MODULE – 4

Synchronous generators (continuation): Generator load characteristic. Voltage regulation, excitation control for constant terminal voltage. Generator input and output. Parallel operation of generators and load sharing. Synchronous generator on infinite busbars – General load diagram, Electrical load diagram, mechanical load diagram, O – curves and V – curves. Power angle characteristic and synchronizing power.Effects of saliency, two-reaction theory, Direct and Quadrature reactance, power angle diagram, reluctance power, slip test.

10 Hours

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.

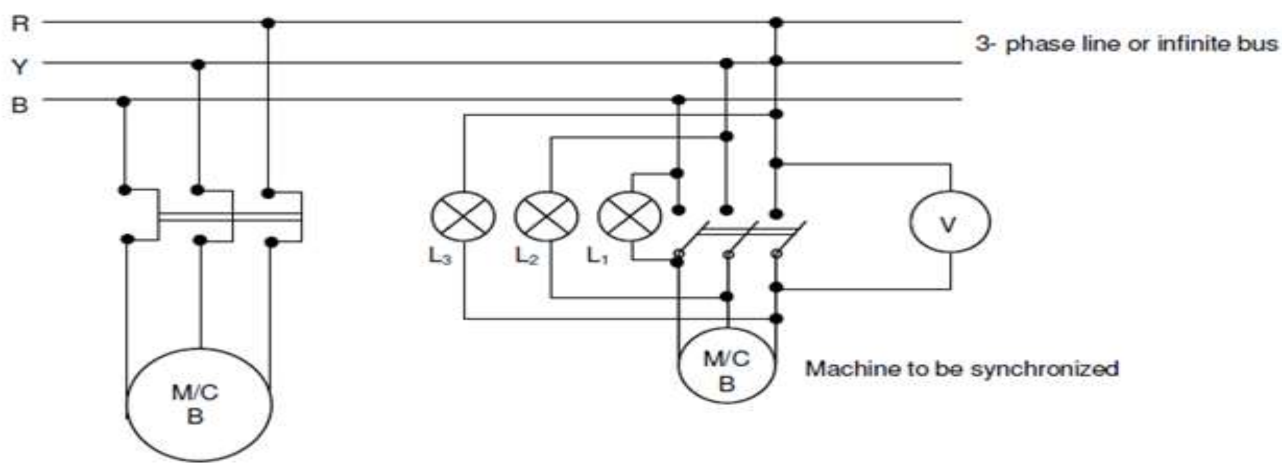

Figure 6.1: Illustration of Method of Synchronizing

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.

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.

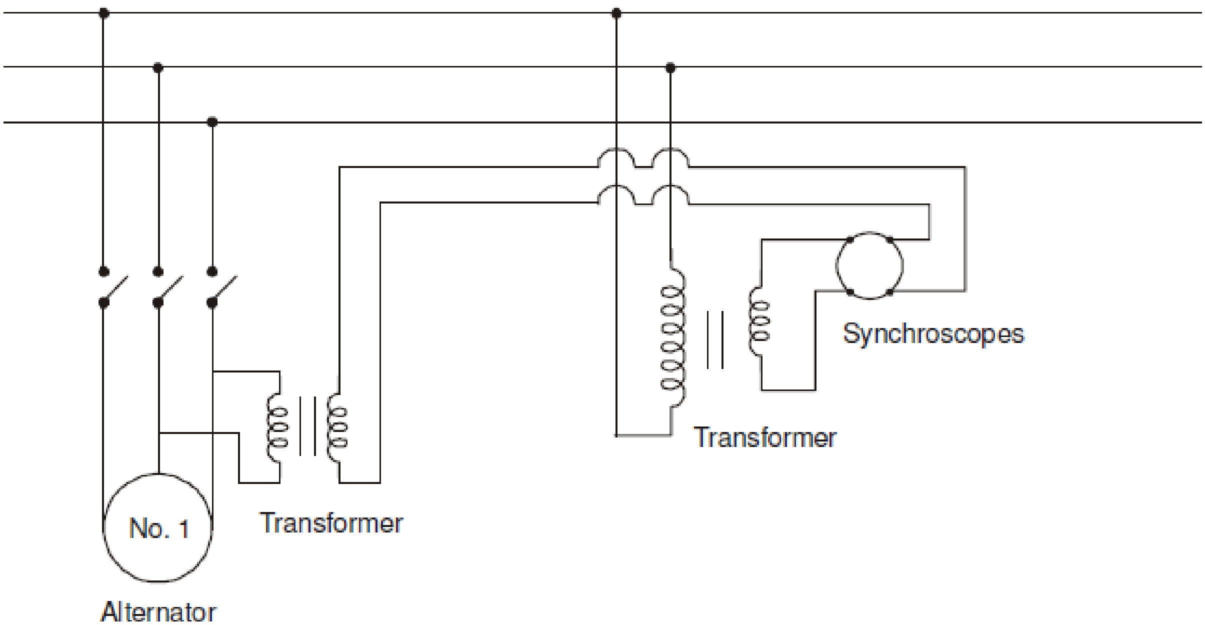

Figure 6.1(b) : Method of Synchronizing by Synchronoscope

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 1i.e. *E*1 is equal to and in phase opposition to emf of alternator 2.

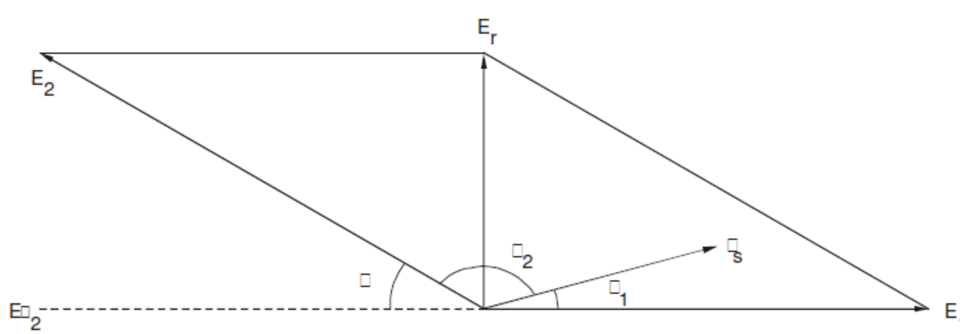

Fig6.2: *E*2 Falling Back

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 q. 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 *Is* is very nearly in quadrature with the resultant emf *Er* acting on the circuit. Figure 6.2 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, *Er*, is almost in quadrature with both the emfs, and gives rise to a current, *Is*, lagging behind *Er* by an angle approximating to a right angle. It is, thus, seen that *E*1 and *Is* are almost in phase. The first alternator is generating a power *E*1 *Is* cos f1, which is positive, while the second one is generating a power *E*2 *Is* cos f2, which is negative, since cos f2 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 *Is* 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, *Is*, is called the synchronizing current.

Synchronizing Power

Suppose that one alternator has fallen behind its ideal position by an electrical angle q, 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

□□is very small *Er* is very nearly equal to □*E*1.

Moreover, since *Er* is practically in quadrature with *E*1 and *Is* 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 as

$$\frac{\theta E^2}{X} = E\, I_x \theta$$

although the current *Ix* does not actually flow.

In an *m*-phase case the synchronizing power becomes *Ps* = *m E Ix* q watts, *E* and *Ix* 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 *Is* 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.

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 *Er*, now inphase with *E*1, assumed to be the greater of the two. The synchronizing current, *Is*,

now lags by almost 90° behind *E*1, so that the synchronizing power, *E*1 *Is* cos f1 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 othernmachine 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.

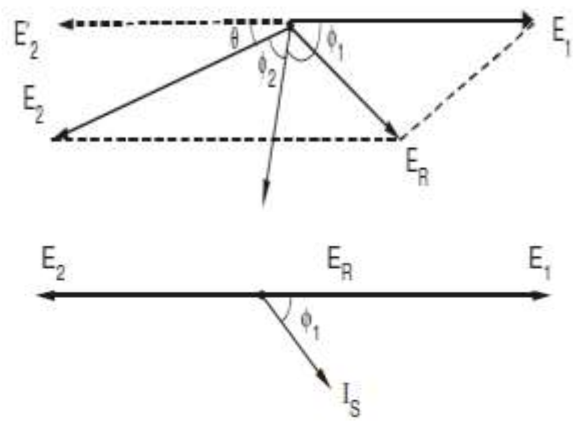

Fig 2a and Fig 2b

Let two similar alternators of the same rating be operating in parallel, receivingequal 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 f, each alternator delivers half the total current and

$I1 = I2 = 0.5\ I$

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, *Is*, 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_{S1} and X_{S2} are the synchronous reactances of the two alternators respectively. Now examine the effect of reducing the excitation of the second alternator. $E2$ 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 $I2$ is changed due to the change in $E2$, but the active components of both $I1$ and $I2$ 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 $I1 + I2 = I$, 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,Bit 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.

V-Curves

If the excitation is varied, the armature current will vary for constant load. When armature curve is plotted against exciting current, the resulting curve takes the shape of word *V*, as shown in Figure 7.8, and is known as a *V*-curve. With one particular excitation the armature current is a minimum for unity power-factor. For smaller exciting currents, the armature mmf, *Fa* is made to lag, since the flux, f, and the resultant m.m.f., *Fr* are the same as before. A lagging armature mmf, *Fa*, is only brought about by a lagging armature current, *I* and motor operates as lagging *PF* load. For larger exciting currents, the armature mmf, *Fa*, is made to lead, in order

that *Fr* shall again remain unaltered and motor operates as leading *PF* load. This effect can be seen more clearly from the approximate vector diagram given in Figure 7.5. A low excitation here corresponds to a reduced back emf, giving rise to a resultant voltage that leads the applied voltage by a relatively small angle, thus causing the current to lag by a considerable angle. Since the power-factor is low, the current is relatively large. As the exciting current is increased, the back e.m.f. is also increased, thus swinging the resultant voltage vector round and advancing it in phase. The current is also advanced in phase, its magnitude decreasing since the power-factor is increasing. When the current becomes in phase with the applied voltage it reaches a minimum value, the power-factor being unity. A further increase in exciting current causes an increase in the armature current, which is now a leading one.

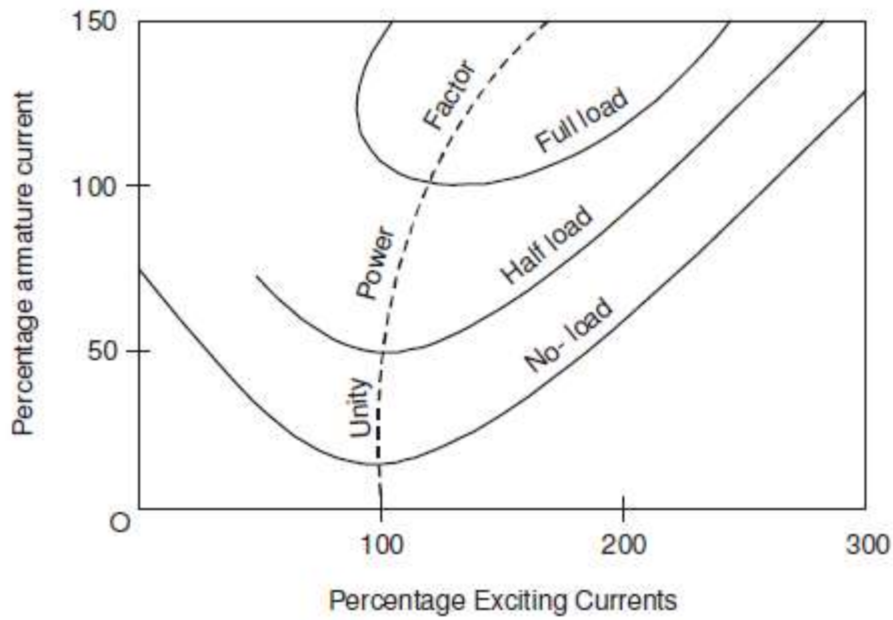

Figure 7.8 : *V*-Curves

The excitation corresponding to unity power-factor and minimum current is called the normal exciting current for that particular load. A smaller exciting current (under-excitation) results in a lagging armature current and a larger exciting current (over-excitation) in a leading armature current, due to the reduction and increase in the induced back e.m.f. respectively.

The excitation necessary for unit power-factor goes up as the load increases. On noload the point on the *V*-curve is sharply accentuated, but if the machine is loaded the tendency is to round off the point, this effect being more marked at the higher loads.