Lecture 6

Chapter 37
Alternator

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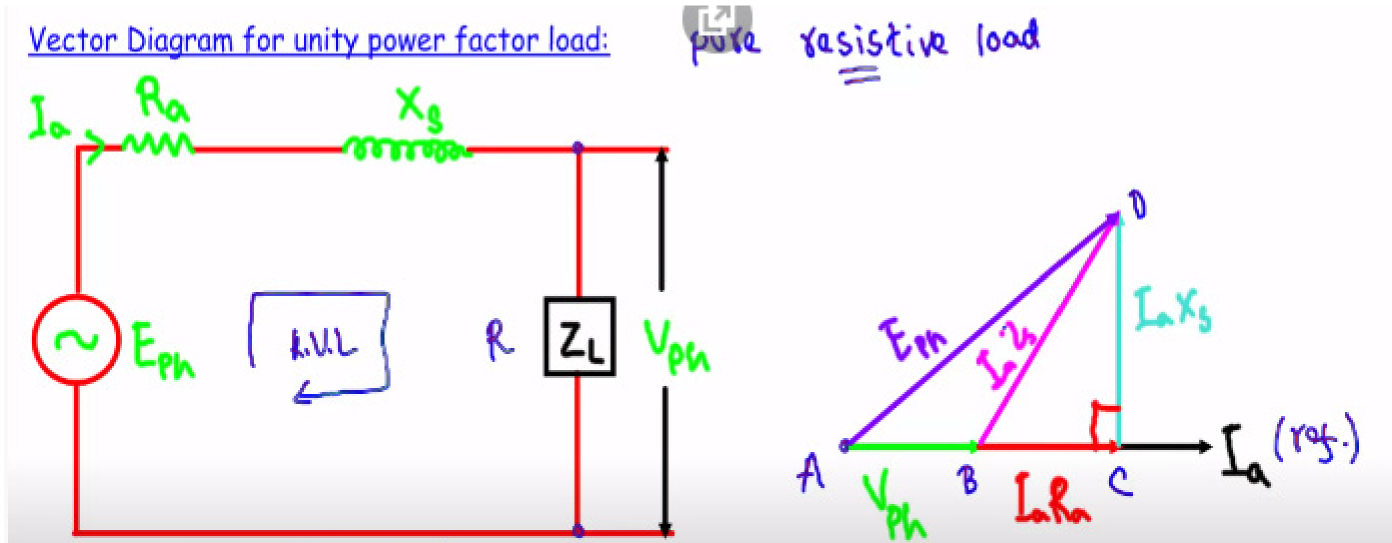
Vector Diagram of loaded Alternator

1. Resistive load (Unity pf)



$$\vec{E}_{ph} = \vec{V}_{ph} + \vec{I_a R_a} + \vec{I_a X_s}$$

$$\therefore \vec{E}_{ph} = \vec{V}_{ph} + \vec{I_a Z_s}$$

$AB = V_{ph}$

$BC = I_a R_a$

$CD = I_a X_s$

$AD = E_{ph}$

$BD = I_a Z_s$

ΔACD is a right angle triangle. Apply Pythagorean

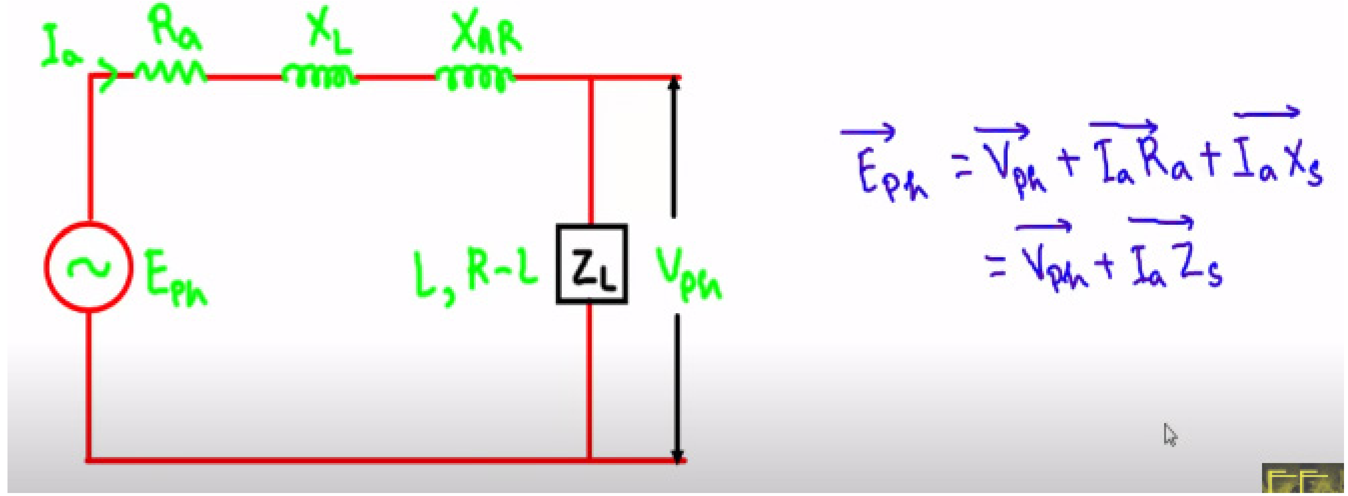
$$AD^2 = AC^2 + CD^2 = (AB + BC)^2 + CD^2$$

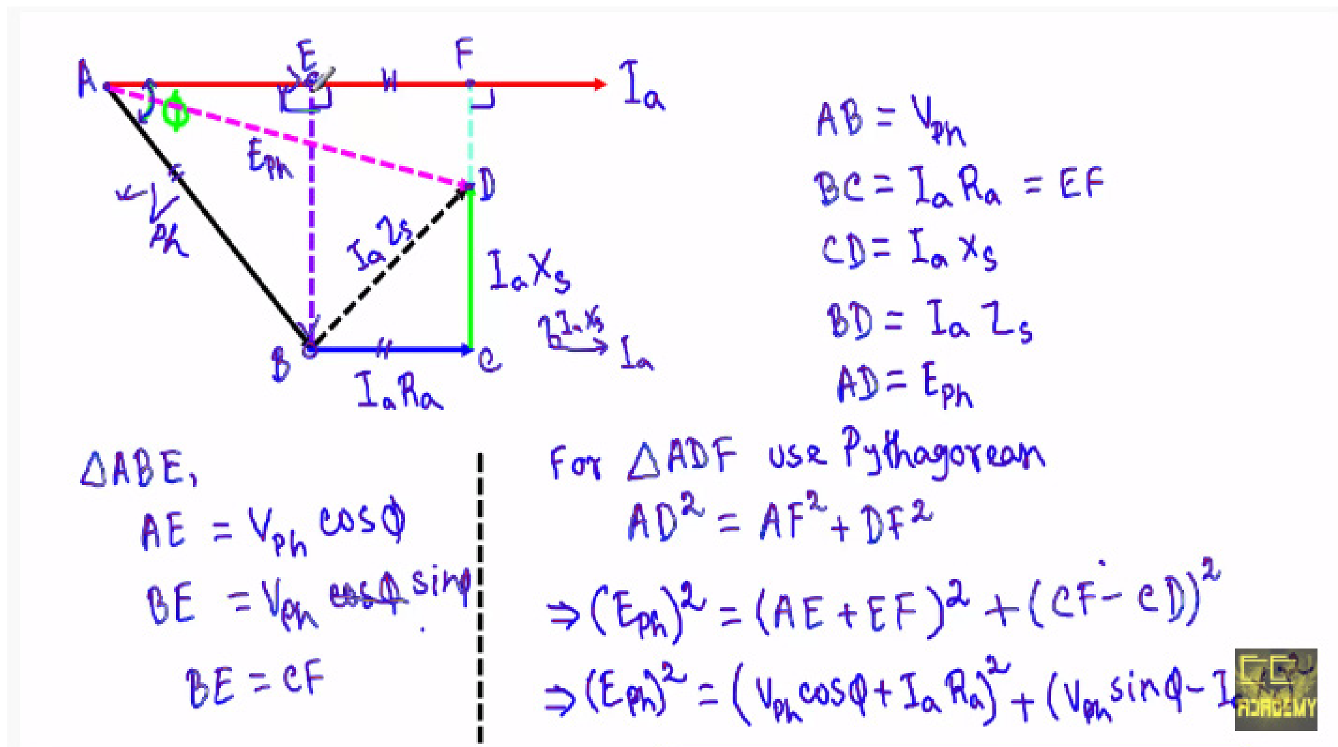
$$\Rightarrow E_{ph}^2 = (V_{ph} + I_a R_a)^2 + (I_a X_s)^2$$

$$\therefore E_{ph} = \sqrt{(V_{ph} + I_a R_a)^2 + (I_a X_s)^2}$$

Vector Diagram of loaded Alternator

2. Capacitive load (Leading pf)

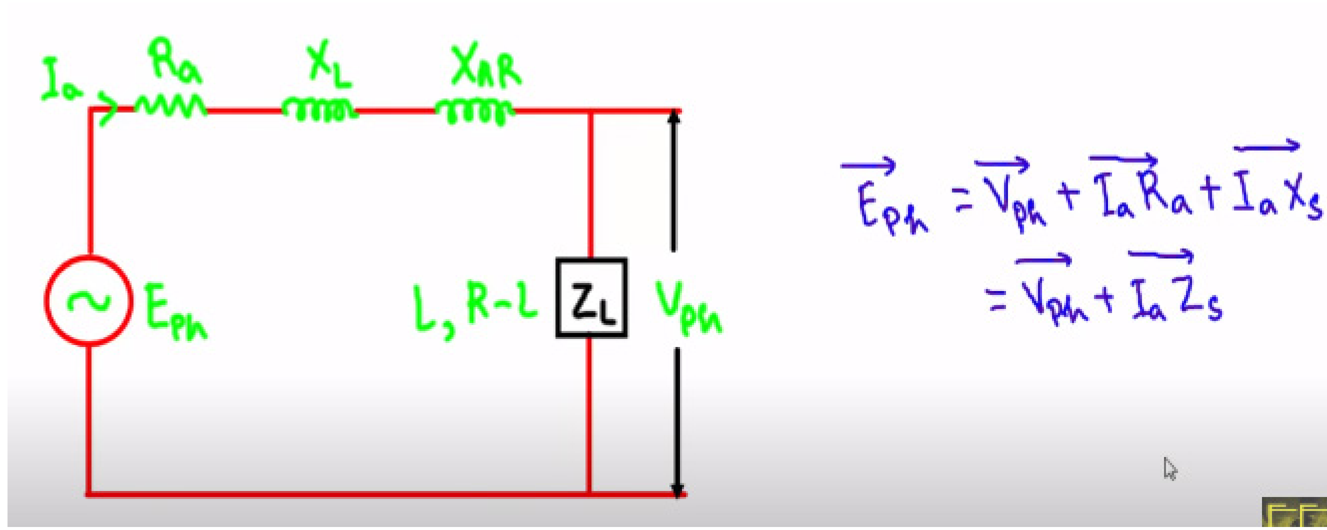


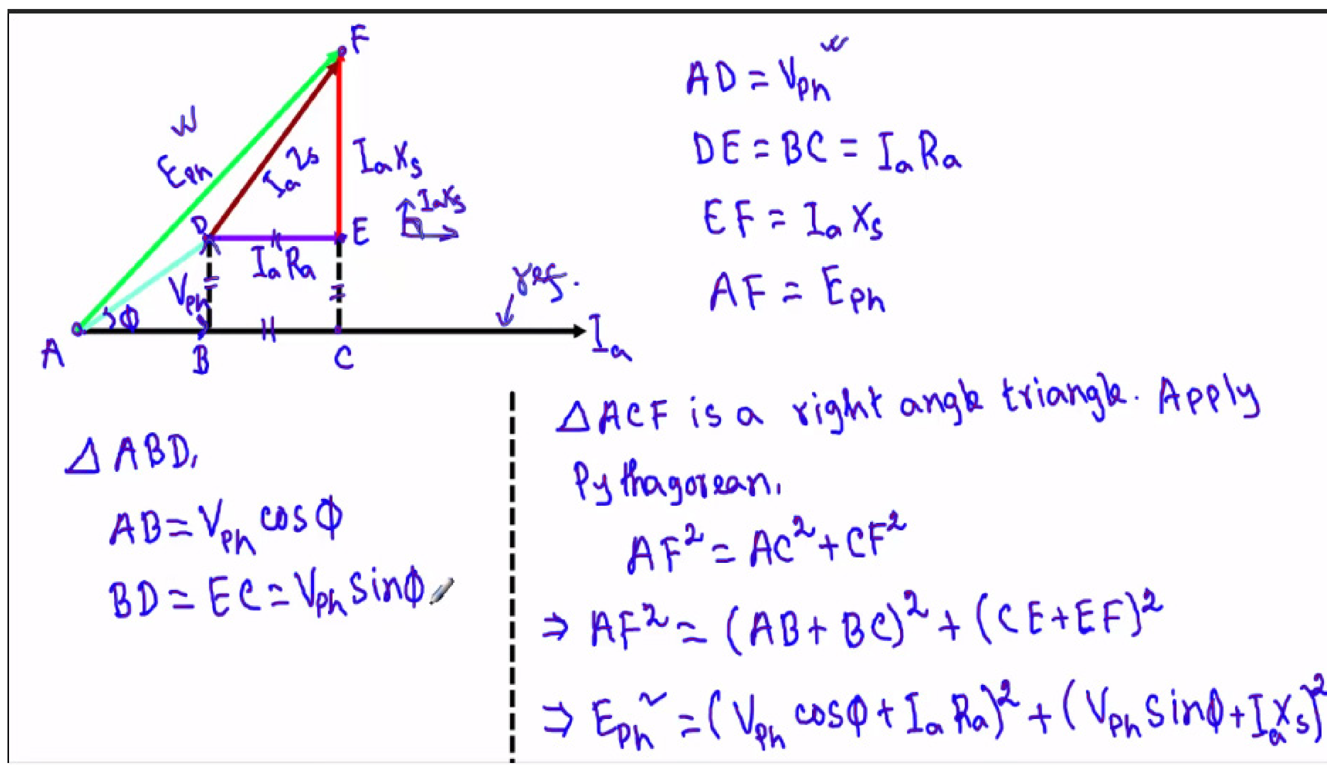


Vector Diagram of loaded Alternator

3. Inductive load (Lagging pf)

Self Study
Article No. 37.19
(Voltage Regulation)





Example 37.21. *A 100-kVA, 3000-V, 50-Hz 3-phase star-connected alternator has effective armature resistance of 0.2 ohm. The field current of 40 A produces short-circuit current of 200 A and an open-circuit emf of 1040 V (line value). Calculate the full-load voltage regulation at 0.8 p.f. lagging and 0.8 p.f. leading. Draw phasor diagrams.*

(Basic Elect. Machines, Nagpur Univ. 1993)

Solution.

$$Z_S = \frac{\text{O.C. voltage/phase}}{\text{S.C. current/phase}} \quad \text{— for same excitation}$$

$$= \frac{1040/\sqrt{3}}{200} = 3\ \Omega$$

$$X_S = \sqrt{Z_S^2 - R_a^2} = \sqrt{3^2 - 0.2^2}$$

$$= 2.99\ \Omega$$

F.L. current,

$$I = 100{,}000/\sqrt{3} \times 3000$$
$$= 19.2\text{ A}$$
$$IR_a = 19.2 \times 0.2 = 3.84\text{ V}$$
$$IX_S = 19.2 \times 2.99 = 57.4\text{ V}$$

Voltage/phase

$$= 3000/\sqrt{3} = 1730\text{V}$$

$\cos\phi = 0.8$; $\sin\phi = 0.6$

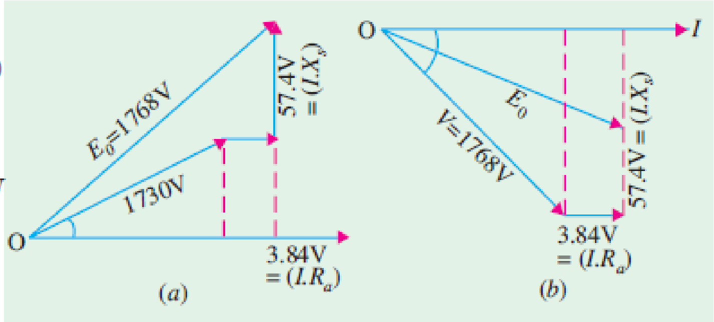


Fig. 37.36

(*i*) **p.f. = 0.8 lagging**

—Fig. 37.36 (*a*)

$$E_0 = [(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2]^{1/2}$$
$$= (1730 \times 0.8 + 3.84)^2 + (1730 \times 0.6 + 57.4)^2]^{1/2} = 1768\text{ V}$$

$$\%\text{ regn. 'up'} = \frac{(1768 - 1730)}{1730} \times 100 = 2.2\%$$

(*ii*) **0.8 p.f. leading**—Fig. 37.36 (*b*)

$$E_0 = [(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_S)^2]^{1/2}$$
$$= [(1730 \times 0.8 + 3.84)^2 + (1730 \times 0.6 - 57.4)^2]^{1/2}$$
$$= 1699\text{ V}$$

$$\%\text{ regn.} = \frac{1699 - 1730}{1730} \times 100 = -1.8\%$$

MATH

Example 37.17 (*b*). *A 60-KVA, 220 V, 50-Hz, 1-φ alternator has effective armature resistance of 0.016 ohm and an armature leakage reactance of 0.07 ohm. Compute the voltage induced in the armature when the alternator is delivering rated current at a load power factor of (a) unity (b) 0.7 lagging and (c) 0.7 leading.* **(Elect. Machines-I, Indore Univ. 1981)**

Solution. Full load rated current $I = 60{,}000/220 = 272.2$ A

$$IR_a = 272.2 \times 0.016 = 4.3 \text{ V};$$
$$IX_L = 272.2 \times 0.07 = 19 \text{ V}$$

(*a*) Unity p.f. — Fig. 37.30 (*a*)

$$E = \sqrt{(V + IR_a)^2 + (I X_L)^2} = \sqrt{(220 + 4.3)^2 + 19^2} = \mathbf{225\ V}$$

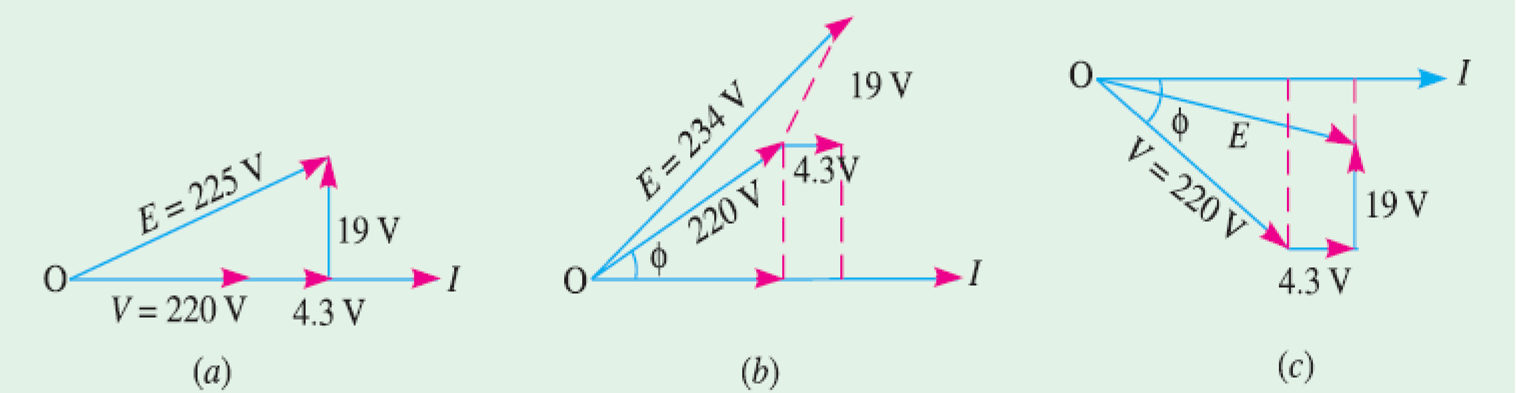


Fig. 37.30

(*b*) p.f. 0.7 (lag) —Fig. 37.30 (*b*)

$$E = [V\cos\phi + IR_a)^2 + (V\sin\phi + IX_L)^2]^{1/2}$$
$$= [(220 \times 0.7 + 4.3)^2 + (220 \times 0.7 + 19)^2]^{1/2} = \mathbf{234\ V}$$

(*c*) p.f. = 0.7 (lead) —Fig. 37.30 (*c*)

$$E = [(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_L)^2]^{1/2}$$
$$= [(220 \times 0.7 + 4.3)^2 + (220 \times 0.7 - 19)^2]^{1/2} = \mathbf{208\ V}$$

Parallel Operation of Alternators

The operation of connecting an alternator in parallel with another alternator or with common busbars is known as **synchronizing**. Generally, alternators are used in a power system where they are in parallel with many other alternators.

Conditions

For proper synchronization of alternators, the following four conditions must be satisfied:

1. The terminal voltage (effective) of the incoming alternator must be the same as busbar voltage.
2. The speed of the incoming machine must be such that its frequency (= PN/60) equals busbar frequency.
3. The phase of the alternator voltage must be identical with the phase of the busbar voltage.
4. The phase angle between identical phases **must be zero**.

It means that the switch must be closed at (or very near) the instant the two voltages have correct phase relationship. Condition (1) is indicated by a voltmeter, conditions (2), (3) and (4) are indicated by synchronizing lamps or a synchronoscope.

Parallel Operation of Alternators

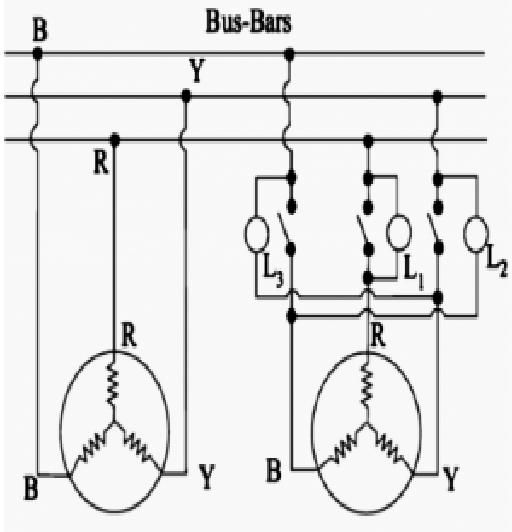


Figure 1 – Synchronizing lamp method

The synchronizing lamp method is consists of **3 lamps connected between the phases of the running 3-ph generator and the incoming generator** as shown in Figure 1 above.

> In three phase alternators, **it is necessary to synchronize one phase only**, the other two phases be will then synchronized automatically.

However, first it is necessary that the incoming alternator is **correctly 'phased out'** i.e. the phases are connected in the proper order of **R, Y and B** not R, B, Y etc. Lamp L_1 is connected between R and R′, L_2 between Y and B′ (not Y and Y′) and L_3 between B and Y′ (and not B and B′) as shown in Figure 2.

Two set of star vectors will rotate at unequal speeds if the frequencies of the two are different. If the incoming alternator is running faster, then voltage star R′ Y′ B′ appear to rotate anticlockwise with respect to the busbar voltage star RYB at a speed corresponding to the difference between their frequencies.

With reference to Figure 3, it is seen that voltage across L_1 **is RR′ to be increasing from zero, and that across L_2 is YB′ which is decreasing**, having just passed through its maximum, and that across L_3 BY′ which is increasing and approaching its maximum.

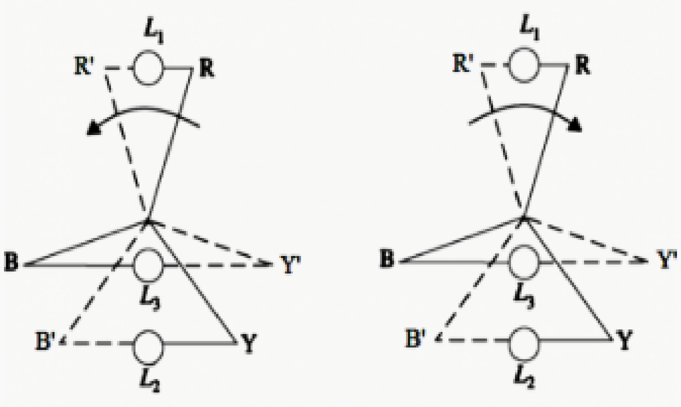


Figure 3 – Synchronizing lamp method

Hence the lamps will light up one after the other in the order **2, 3, 1, 2, 3, 1** or **1, 2, 3**. If the incoming alternator is running slower, then the sequence of light up will be 1, 3, 2.

> *“* ***Synchronization is done at the moment the uncrossed lamp L_1 is in the middle of the dark period and other two lamps are equally bright.*** *Hence this method of synchronization is known as* ***two bright one dark lamp method****.*

MATH

Example 37.52. *Two alternators A and B operate in parallel and supply a load of 10 MW at 0.8 p.f. lagging (a) By adjusting steam supply of A, its power output is adjusted to 6,000 kW and by changing its excitation, its p.f. is adjusted to 0.92 lag. Find the p.f. of alternator B.*

(b) If steam supply of both machines is left unchanged, but excitation of B is reduced so that its p.f. becomes 0.92 lead, find new p.f. of A.

Solution. (*a*) $\cos\phi = 0.8$, $\phi = 36.9°$, $\tan\phi = 0.7508$; $\cos\phi_A = 0.92$, $\phi_A = 23°$; $\tan\phi_A = 0.4245$

load kW = 10,000, load kVAR = 10,000 × 0.7508 = 7508 (lag)

kW of A = 6,000, kVAR of A = 6,000 × 0.4245 = 2547 (lag)

Keeping in mind the convention that lagging kVAR is taken as negative we have,

kW of *B* = (10,000 − 6,000) = 4,000 : kVAR of *B* = (7508 − 2547) = 4961 (lag)

$\therefore$ kVA of *B* = $4{,}000 - j4961 = 6373 \angle -51.1°$; $\cos\phi_B = \cos 51.1° =$ **0.628**

(*b*) Since steam supply remains unchanged, load kW of each machine remains as before but due to change in excitation, kVARs of the two machines are changed.

kW of *B* = 4,000, new kVAR of B = 4000 × 0.4245 = 1698 (lead)

kW of *A* = 6,000, new kVAR of A = −7508 − (+1698) = − 9206 (lag.)

$\therefore$ new kVA of *A* = $6{,}000 - j9206 = 10{,}988 \angle -56.9°$; $\cos\phi_A =$ **0.546 (lag)**

Effect of unequal Voltage on Alternator

37.39. Effect of Unequal Voltages

Let us consider two alternators, which are running exactly in-phase (relative to the external circuit) but which have slightly unequal voltages, as shown in Fig. 37.91. If E_1 is greater than E_2, then their resultant is $E_r = (E_1 - E_2)$ and is in-phase with E_1. This E_r or E_{SY} set up a local synchronizing current I_{SY} which (as discussed earlier) is almost 90° behind E_{SY} and hence behind E_1 also. This lagging current produces demagnetising effect (Art. 37.16) on the first machine, hence E_1 is reduced. The other machine runs as a synchronous motor, taking almost 90° leading current. Hence, its field is strengthened due to magnetising effect of armature reaction (Art. 37.16). This tends to increase E_2. These two effects act together and hence lessen the inequalities between the two voltages and tend to establish stable conditions.

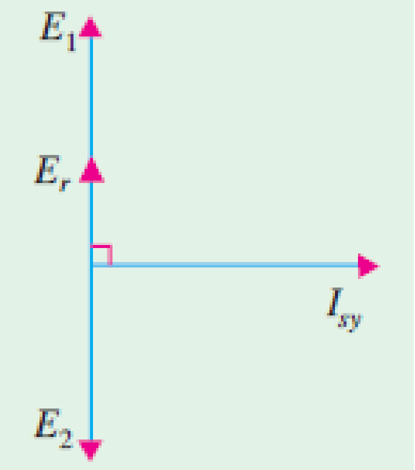


Fig. 37.91