SYNCHRONOUS MACHINE $P-\delta$ CURVE

**Aim:** To study the power angle characteristics of a given synchronous machine with the main bus bars.

**Theory:**

The Synchronous machine can be connected to the grid (represented by an equivalent generator) only when each of the voltages between the terminals $R_g, R_s, Y_g, Y_s$ and $B_g, B_s$ is zero at any instant of time. This condition is fulfilled when the line voltages on the generator side are equal, at all instants of time, to the corresponding voltages on the bus bar side. This is possible only if the following conditions are fulfilled:

- The voltages $V_{\text{grid}}$ and $V_{\text{syn} \text{chronous Machine}}$ are equal in magnitude and are in phase.
- Both the Grid and synchronous generator must have same frequency of supply voltage.
- The generator and grid voltages should have the same phase sequence.

When these conditions are fulfilled, the synchronizing switch between the generator and the grid can be switched on.

![Fig. 1 Synchronization with grid using lamp method](image-url)
Fulfillment of these conditions is checked by the following methods:

A. Synchronization by three dark lamp method:

Connect the D.C. motor - synchronous generator as shown in Fig 1. Start the D.C. motor and bring its speed to the synchronous speed of the generator (1500-rpm). Adjust the field excitation of the synchronous machine so that about rated voltage (200V, L-L) is obtained. Assume that the grid has 200V, L-L. Let the phase sequence of the generator terminals RYB be the same as that of the respective terminals of the grid, RYB. The voltage phasors for this condition are shown in Fig 2. If the generator frequency is slightly more than that of the bus, then the phasors \( R_g, Y_g \) and \( B_g \) move anti-clockwise relative to \( R_s, Y_s \) and \( B_s \). The voltages across the lamps \( L_R, L_Y \) and \( L_B \) (which are indicated by the phasors \( R_g R_s, Y_g Y_s \) and \( B_g B_s \)) will increase & decrease simultaneously and therefore, the three lamps will brighten up and darken at the same time.

![Voltage Phasors and Lamp connection for dark lamp method.](image)

If the phase sequences are \( R_g Y_g B_g \) and \( R_s B_s Y_s \), for this condition the voltages across lamps given by phasors \( R_g R_s, Y_g Y_s \) and \( B_g B_s \) are not equal to each other at any instant. Therefore the lamps go through their zero voltage one after the other. The phase sequences are thus different and can be corrected by interchanging any two terminals either on the generator.
side or on the bus side. When such a change is made both the three-phase main switch S2 and the D.C. main switch S1 should be switched off.

With the phase sequence corrected, if there is a large difference between the frequency of the generator and that of the bus, the lamps will brighten & darken in quick succession. By adjusting the speed of the generator, this rapidity can be reduced, which indicates that the frequencies are coming closer and the lamps will brighten up & darken slowly.

The correct moment of synchronization in this method is when all the lamps are completely dark, at which time all the voltages of bus are exactly in phase with the corresponding voltages of the generator. At this moment the synchronizing switch S3 is closed and the generator is synchronized with the mains.

B. **Bright lamp method:**

With the switches S1 & S2 closed and S3 open, if all the conditions of synchronization are satisfied lamp across C & c will remain dark and the other lamps will remain equally bright. This permits closing of the synchronization switch. If the frequencies are differ, a wave or light will travel and the speed of the incoming machine must be adjusted to make the incoming machine frequency equal to that of mains. By lowering the beat frequency to a very low value, the darkness of one lamp and brightness of other lams are prolonged. Synchronizing switch is closed in the middle of this period.

C. **Method of using synchroscope:**

The instrument used to indicate the correct instant for synchronization is known as synchroscope. It’s basically a single phase instrument and unlike synchronizing lamps which is capable to indicate whether the incoming machine is slow or fast.
Circuit Diagram:

Fig 3. Circuit Diagram.
Power – Angle Characteristics of the Synchronous Machine:

Procedure:
1. Make connections as per the circuit diagram. Initially keep all the switches open.
2. Switch ON the DC supply & start the DC machine by closing switch S5.
3. Adjust the speed of the DC machine to synchronous speed by field control.
4. Note the armature voltage $V_{ao}$, armature current $I_{amo}$, and field current $I_{fmo}$. $R_{s1}$ is the starting resistance. If it has been cut out, close the switch S6.
5. Switch on the main supply to the alternator field by closing the switch S1 and adjust the excitation until the alternator voltage equal the bus voltage.
6. Close the switch S3 and synchronize the machine with the supply system by dark lamp method as shown.
7. After synchronization the synchronous machine field current $I_f$ is kept constant and the DC machine field current $I_{fpm}$ is slowly decreased and as a consequence the power generated by the synchronous machine will increase and it will be shown by the wattmeter.
8. For each value of $I_{fpm}$, the values of $I_a$, $W_1$, $W_2$, $V$, and the power angle ($\delta$) are to be noted. The power angle may be noted by using a stroboscope. This can be continued until the current in one of the machines reaches rated value.
9. The synchronous machine field current $I_f$ is kept constant and the DC machine field current $I_{fpm}$ is slowly increased until the power generated by the synchronous machine comes close to ‘0’ or negative by few watts.
10. The synchronous machine now behaves as a motor. By increasing $I_{fpm}$, for each value of $I_{fpm}$, the values of $I_a$, $W_1$, $W_2$, $V$, and the power angle ($\delta$) are to be noted. This can be continued until the current in one of the machines reaches rated value.
### Table:

<table>
<thead>
<tr>
<th>S.No</th>
<th>Synchronous Machine Armature current (Ia)</th>
<th>Synchronous Machine Voltage (V)</th>
<th>DC Machine Armature current</th>
<th>DC Machine Field current</th>
<th>Power (P) (Watts)</th>
<th>Power Angle (δ)</th>
</tr>
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</table>

### Report:

1. Plot the graph between Power P (y-axis) against δ (x-axis).
2. Suppose 2 & 3 lamps are cross connected how will the lamps glow for:
   i) Correct phase sequence
   ii) Incorrect phase sequence
**Discussion:**

When load is applied to a synchronous machine, the machine poles fall back a certain angle $\delta$ behind the forward rotating poles of the stator. The value of this angle depends upon the load power factor and the excitation of the machine.

For cylindrical rotor machines these quantities are related by the expression:

$$P = \frac{EV}{X_S} \sin \delta$$

Where, $P$ = Power developed  
$V$ = Applied voltage  
$E$ = Induced voltage due to field excitation  
$X_S$ = Synchronous reactance  
$\delta$ = Load angle.

For a machine working at particular excitation (and therefore constant K) a sudden increase in load has to be accompanied by a decrease in the value of $\delta$. To accomplish this, the rotor momentarily accelerates, but does not become stable at the approximate value of load angle (say $\delta_1$), and travels further on account of its inertia, decreasing the load angle to a value lower than $\delta_1$. Under this condition, the developed power becomes less than the load power, and the rotor slows down to increase the load angle. Again, on account of inertia, the rotor travels and the load angle becomes more than $\delta_1$. The rotor then tends to accelerate and the oscillations of the rotor about the mean position of equilibrium continue. These oscillations are known as hunting.

To suppress the tendency of hunting, synchronous machine field poles are provided with damper windings which consist of copper bars placed in slot in the pole shoes and short circuited at the two ends, as in squirrel cage rotor.

From the expression of power developed, it may be noted that for a particular power output, the value of $\delta$ depends upon excitation. Further the maximum possible value of $\delta$ for which a cylindrical-rotor machine remains inherently stable is $90^\circ$. It is thus clear that an under-excited machine is less stable than an over-excited one.

**Questions:**

1. State the conditions for synchronization of two alternators.
2. State the effect of wrong synchronization.
3. State why pair of lamps are required in lamp method of synchronization?
4. Explain the necessity of synchronization of alternators.
5. State the advantages of using number of small generating units instead of single large unit for supplying power.
6. Why the frequency of incoming alternator is kept slightly higher than bus-bar frequency?
7. What is the difference between synchronous motor and synchronous condenser?
8. For the given test set up how can you make the synchronous machine become a generator feeding power to the bus?
9. If the two 400V machines are to be synchronized by either dark lamp or bright lamp method what will be the voltage rating of the bulb?