Parallel Operation of Synchronous Generators

An electric power station often has several synchronous generators operating in parallel with each other. Some of the ***advantages of parallel operation*** are :

1. In the **absence** of the several machines, for maintenance or some other reason, the power station can function with the remaining units.

2. **Depending on the load**, generators may be brought on line, or taken off, and thus result in the most efficient and economical operation of the station.

3. For **future expansion**, units may be added on and operate in parallel.

In order that a synchronous generator may be connected in parallel with a system (or bus), the following ***conditions must be fulfilled***:

1. The frequency of the incoming generator must be the same as the frequency of the power system to which the generator is to be connected.

2. The magnitude of the voltage of the incoming generator must be the same as the system terminal voltage.

3. With respect to an external circuit, the voltage of the incoming generator must be in the same phase as system voltage at the terminals.

4. In a three-phase system, the generator must have the same phase sequence as that of the bus.

The process of properly connecting a synchronous generator in parallel with a system is known as ***synchronizing.*** Tow generators can be synchronized either by using a synchroscope or lamps. Figure 1. shows a circuit diagram showing lamps as well as synchroscope. The potential transformers (PTs) are used to reduce the voltage for instrumentation. Let the generator $\mathbf{G_1}$ be already in operation with its switch $\mathbf{S_{g1}}$ closed. Other switches $\mathbf{S_{g2}}$, $\mathbf{S_1}$, and $\mathbf{S_2}$ are all open.

After the generator $\mathbf{G_2}$ is started and brought up to approximately synchronous speed, $\mathbf{S_2}$ is closed. Subsequently, the lamps $\mathbf{L_a}$ **,** $\mathbf{L_b}$,and $\mathbf{L_c}$ begin to flicker at a frequency equal to the difference of the frequencies of $\mathbf{G_1}$ and $\mathbf{G_2}$. The equality of the voltages of the two generators is ascertained by the voltmeter **V**, connected by the double-pole double-throw switch **S**. Now, if the voltages and frequencies of the two generators are the same, but there is a phase difference between the two voltages, the **lamps will glow steadily**. The speed of G_2 is then slowly adjusted until the lamps remain permanently dark (because they are connected such that two voltages through them are in opposition). Next, S_{g2} is closed and S_2 may be opened.

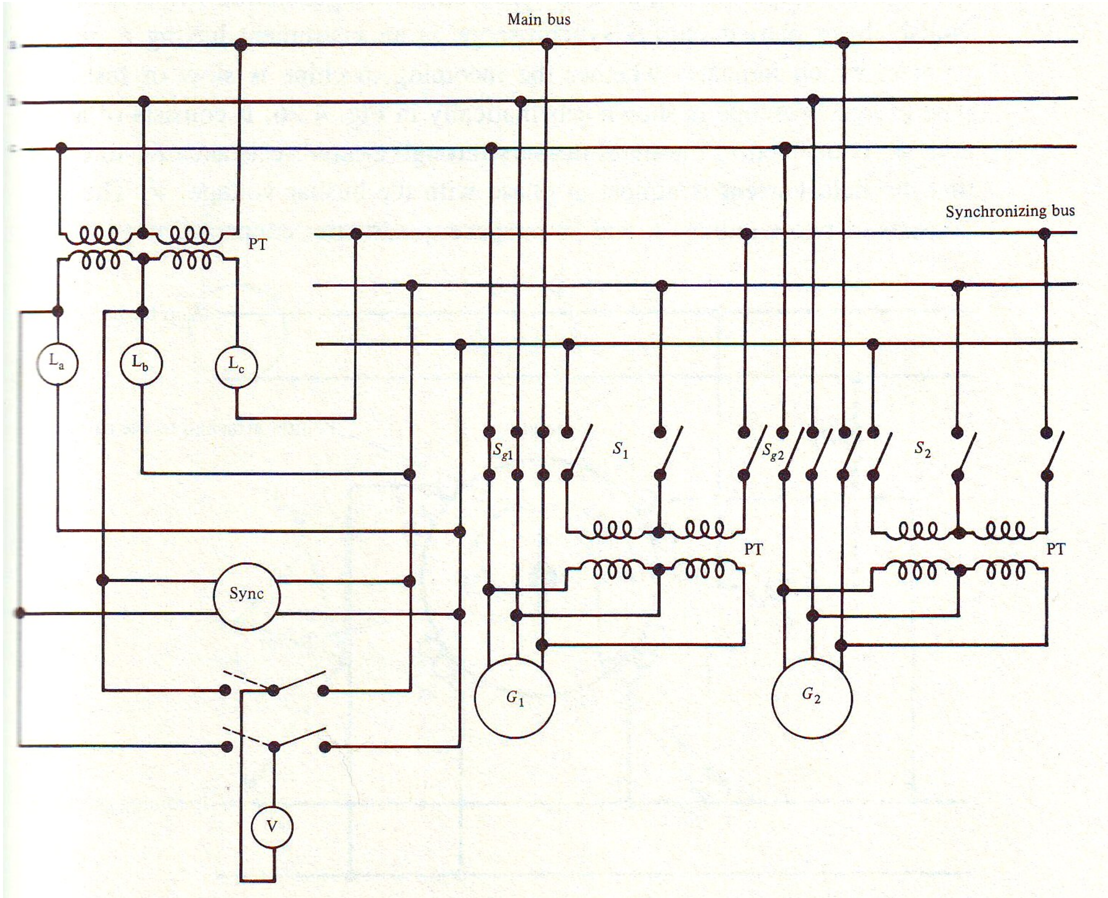


Fig 1. Synchronizing Two Generators

In the discussion above, it has been assumed that G_1 and G_2 both have the same phase rotation. On the other hand, let the phase sequence of G_1 be **abc** counterclockwise and that of G_2 be **a'b'c'** clockwise. At the synchronous speed of G_1, **a** and **a'** may be coincident. This will be indicated by a dark L_a, but L_b and L_c will have equal brightness,the phase rotation of G_2 must be reversed. When G_2 runs at a speed slightly less than the synchronous speed, with reverse phase sequence with respect to G_1 ,the lamps will be dark and bright in the cyclical order L_a, L_b and L_c, the phase rotation of G_2 must be reversed with increasing of its speed to synchronous speed. This process of testing the phase sequence is known as **phasing out**.

A synchroscope is often used to synchronize two generators which have Previously been phased out. A synchroscope is an instrument having a rotating pointer, which indicates whether the incoming machine is slow or fast. One type of synchroscope is shown schematically in Fig. 2. It consists of a field coil, **F**, connected to the main busbars through a large resistance $\mathbf{R_f}$ to ensure that the field current is almost in phase with the busbar voltage, **V.** The rotor consists of two windings **R** and **X**, in space quadrature, connected in parallel to each other and across the incoming generator.

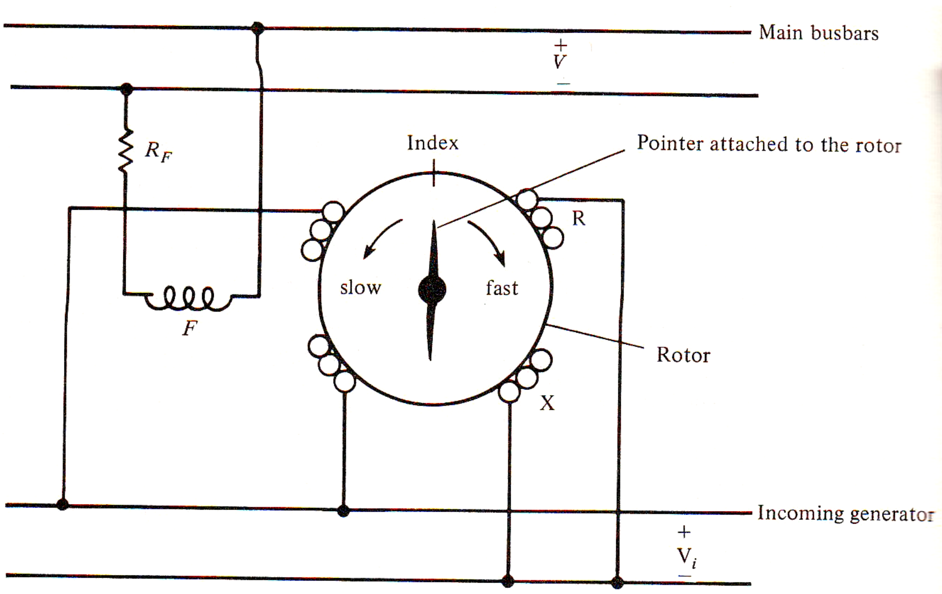


Fig 2 A Synchroscope

The windings **R** and **X** are so designed that their respective currents are approximately in phase and **90°** behind the terminal voltage, $\mathbf{V_i}$, of the incoming generator. The rotor will align itself so that the axes of **R** and **F** are inclined at an angle equal to the phase displacement between V and V_i. If there is a difference between the frequencies of **V** and $\mathbf{V_i}$, the pointer will rotate at a speed proportional to this difference. The direction of rotation of the pointer will determine if the incoming generator is running below or above synchronism. At synchronism, the pointer will remain stationary at the index. In present-day power stations, automatic synchronizers are used.

Circulating Current and Load Sharing

At the time of synchronizing (that is, when $\mathbf{S_2}$ of Fig.1 is closed), if $\mathbf{G_2}$ is running at a speed slightly less than that of $\mathbf{G_1}$ the phase relationships of their terminal voltages with respect to the local circuit are as shown in Fig.3(a). The resultant voltage $\mathbf{V_c}$ acts in the local circuit to set up a circulating current $\mathbf{I_c}$ lagging $\mathbf{V_c}$ by a phase angle $\boldsymbol{\varphi_c}$ For simplification, if we assume the generators to be identical, then

$$\tan \varphi_c = R_a / X_s$$

$$I_c = V_c / 2Z_s$$

Where $\mathbf{R_a + J\, X_s}$ = synchronous impedance , $\mathbf{R_a}$ = armature resistance , $\mathbf{X_s}$ = synchronous reactance.

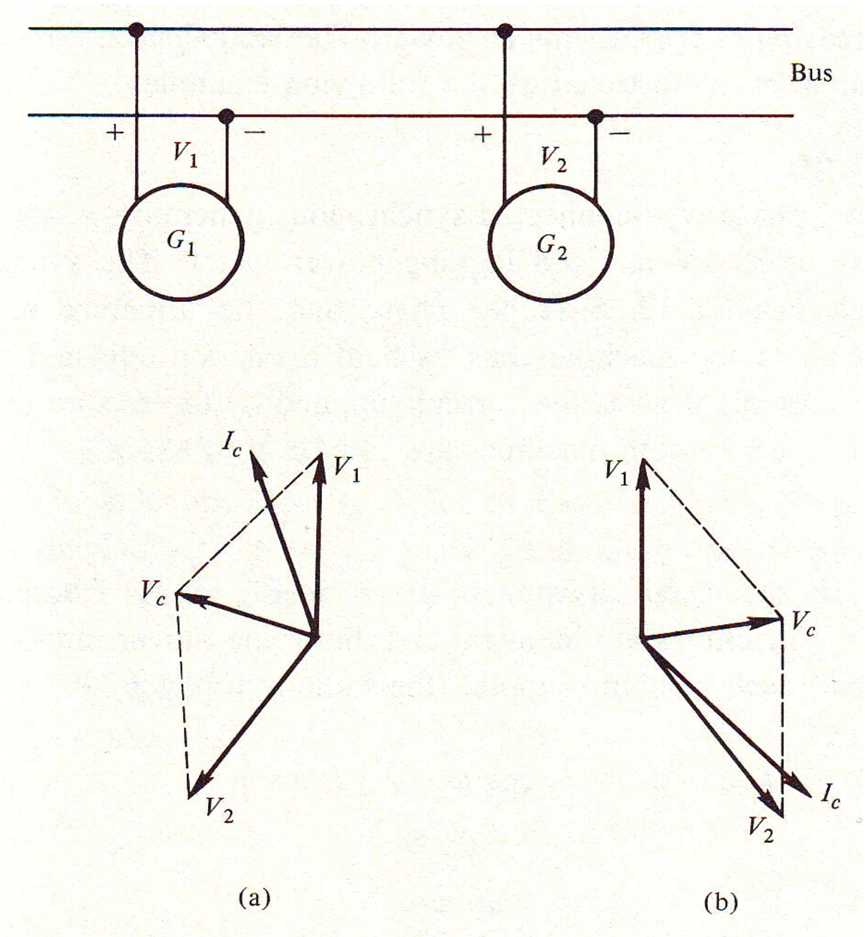


Fig 3 Circulating Currents between Tow Generators

Notice from Fig. 3(a) that $\mathbf{I_c}$ has a component in phase with $\mathbf{V_1}$, and thus acts as a load on $\mathbf{G_1}$ and tends to slow it down. The component of $\mathbf{I_c}$ in phase opposition to $\mathbf{V_2}$ aids $\mathbf{G_2}$ to operate as a motor and thereby $\mathbf{G_2}$ picks up speed. On the other hand, if $\mathbf{G_2}$ was running faster than $\mathbf{G_1}$ at the instant of synchronization, the phase relationships of the voltages and the circulating current become as shown in Fig. 3(b). Consequently, $\mathbf{G_2}$ will function as a generator and will tend to slow down; and while acting as a motor, $\mathbf{G_1}$ will pick up speed. Thus there is an inherent synchronizing action which aids the machines to stay in synchronism.
We now recall the power developed by a synchronous machine that $\mathbf{V_t}$ is the terminal voltage, which is the same as the system busbar voltage. The voltage **E** is the internal voltage of the generator and is determined by the field excitation. As we have discussed earlier, a change in the field excitation merely controls the power factor and the circulation current at which the synchronous machine operates. The power developed by the machine depends on the power angle $\boldsymbol{\delta}$. For $\mathbf{G_2}$ to share the load, for a given $\mathbf{V_t}$ and **E** the power angle must be increased by increasing the prime-mover power. The load sharing between two synchronous generators is illustrated by the following examples.

Example 1:

Two identical three-phase wye-connected synchronous generators share equally a load of 10 MW at 33 kV and 0.8 lagging power factor. The synchronous reactance of each machine is 6 Ω per phase and the armature resistance is negligible.If one of the machines has its field excitation adjusted to carry 125 A of lagging current, what is the current supplied by the second machine ? The prime mover inputs to both machines are equal.

SOLUTION

The phasor diagram of current division is shown in Fig.4, where in $\mathbf{I_1}$= 125 A. Because the machines are identical and the prime-mover inputs to both machines are equal, each machine supplies the same true power:

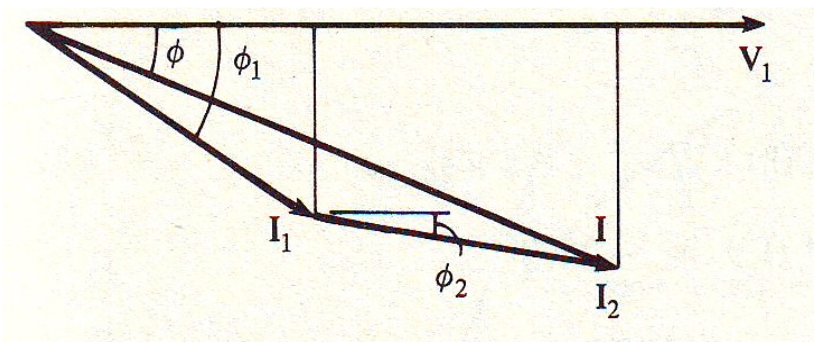


Fig 4

$I_1 \cos \varphi_1 = I_2 \cos \varphi_2 = 0.5\ I \cos \varphi$

$I = 10 * 10^6 / (\sqrt{3} * 33*10^3 * 0.8) = 218.7$ A

$I_1 \cos \varphi_1 = I_2 \cos \varphi_2 = 0.5 * 218.7 * 0.8 = 87.5$ A

The reactive current of the first machine is therefore
$I_1 \mid \sin \varphi_1 \mid = \sqrt{(125^2 – 87.5^2)} = 89.3$ A

And since the total reactive current is
$I \mid \sin \varphi \mid = 218.7 * 0.6 = 131.2$ A

The reactive current of the second machine is
$I_2 \mid \sin \varphi_2 \mid = 131.2 – 89.3 = 41.9$ A

Hence
$I_2 = \sqrt{(87.5^2 + 41.9^2)} = 97$ A

Example 2:

Consider the tow machines of example 1. if the power factor of the first machine is 0.9 lagging and the load is shared equally by the tow machines, what are the power factor and current of the second machine?

SOLUTION

Load:

Power = 10,000 KW, Apparent power =12,500 KVA, Reactive power = 7500 KVar

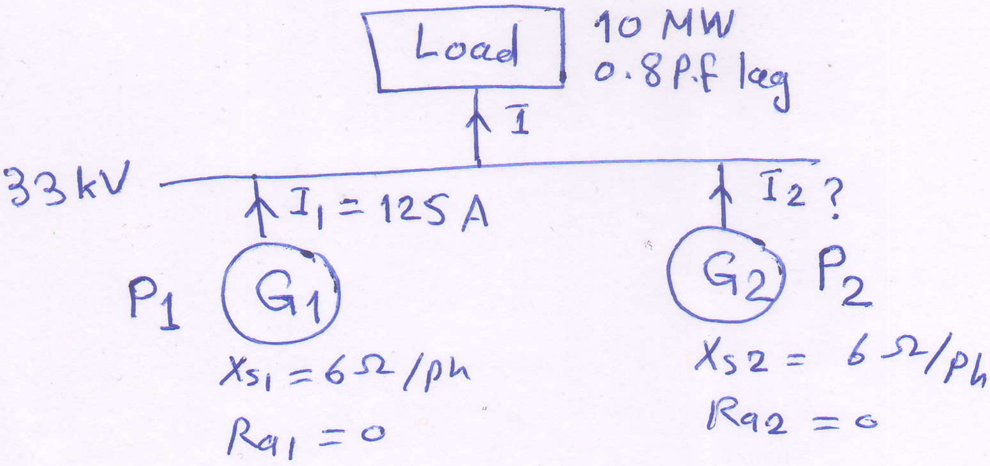
First machine:

Power = 5000 KW
$\varphi_1 = \cos^{-1} 0.9 = –25.8^o$
Reactive power = 5000 $\tan \varphi_1 = –2422$ KVar

Second machine:

Power = 5000 KW
Reactive power = –7500 – (–2422) = – 5078 KVar
$\tan \varphi_2 = – 5078 / 5000 = – 1.02$
$\cos \varphi_2 = 0.7$
$I_2 = 5000 / (\sqrt{3} * 33 * 0.7) = 124.7$ A

Ex. 1



$$P_1 = \frac{E_1 V_1}{X_{s1}} \sin \delta_1 \qquad P_2 = \frac{E_2 V_2}{X_{s2}} \sin \delta_2$$

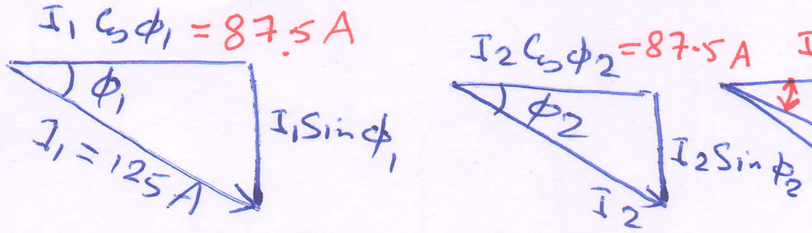
since two gen. are adentical so $\left(\frac{E_1 V_1}{X_{s1}} = \frac{E_2 V_2}{X_{s2}} \right)$

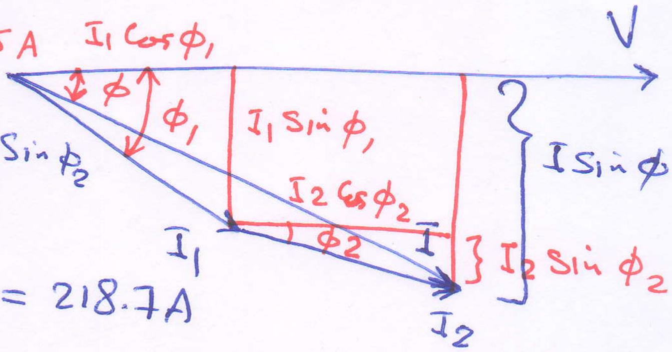
Since Prime mover inputs to both gen are equal, so $(\delta_1 = \delta_2)$

so, $P_1 = P_2 = \frac{P_{Load}}{2}$

$$\cancel{V_1} I_1 \cos\phi_1 = \cancel{V_2} I_2 \cos\phi_2 = \frac{\cancel{V_{BB}}\, I \cos\phi}{2}$$

$$\boxed{I_1 \cos\phi_1 = I_2 \cos\phi_2 = 0.5\, I \cos\phi}$$





$$I = \frac{P}{\sqrt{3}\, V \cos\phi} = \frac{10 \times 10^6}{\sqrt{3} \times 33 \times 10^3 \times 0.8} = 218.7\,A$$

$$\therefore\ I_1 \cos\phi_1 = I_2 \cos\phi_2 = 0.5 \times 218.7 \times 0.8 = 87.5\,A$$

$$I_1 \sin\phi_1 = \sqrt{125^2 - 87.5^2} = 89.3\,A$$

$$I_2 \sin\phi_2 = I \sin\phi - I_1 \sin\phi_1 = 218.7 \times 0.6 - 89.3 = 41.9\,A$$

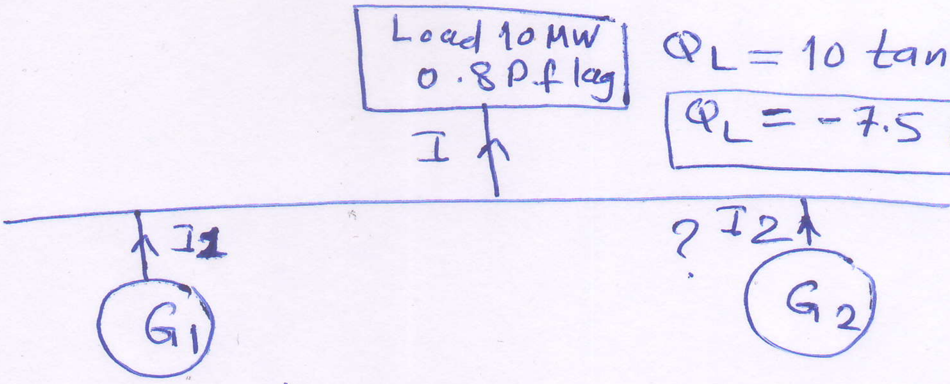
$$I_2 = \sqrt{87.5^2 + 41.9^2} = 97\,A$$

Ex. 2

$\phi_L = \cos^{-1} = 0.8$

$Q_L = 10 \tan \phi_L$

$Q_L = -7.5$ MVAR

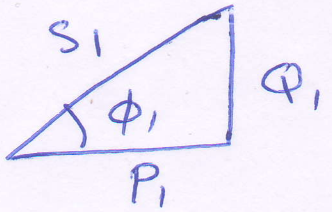


$P.f_1 = 0.9$ lag

$$P_1 = P_2 = \frac{10}{2} = 5 \text{ MW} \quad (\text{as in Ex. 1})$$

$$\phi_1 = \cos^{-1} 0.9 = -25.8^\circ (\text{lag})$$

for G_1 →



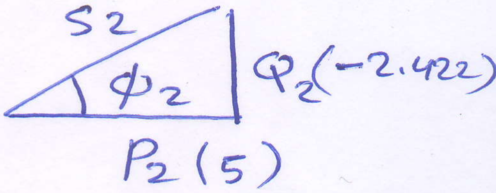
$$\tan \phi_1 = \frac{Q_1}{P_1} \rightarrow Q_1 = P_1 \tan \phi_1 = 5 \tan(-25.8^\circ)$$

$$Q_1 = -2.422 \text{ MVAR}$$

$$Q_2 = Q_L - Q_1 = (-7.5) - (-2.422) = -5.078 \text{ VAR}$$

$$\tan \phi_2 = \frac{Q_2}{P_2} = \frac{-5.078}{5} = -1.02$$

for G_2 →



$$\phi_2 = \tan^{-1}(-1.02) = -45.56^\circ$$

$$\cos \phi_2 = \cos(-45.56^\circ) = 0.7 \text{ lag}$$

$$\therefore I_2 = \frac{P_2}{\sqrt{3} V_2 \cos \phi_2} = \frac{5 \times 10^6}{\sqrt{3} \times 33 \times 10^3 \times 0.7} = 124.7 \text{ A}$$