 2\delta$$

The coefficient Psy is equal to the slope of the power angle curve and its variation with load angle is illustrated in fig.5.11



. . Synchronous-power coefficient variation with δ for (a) cylindrical rotor machine and (b) salient-pole machine.

Fig 5.11

The synchronizing power coefficient is a measure of the stiffness of electromagnetic coupling between stator and rotor fields. Too large stiffness of coupling means that the motor tends to follow closely, the variation of speed caused by the disturbance in electric power supply. In case there is no power supply disturbance, then too much stiffness of coupling would cause the motor speed to remain practically constant, regardless of the mechanical load fluctuations. In view of this, too rigid electromagnetic coupling causes undue mechanical shocks, whenever there are fluctuations in the mechanical load or the supply. Note that the units of synchronizing power coefficient are watts per electrical radian.

$$P_{sy} = \frac{\pi}{180} \cdot \frac{E_f \cdot V_t}{X_s} \cos\delta \text{ watts/electrical degree.}$$

Now consider a synchronous machine in which the load angle has changed from δ to $\delta+\Delta\delta$

Due to some transient disturbance. The variation of synchronous power associated with the change of load angle $\Delta\delta$, is called the synchronizing power Ps. The synchronizing power is given by

$$P_s = \frac{dP}{d\delta} \cdot \Delta\delta = \frac{E_f V_t}{X_s} \cos\delta\, \Delta\delta$$

$$P_s = \left[\frac{E_f V_t}{X_d} \cos\delta + V_t^2 \left(\frac{1}{X_q} - \frac{1}{X_d}\right) \cos 2\delta\right] \Delta\delta$$

The above equations give the synchronizing power for a cylindrical rotor and salient pole machines respectively, for a phase displacement of angle $\Delta\delta$

At no load, $\delta \cong 0$ and Vt = Ef. Therefore synchronizing power at no load is

$$P_s = \frac{V_t^2}{X_s} \Delta\delta$$

$$\frac{E_f}{X_s} = \frac{V_t}{X_s} = \text{steady-state short circuit } I_{sc}.$$

$$P_s = V_t I_{sc} \Delta\delta \text{ watts}$$

A careful consideration reveals that synchronizing power is transient in nature, it comes into play only when there is a sudden disturbance in the steady state operating conditions. In case of generator, a sudden disturbance in prime mover torque causes the synchronizing power to flow from, or to, the bus, in order to restore the rotor to its previous position. A sudden disturbance in the generator field current also causes the synchronizing power to come into play, so as to maintain the synchronism. In short, the synchronizing power comes into play only when the steady state operating conditions are disturbed. Once the steady state condition is reached after the disturbance, the synchronizing power reduces to zero. Thus the synchronizing power is transient in nature and exists only for the time during which the disturbance persists.

The synchronizing power gives rise to synchronizing torque Ts and its magnitude for a small displacement $\Delta\delta$ is given by

$$T_s = \frac{1}{\omega_s} P_s = \frac{1}{\omega_s} m \frac{dP}{d\delta} \cdot \Delta\delta$$

If armature resistance is not neglected for cylindrical rotor machine, then synchronizing power is given by

$$P_s = \frac{E_f V_t}{Z_s} \cos(\delta + \alpha_z) \cdot \Delta\delta$$

$$\alpha_z = \tan^{-1} \frac{r_a}{X_s}.$$

Synchronization:

Synchronization is the process of switching on of an alternator to another alternator (or bus bars) under voltage, without any interruption. This may alternatively be defined as the process of connecting two alternators in parallel, without any interruption. The synchronous machine which is to be synchronized is usually called an incoming machine. Certain conditions, which must be fulfilled before synchronization can be carried out, are given below.

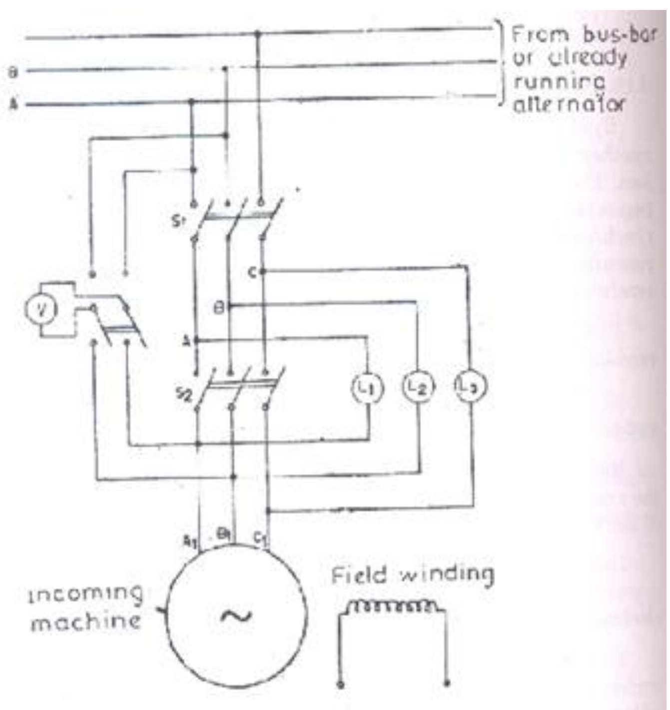
1. The terminal voltage of the incoming machine and already running alternator or bus bars must be equal.
2. The frequency of the two voltage sources must be nearly the same.
3. The two voltages must be in the same phase with respect to the external load. This condition also means that the phase sequence of the two voltages must be the same.

Departure from the above conditions cause the appearance of current and power surges which are accompanied by undesirable electromechanical oscillations of the rotor.

Synchronizing by dark lamp method:

This is the simplest method of synchronizing an incoming machine with another alternator or bus bars.

Fig. 4.5 illustrates the connection scheme, where the lamps are connected across the synchronizing switch S2.



Synchronizing by dark-lamp method.

Fig5.12

The incoming machine is brought up to its synchronous speed by the prime mover and then its field circuit is energised. Now the current is adjusted till terminal voltage of the incoming machine becomes equal to that of the already running alternator or busbar. In this way first condition of equal voltages is satisfied and switch S1 is closed. The other two conditions of synchronisation require special considerations.

Suppose the frequencies of the bus bar and the incoming machine are f and f1 respectively. Then for equal voltages, the voltage across the synchronizing switch S2 is

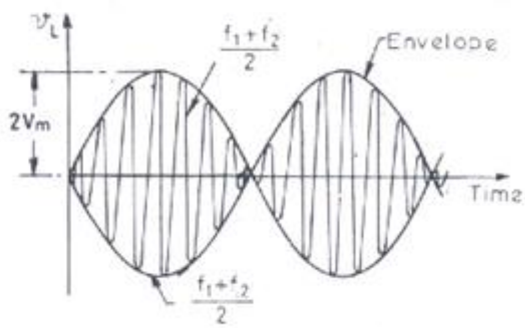
$$v_L = V_m \cos \omega t - V_m \cos \omega_1 t.$$

With the help of trigonometric relation

$$\cos y - \cos x = 2 \sin \frac{x-y}{2} \cdot \sin \frac{x+y}{2}$$

The above equation can be written as

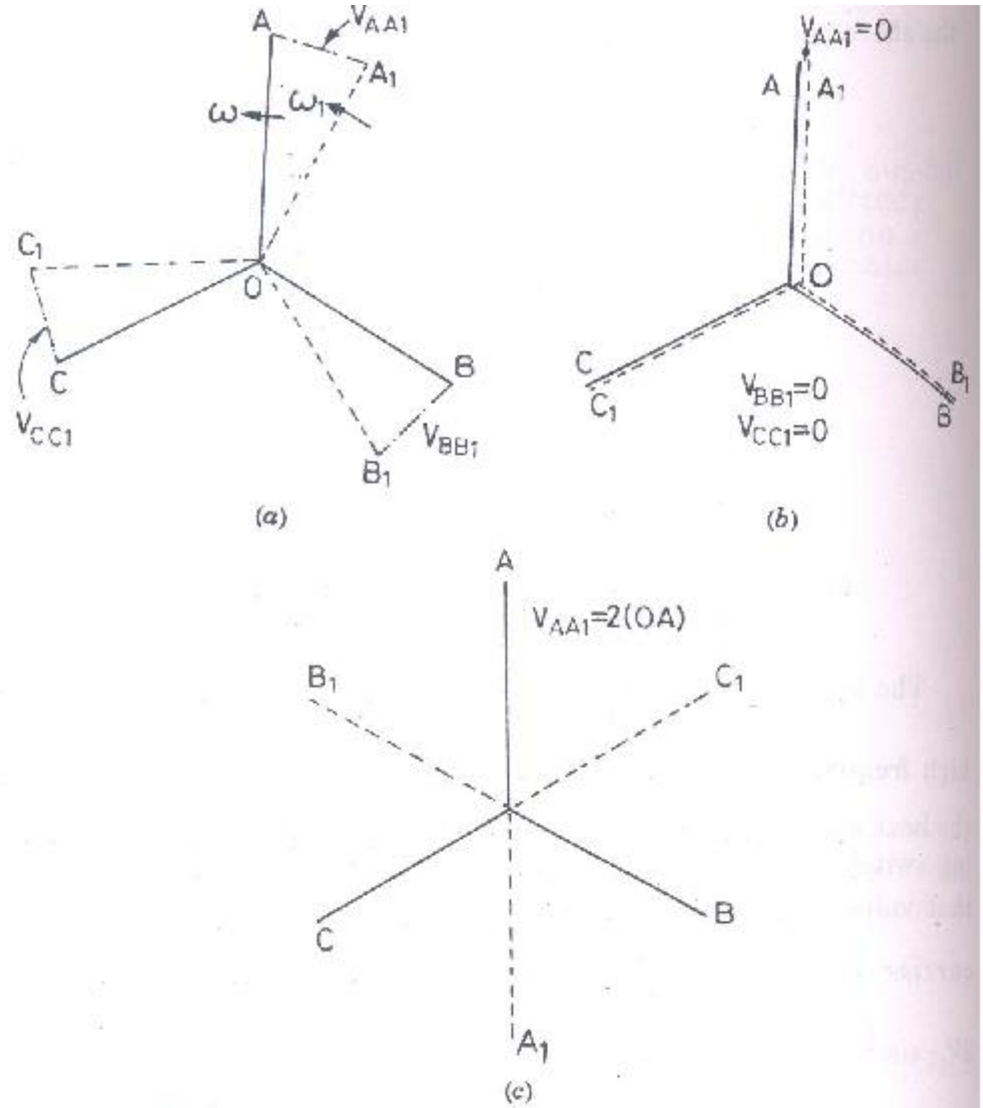
$$V_L = 2V_m \left[\sin \left\{ \frac{f_1 - f}{2} (2\pi t) \right\} \sin \left\{ \frac{f_1 + f}{2} (2\pi t) \right\} \right]$$



Oscillogram of beat and carrier frequencies of the voltage across synchronizing switch or lamp terminals.

Fig 5.13

The low frequency (f1-f)/2 is known as beat frequency and the high frequency (f1+f)/2 the carrier frequency. An oscillogram, showing the beat and carrier frequencies of the voltage across the synchronizing switch S2 is illustrated in fig. 5.13 It is seen from the fig. That voltage impressed on the lamp has a frequency equal to the carrier frequency (f+f1)/2. Since the lamps are bright once in each half of the voltage wave shown in fig. 5.13, the lamps flicker (f1-f) times in one second.



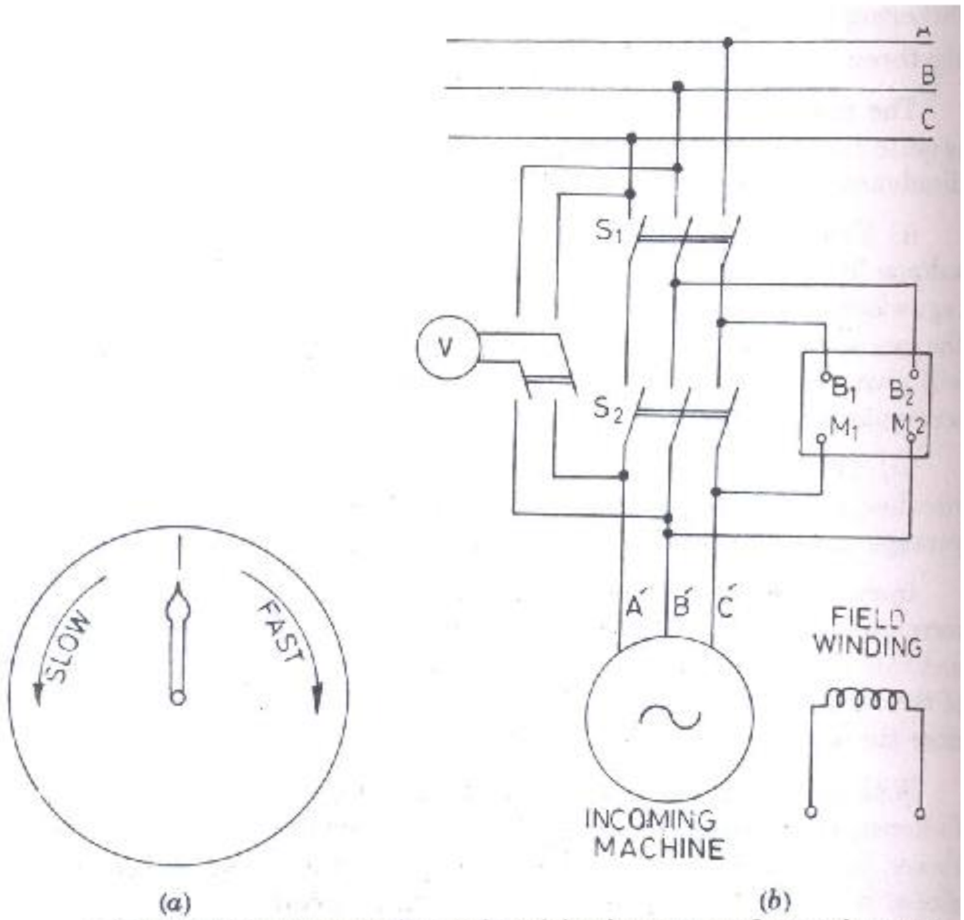
. Phasor diagram pertaining to the synchronization of an alternator with another alternator or bus-bar.

Fig 5.14

In fig5.14, 3 phase bus bar voltage is represented by phasors OA,OB,OC rotating at angular speed of w rad/sec. The incoming machine phasors are OA1, OB1, OC1and these are shown rotating at speed w1. The phasor VAA1 joining the tips A and A1 gives the voltage across the lamp1. Similarly VBB1 and VCC1 are the voltages across the lamps 2 and 3 respectively. When the rotating tips A and A1 coincide fig 5.14(b) voltages VAA1, VBB1, and VCC1 are equal to zero as indicated by dark lamps and this is the correct instant for closing the synchronizing switch S2. Actually, the frequency f1 is made to differ very slightly from f, so that the beat frequency is considerably low and the flickering subsides, now the S2 is closed when the three lamps are in the middle of their dark period.

Synchronizing by Synchroscope:

A synchroscope is an instrument, fitted with a rotating pointer to indicate the correct instant of closing the synchronizing switch. If the pointer rotates anti clockwise the incoming machine is running slow which is not desirable. Clockwise rotation of the pointer indicates that the incoming machine is running faster which is desirable. The pointer rotates at a speed proportional to the difference in two frequencies. For a favourable synchronization, the pointer should rotate at a very low speed in the direction of the arrow marked fast, Fig. 4.8(a).



(a) Synchroscope and (b) synchronizing by means of a synchroscope.

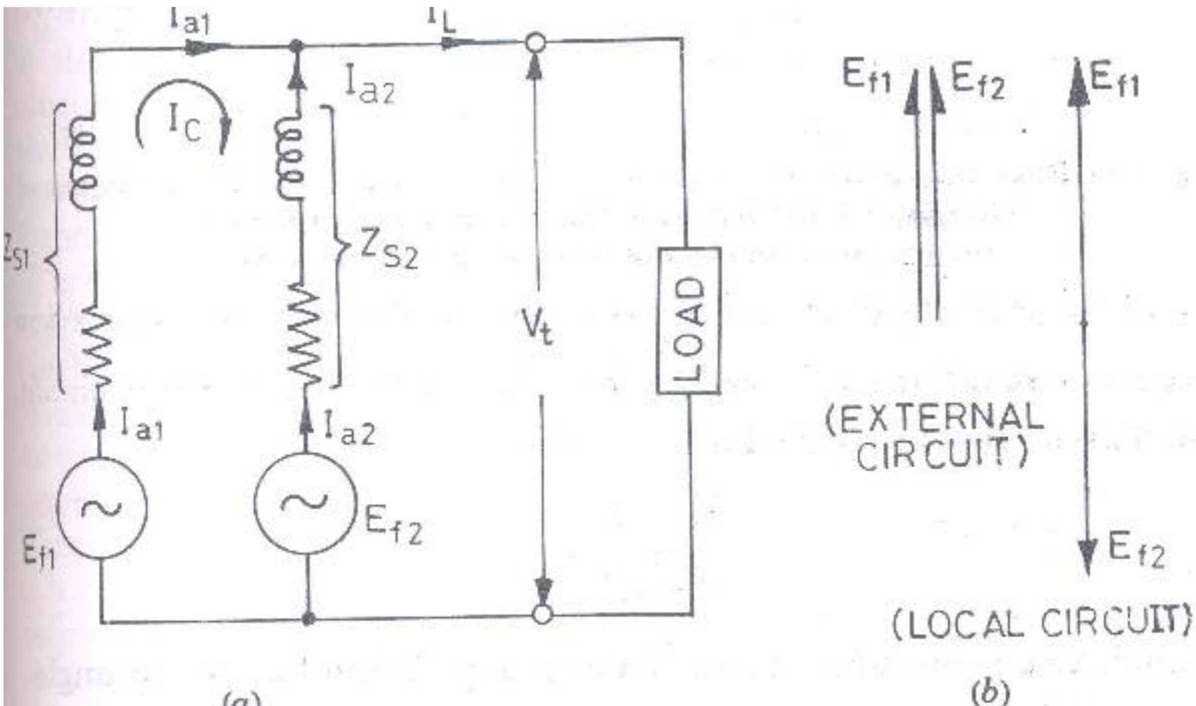
Fig 5.15

When rotating pointer reaches the vertical position a slow speed, the synchronizing switch must at once be closed. If the difference in frequencies of the two voltage sources is large, the pointer does not rotate but merely oscillates about some mean position. This state of affairs can be rectified by adjusting the speed of the incoming machine. An elementary connection scheme of synchronizing by means of synchroscope is as shown in fig5.15 (b). Synchroscope terminals B1, B2 should be connected to any two bus bar lines and its other terminals M1, M2 are connected to the correspondingly marked lines of the incoming machine. Phase sequence of the voltages, coming from bus bars and that coming from the incoming machine, must be same and this can be ascertained only with the help of phase sequence indicator, because synchroscope is a single phase instrument. Now the synchronization is carried out as explained before.

Parallel operation of alternators:

Effecting of changing mechanical torque:

The driving torque of an alternator can be varied by controlling the gate opening in case of hydrogenerators or by controlling the throttle opening in case of turbo generators. The effect of changing the mechanical torque is considered first with the alternator on no-load and then with the alternator on load. Here the cylindrical rotor alternators are assumed for simplicity, but the results are applicable both to the non-salient and salient pole alternators.

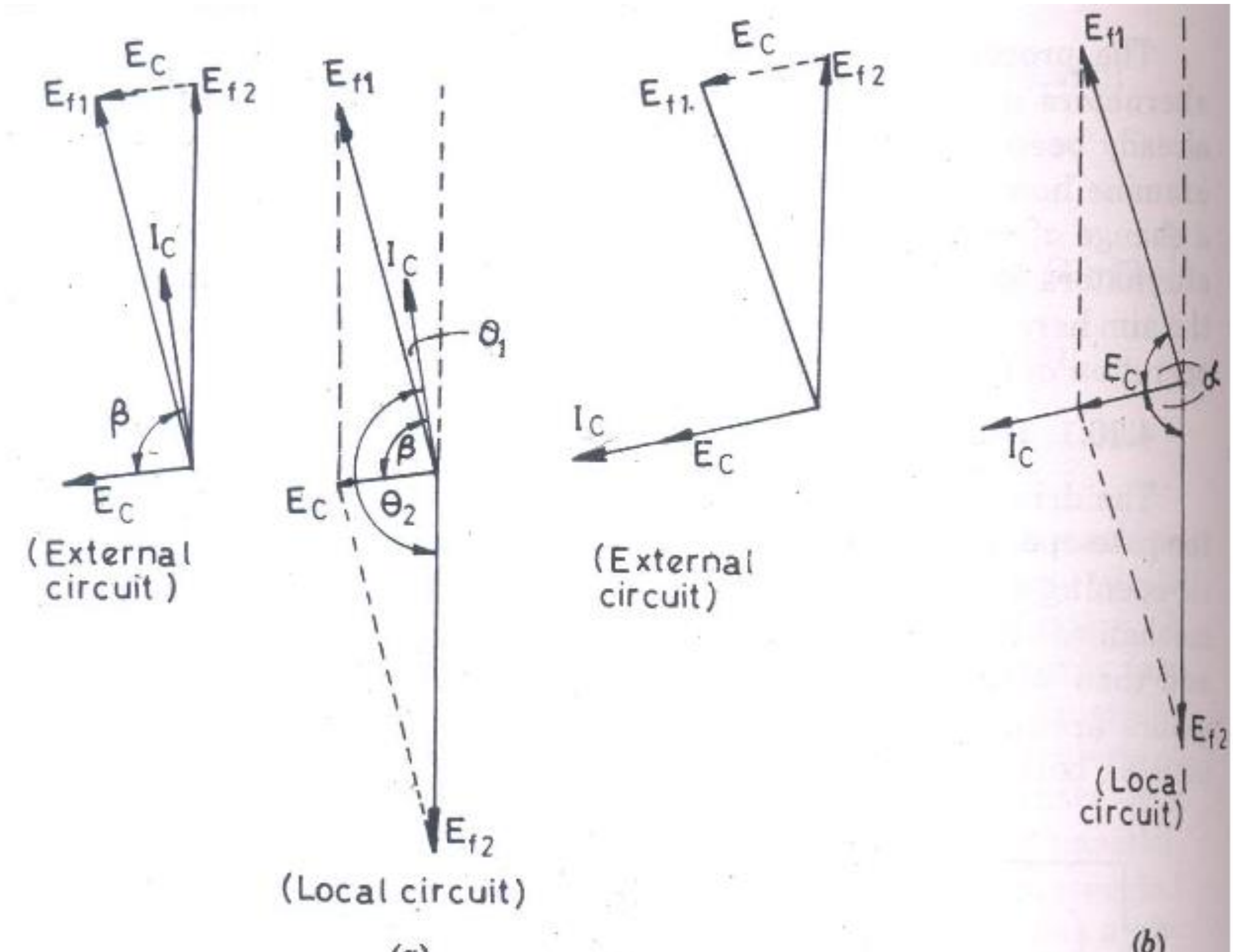


(a) Two alternators in parallel and
(b) phasor diagram of two unloaded alternators under floating conditions.

Fig 5.16

(a) No-load operation:

Consider two unloaded alternators running in parallel as shown in fig. 5.16 (a). Subscripts 1 and 2 are used to indicate alternators 1 and 2 respectively. Here excitation voltages Ef1 and Ef2 are equal in magnitude and are in phase, so that the resultant voltage in the local circuit formed by Ef1, Zs1, Ef2, Zs2 is zero. It can be stated that excitation emfs Ef1 and Ef2 are in phase with respect to the external circuit or are in phase opposition with respect to the local circuit as illustrated in fig.5.16 (b). Suppose the driving torque of alternator 1 is increased. This increment in torque tends to accelerate the rotor and as a result of it, emf Ef1 gets ahead of Ef2 as shown in fig. 5.17 (a).



. Phasor diagram showing the effect of increase in the driving torque of alternator 1, (*a*) armature impedance mainly reactive (*b*) armature impedance assumed purely resistive.

Fig 5.17

There now appears a resultant voltage Ec = Ef1-Ef2 in the local series circuit, which gives rise to a circulating current

$$\overline{I}_c = \frac{\overline{E}_{f_1} - \overline{E}_{f_2}}{\overline{Z}_{s_1} + \overline{Z}_{s_2}}$$

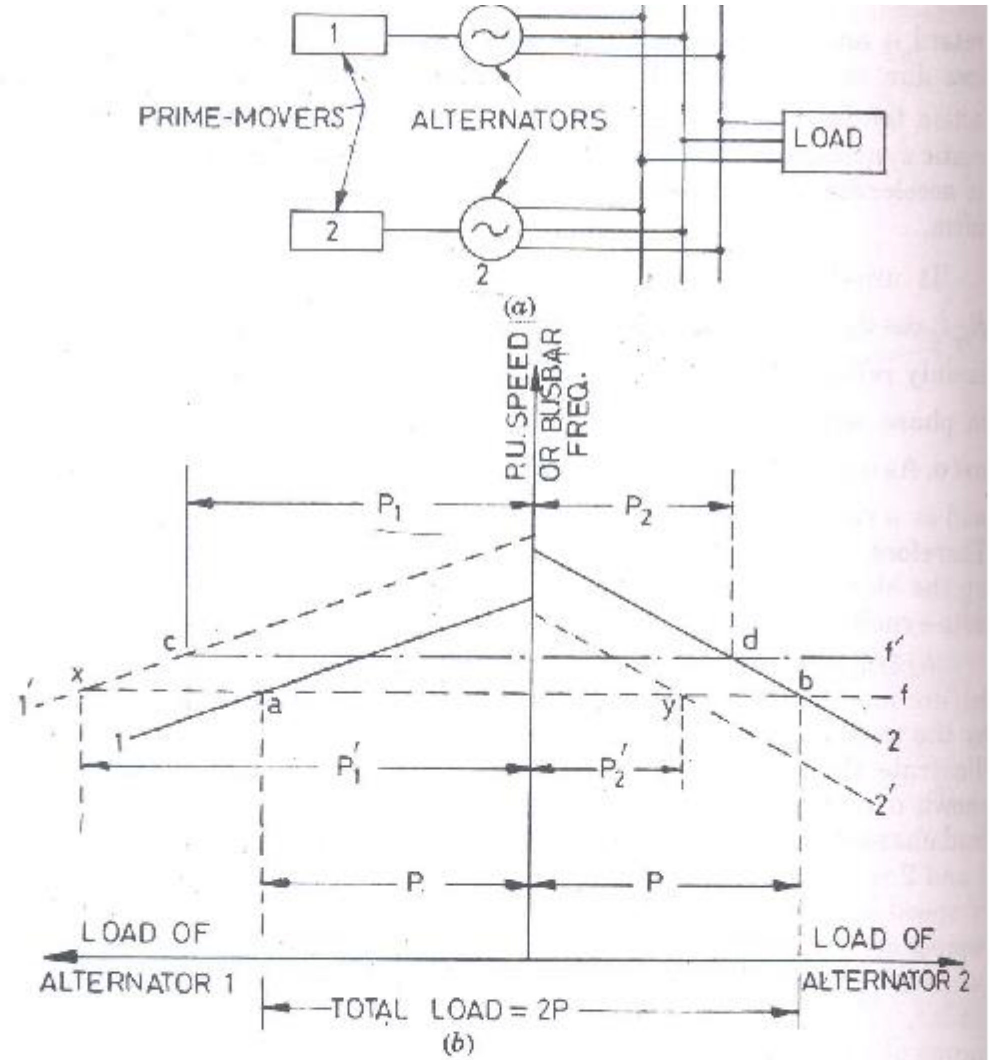
through two armatures. The current Ic lags behind Ec by an angle

$$\beta = \tan^{-1}\frac{X_{s_1} + X_{x_2}}{r_{a_1} + r_{a_2}} \cong 90°,$$

Because Zs1 and Zs2 are predominantly reactive. In fig. 5.18 (a), the phasor diagram pertaining to the local series circuit gives better physical insight into the internal happenings. It is seen that Ic is known as the synchronizing current, is almost in phase with Ef1 and in phase opposition with Ef2. Therefore, alternator 1 generates a power $E_{f_1} I_c \cos\theta_1$ which is positive, while the alternator 2 generates a power $E_{f_2} I_c \cos\theta_2$ which is negative. In otherwords, alternator 1 experiences generating action tending to retard it and alternator 2 receives power generated by 1 and therefore it experiences a motoring action tending to accelerate it. It is thus seen that there is an automatic synchronizing action tending to retard the faster machine and to accelerate the slower machine, in order to maintain the synchronism.

(b) On load operation:

When two alternators running in parallel are loaded, the division of load between them is governed mainly by the speed load characteristics of their prime movers. In order to illustrate this refer fig. 5.18 (a),

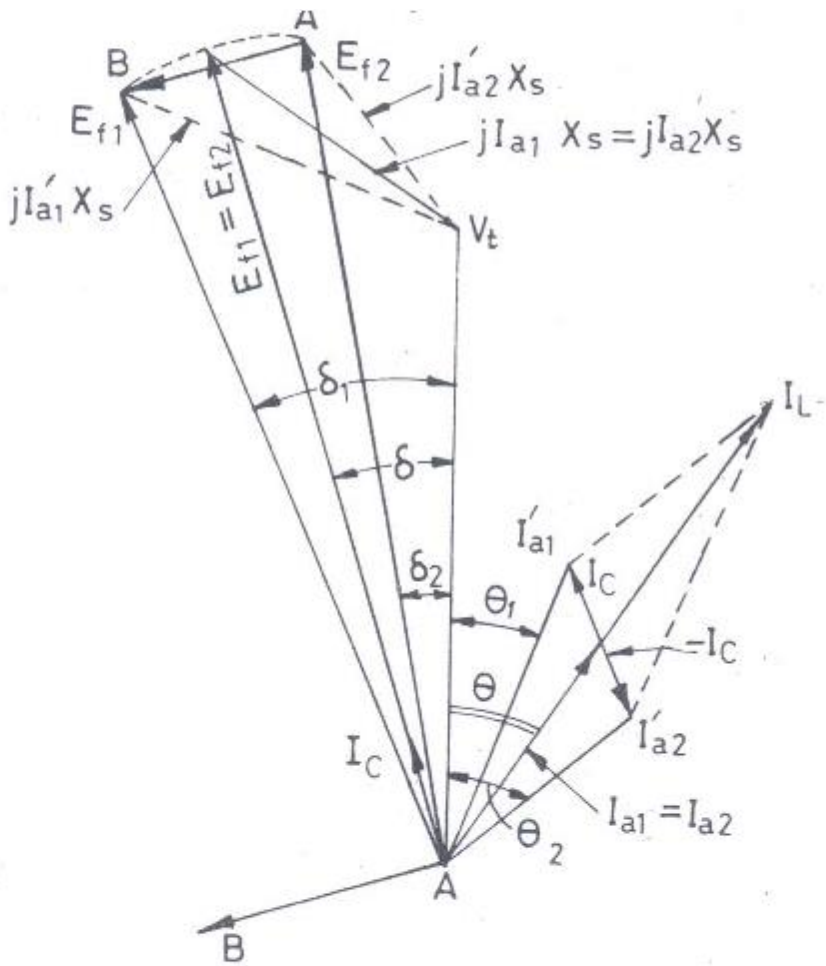


Effect of changing mechanical torque on the load division between two alternators.

Fig 5.18

Where alternators 1 and 2 are driven by their respective prime movers 1 and 2. The speed load characteristics of prime movers 1 and 2 are shown by solid lines 1 and 2 respectively in fig.5.18 (b). The total load 2P is represented by the horizontal line ab and the per unit speed or bus bar frequency is f. Both the alternators are equally loaded. If the mechanical torque of p.m. 1 is increased by its governor setting, its speed becomes more and its speed load curve shifts upwards as show by dotted line 1'. For a constant load of 2P, the operating points a, b shifts to new operating points c, d. Thus the horizontal line cd defines the new operating conditions from which it is seen that load on machine 1 increased from P to P1 and that on machine 2 has decreased from P to P2, such that P1+P2 = 2P. Fi.g 5.18 (b) also reveals that the bus bar frequency has increased from f to f'. If it is required to maintain the system frequency constant at f, the mechanical input to prime mover 2 must be suitably reduced so that its speed load curve shifts downward as shown by dotted line 2'. The operating points c, d now shift to new operating points x, y. The horizontal line xy shows that load on alternator 1 has further increased from P1 to P1' and that on alternator 2 has further reduced from P2 to P2', such that P1'+P2' = 2P.

For the two alternators running in parallel, it is first of all assumed, for the sake of simplicity, that their excitation voltages Ef1, Ef2 and armature currents Ia1, Ia2 are equal such that Ef1=Ef2, Ia1=Ia2 and load current IL=2Ia1=2Ia2. Their terminal voltage Vt is taken to be constant and for equal synchronous reactances, the phasor diagram fig. 5.19 is obtained. Each alternator is sharing load equal to $\frac{E_{f_1} V_t}{X_s} \sin \delta = \frac{E_{f_2} V_t}{X_s} \sin \delta = P.$



. Phasor diagram illustrating the effect of increasing the driving torque of alternator 1.

Fig 5.19

When the mechanical torque of alternator 1 is increased, its electrical output must increase accordingly. Since Ef, Vt and Xs are constant, the electrical power output of alternator 1 can increase only by an increment in load angle from δ to say $\delta 1$. In view of this Ef1 becomes ahead of its previous position as shown in fig. 5.19 so that $\frac{E_{f_1} V_t}{X_s} \sin \delta_1 > P$. Now that alternator 1 shares a load greater than P, therefore load on alternator 2 must be less than P for constant load of 2P. For a load less that P, Ef2 must fall back from its previous position as shown in fig 4.12, so that $\frac{E_{f_2} \cdot V_t}{X_s} \sin \delta_2 < P.$

But of both powers is again 2P. With Ef1 getting ahead and Ef2 falling back their previous position, the voltage AB appears in the local circuit of these two alternators. This voltage AB sends a local current Ic, lagging AB by 90. An examination of fig reveals that Ic must be added to Ia1 and subtracted from Ia2. As a result of this alternator 1 carries an increased current Ia1' and alternator 2 shares decreased current Ia2'. It is also seen that operating power factor of alternator 1 is improved and that of alternator 2 is worsened, but the load power factor remains unaltered. Thus the effect of increasing the mechanical torque of an alternator is to (i) increase its armature current and (ii) improve its operating power factor. As before it is seen that the effect of increasing the driving torque of an alternator is to make it take an increased share of load, where as the other alternator operating in parallel with it is relieved of its load by a corresponding amount.

Effect of changing Excitation:

Here again the effect of changing the excitation is considered first on an unloaded alternator and then on loaded alternator. For parallel running alternators, it will be seen that a change in field current effects only the operating power factor of the alternator and has almost no effect on the active power shared by the alternators.

(a) No load operation:

Consider again two alternators running in parallel and at no load. Their excitation emf Ef1 and Ef2 are equal so that there is not current in their local path. Now if the excitation of alternator 1 is increased, magnitudeof Ef1 becomes more tahn the magnitude of Ef2 and consequently, a resultant voltage Ec = Ef1 – Ef2 appears in the local circuit as shown in fig.5.19.

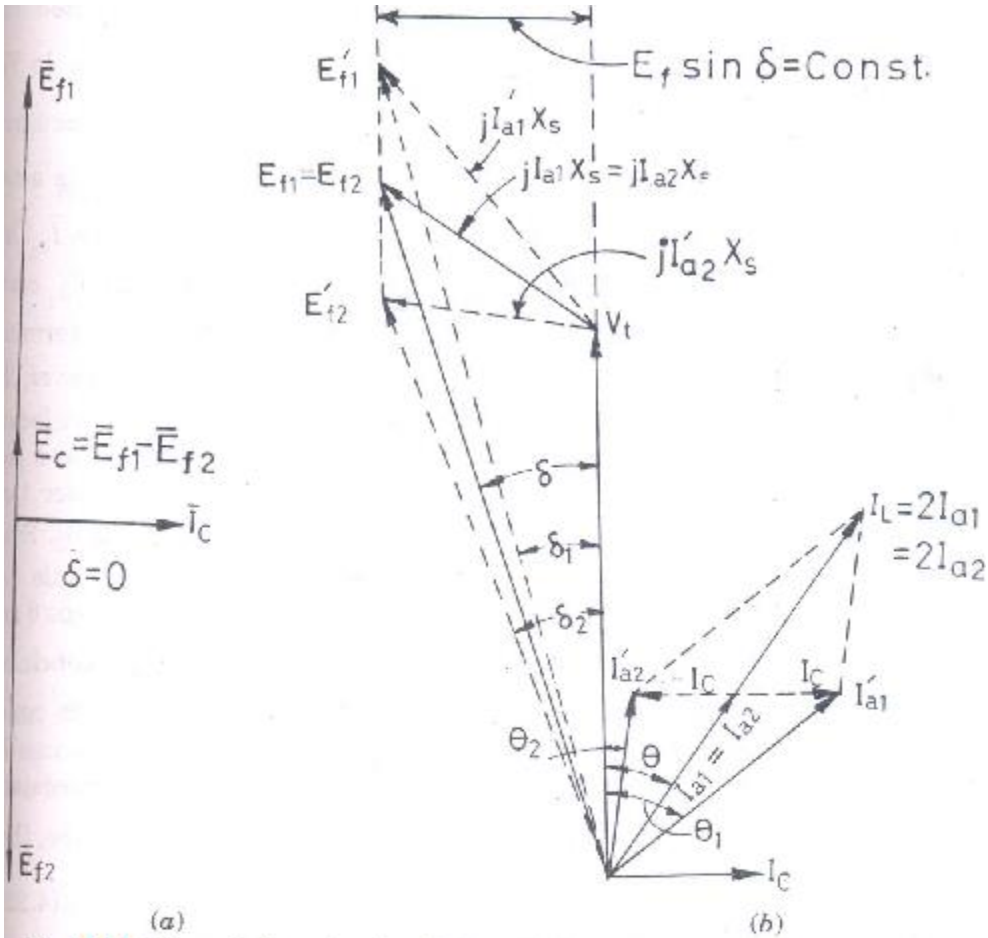


Fig 5.20 Effect of changing the field excitation of two parallel connected alternators (a) No load Operation and (b) On-load Operation

Since the synchronous impedance in the local circuit are mainly reactive, local circulating current Ic lags Ec by nealy 90. For alternator 1 Ic lags Ef1 by about 90, its armature reaction is therefore, demagnetizing and this has the effect of lowering the generated voltage Ef1. On the otherhand for alternator 2, Ic leads Ef2 by nearly 90, its armature reaction is therefore magnetizing and it causes strengthening of its field, which increases the generated voltage Ef2. Thus the circulating current Ic tends to lower the increased generated voltage and to raise the decreased generated voltage. In otherwords, the circulating current tends to equalize the two generated emfs at no load.

With an increase in excitation of alternator 1, the terminal voltage changes to a new value as follows.

$$\overline{V}_t = \overline{E}_{f_1} - \overline{I}_c\,\overline{Z}_{s_1}$$

$$\overline{V}_t = \overline{E}_{f_2} + \overline{I}_c\,\overline{Z}_{s_2}$$

$$Z_{s_1} = Z_{s_2}$$

$$\overline{V}_t = \frac{\overline{E}_{f_1} + \overline{E}_{f_2}}{2}$$

(b) On load operation:

When two alternators, running in parallel are loaded, it is assumed again that Ef1 = Ef2, Ia1 = Ia2 and Il = 2Ia1 = 2Ia2. The phasor diagram 5.20(b) illustrates this. An increase in the excitation of alternator 1, increases its excitation voltage Ef1 to a new value Ef1' and this has the effect of raising the terminal voltage Vt . How ever, their terminal voltage can be kept constant by decreasing the excitation of alternator 2. Fig. 5.20(b) illustrates these changes where increased Ef1' and decreased Ef2' are shown such that Ef sin δ remains constant. Thus the voltage Ef1-Ef2 gives rise to circulating current Ic. Ic must be added to Ia1 and subtracted from Ia2. The two new armature currents Ia1' and Ia2' are shown in fig. 5.20. It is seen that Ia1' increased in magnitude, its active component along Vt is unchanged. Similarly Ia2' has decreased in magnitude but its active power component along Vt remains same. The load current, the load terminal voltage Vt and the load power factor have not changed, however the armature currents, excitation voltages and the operating power factors of individual alternators have altered. Alternator 1 operating at poor power factor and is delivering much greater reactive power than alternator 2 which is operating at much better power factor. It can be concluded from the discussion that the distribution of reactive power shared by the alternators and their terminal voltage can be controlled by varying the excitations with the help of field rheostats.

Load division:

If ZL is load impedance, then

$$\overline{V}_t = (\overline{I}_{a_1} + \overline{I}_{a_2})\,\overline{Z}_l$$

$$\overline{V}_t = \overline{E}_{f_1} - \overline{I}_{a_1}\,\overline{Z}_{s_1}$$

$$= \overline{E}_{f_2} - \overline{I}_{a_2}\,\overline{Z}_{s_2}$$

$$\overline{I}_{a_1} = \frac{\overline{E}_{f_1} - \overline{V}_t}{Z_{s_1}}$$

$$\overline{I}_{a_2} = \frac{\overline{E}_{f_2} - \overline{V}_t}{Z_{s_2}}$$

$$\overline{V}_t = \left(\frac{\overline{E}_{f_1} - \overline{V}_t}{\overline{Z}_{s_1}} + \frac{\overline{E}_{f_2} - \overline{V}_t}{\overline{Z}}\right)\overline{Z}_L$$

$$\overline{V}_t\left(\frac{1}{\overline{Z}_{s_1}} + \frac{1}{\overline{Z}_{s_2}} + \frac{1}{\overline{Z}_L}\right) = \frac{\overline{E}_{f_1}}{\overline{Z}_{s_1}} + \frac{\overline{E}_{f_2}}{\overline{Z}_{s_2}}$$

$$\overline{E}_f - \overline{I}_{a_1}\overline{Z}_{s_1} - (\overline{I}_{a_1} - \overline{I}_{a_2})\,\overline{Z}_L = 0$$

$$\overline{E}_{f_2} - \overline{I}_{a_2}\overline{Z}s_2 - (\overline{I}_{a_1} + \overline{I}_{a_2})\,\overline{Z}_L = 0$$

$$\overline{E}_{f_1} - \overline{E}_{f_2} = \overline{I}_{a_1}\overline{Z}_{s_1} - \overline{I}_{a_2}Z_{s_2}$$

$$\overline{I}_{a_2} = \frac{(\overline{E}_{f_2} - \overline{E}_{f_1}) + \overline{I}_{a_1}\overline{Z}_{s_1}}{\overline{Z}_{s_2}}$$

$$\overline{I}_{a_1} = \frac{\overline{E}_{f_1}}{\overline{Z}_{s_1} + \overline{Z}_L + \dfrac{\overline{Z}_{s_1}\overline{Z}_L}{\overline{Z}_{s_2}}} + \frac{\overline{E}_{f_1} - \overline{E}_{f_2}}{\overline{Z}_{s_1} + \overline{Z}_{s_2} + \dfrac{\overline{Z}_{s_1}\cdot\overline{Z}_{s_2}}{\overline{Z}_L}}$$

When two emfs Ef1 and Ef2 are unequal in magnitude or are out of phase, then second term in the above equation represents the circulating current under loaded condition