SYNCHRONOUS MACHINE P-δ CURVE

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

Theory:

The electrical power output, P_e of a synchronous machine (in the simplest form) is given as

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

Where, $V_t\angle 0$ = the terminal voltage of the machine,
E_f = E.M.F. induced in the armature winding, X_s = Synchronous reactance
δ = the angular position of the rotor with respect to a synchronously rotating reference frame
The plot of the variation of P_e with δ for the generating and motoring mode of the synchronous machine is shown in Fig. 1. Stable operation is possible only in the range ($-\pi/2 \le \delta \le \pi/2$).

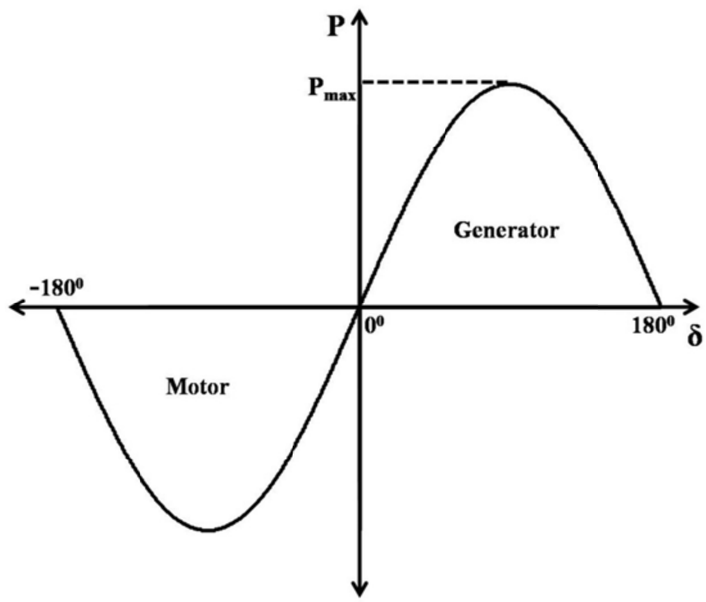

Fig 4. $P_e - \delta$ Characteristics of a Synchronous Machine.

Since the basic function of the synchronous machine is to convert mechanical power to electrical power and vice versa, some prime mover has to be mechanically coupled with the rotor so that exchange of mechanical torque and power can takes place. A dc machine supplied from a dc grid is used in this experiment as the prime mover. At first, the dc machine is started in the motor mode driving the synchronous machine rotor. As field excitation is established in the synchronous machine, E.M.F. gets generated in the armature winding due to the relative motion. The next step is to connect the armature terminals to the ac grid so that power can be exchanged in either direction. The process of establishing this connection is termed as synchronization and can be performed only if the following conditions are fulfilled:

1. The grid voltage(V_g) and synchronous machine terminal voltage (V_t)are equal in magnitude and phase.
2. The grid voltage and synchronous machine terminal voltage should have the same phase sequence.
3. The frequency of the grid voltage and synchronous machine terminal voltage must be very close (but not exactly equal).

As a result of condition 3, the difference between the phase angles of the grid voltage and synchronous machine terminal voltage will keep varying from 0 to 360° with a beat frequency (i.e. the difference of the grid and synchronous machine frequency). The machine can be connected to the grid exactly at the instant when the phase difference is zero.

Once the synchronization is complete, the input electrical power to the dc machine (from the dc grid) can be varied which in turn causes a variation in the mechanical power transferred from the dc machine to the synchronous machine and finally variation in the power exchanged by the synchronous machine with the ac grid. The value of delta can be computed for each value of power exchange.

Connection Diagram:

A circuit diagram is shown in Fig. 2 to provide some idea about the connection. However, the following differences will be there for this virtual experiment in SIMULINK platform.

a. The field winding of the synchronous machine is not explicitly available. Instead, there is a handle to vary the excitation directly.

b. Unlike the circuit diagram, separate load should not be connected to the dc machine armature terminals. For loading, the dc machine will exchange power in either direction with the dc grid.

c. The bright lamp method is not used for synchronization; hence bulbs are not used in the synchronous machine armature winding. The alternative method of synchronization to be used is described in the '**Procedure**' section.

d. The synchronous machine output power is to be measured using 3-phase active power and reactive power calculation block.

Circuit Diagram:

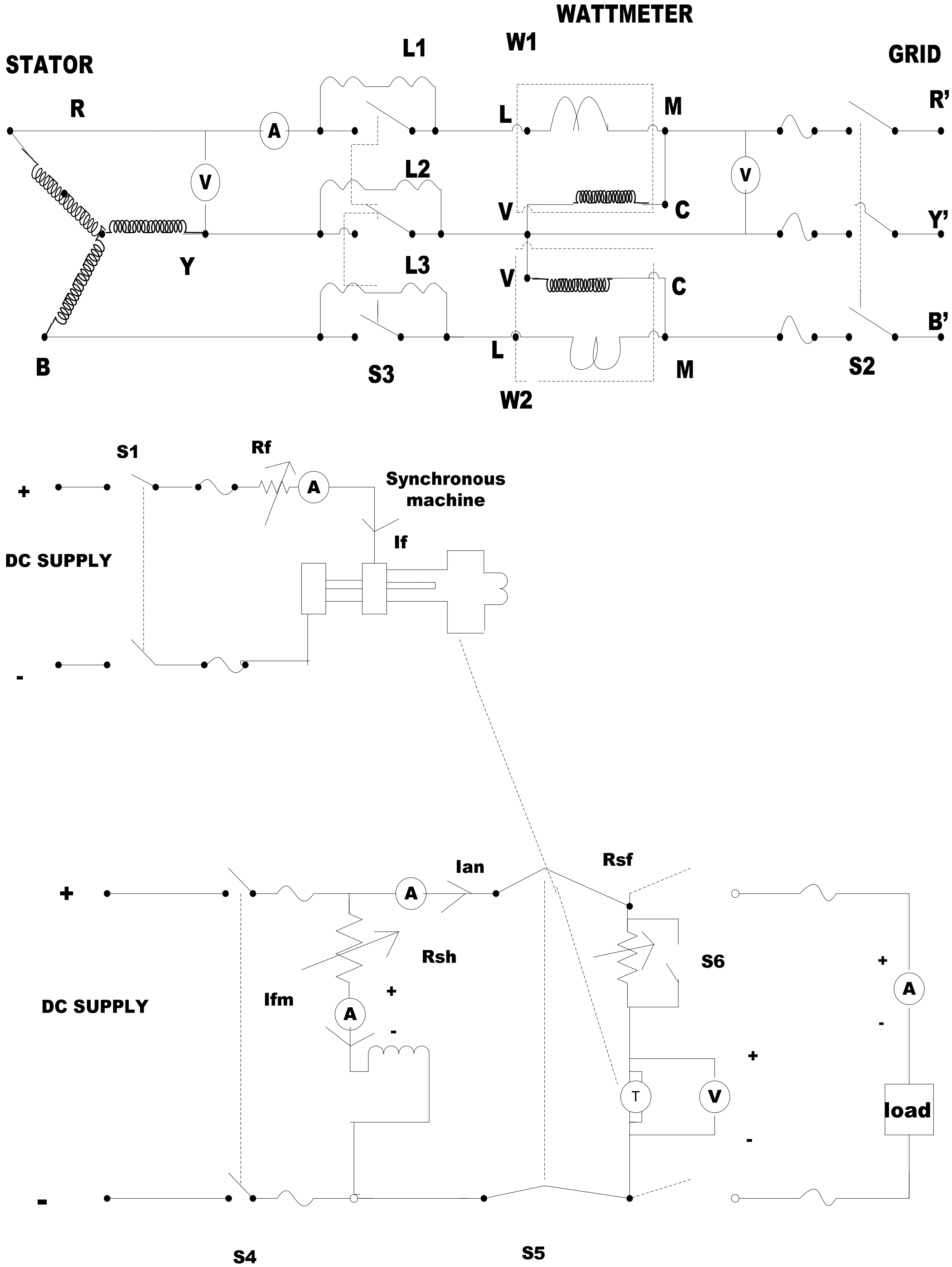

Fig 2. Circuit Diagram.

Procedure:

1. Make connections as per the circuit diagram except the differences for the virtual experiment as specified in the section above. Initially keep all the switches open.
2. Ensure that the variable resistor is in maximum position in the armature winding and in minimum position in the field winding of the dc machine. Start the dc machine by supplying the dc machine windings with rated dc voltage.
3. Adjust the speed of the dc machine by varying the variable resistors in the armature winding (for speeds below rated) and field winding (for speed above rated). Set the speed close to the synchronous speed (little above).
4. Increase the excitation of the synchronous machine and ensure that the magnitude of the armature terminal voltage is same as the grid voltage magnitude.
5. For checking the phase sequence, the space phasor is of the two voltages (grid and machine) are utilized. For this, first the stationary three-phase *a-b-c* voltages are transformed to the stationary two-phase *α-β* frame (Clarke transformation). Now the X-Y plot of the V_α vs V_β shows the movement of the space phasor. This plot for three successive instants are shown in Fig. 3 for better understanding of the movement (direction of rotation). Same direction of rotation indicates same phase sequence.

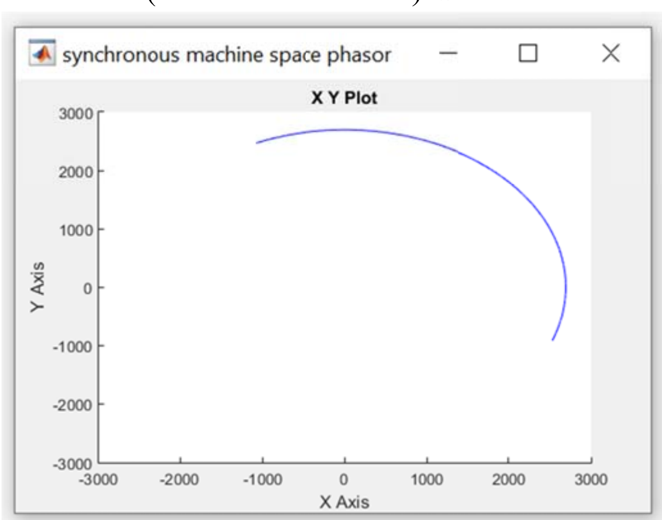

Fig. 3(a)

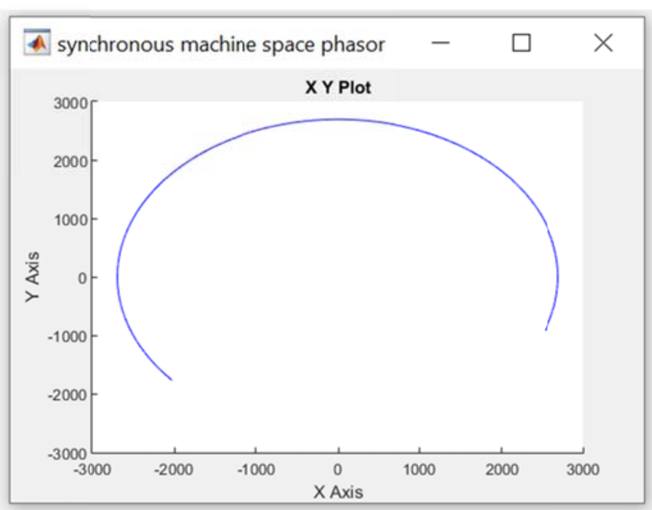

Fig. 3(b)

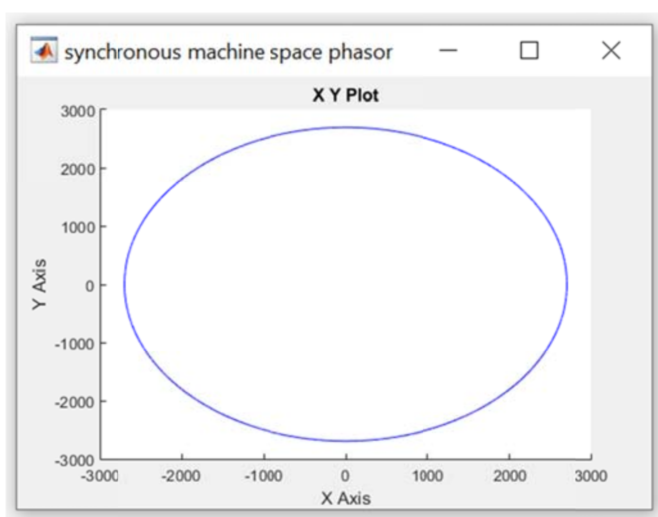

Fig. 3(c)

Let instantaneous synchronous machine terminal voltages are

$$v_a = V_m \sin(\omega_1 t + \theta_1)$$
$$v_b = V_m \sin(\omega_1 t - 120 + \theta_1)$$
$$v_c = V_m \sin(\omega_1 t + 120 + \theta_1)$$

Stationary three-phase *a-b-c* voltages are transformed to the stationary two-phase α-β frame (Clarke transformation. Expression for space phasor is written

$$v_\propto + jv_\beta = V_m \mathrm{e}^{(\omega_1 t + \theta_1)}$$

Similarly after transforming the grid voltages to α-β frame . Expression for space phasor is written

$$v_\propto + jv_\beta = V_m \mathrm{e}^{(\omega_2 t + \theta_2)}$$

6. The phase angle of the voltage, θ can also be obtained as $\theta = tan^{-1}\frac{V_\beta}{v_\alpha}$. The difference of the phase angle of the grid voltage and the synchronous machine terminal voltage can be plotted. A sample plot is provided in Fig. 4.

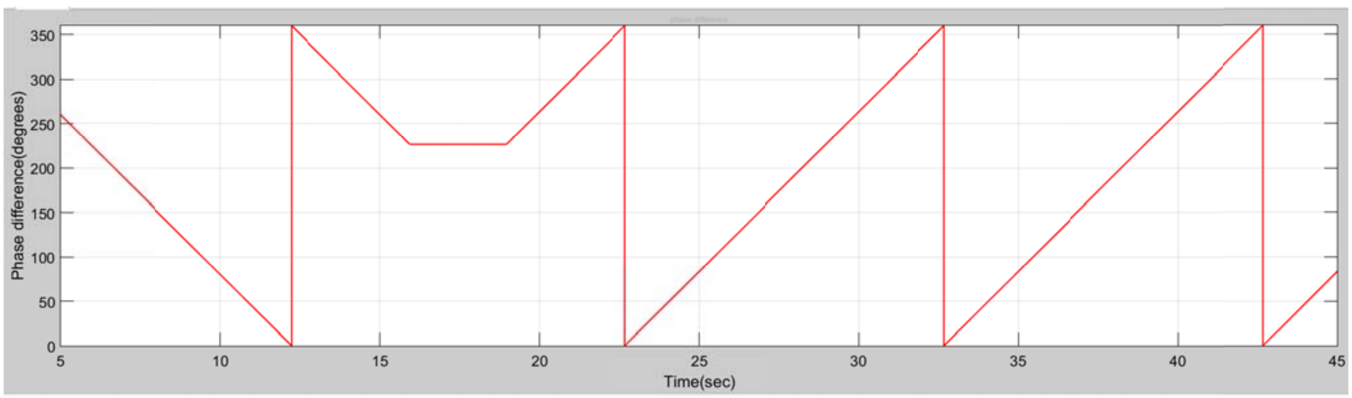

Fig. 4

As mentioned in the theory section, the difference between the phase angles keep varying from 0 to 360° with a beat frequency. The beat frequency can be counted in Fig. 4 as 0.1 Hz. The switch for connecting the synchronous machine with the grid should be connected exactly at the instant when the difference between the phase angles is zero.

7. After synchronization the synchronous machine excitation is kept constant. 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 dc machine armature current, synchronous machine terminal voltage, synchronous machine output active power, reactive power are to be noted and the power angle (δ) is to be computed. This can be continued until the current in one of the machines reaches rated value.

9. Next, 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} further, for each value of I_{fpm}, the values of dc machine armature current, synchronous machine terminal voltage, synchronous machine output active power and reactive power are to be noted and the power angle (δ) is to be computed. This

can be continued until the current in one of the machines reaches rated value. The results may be recorded in a table as shown below.

11. Plot the graph between Power P (y-axis) against δ (x-axis).

Table:

S.No	Synchronous Machine Armature current (Ia)	Synchronous Machine Voltage (V)	DC Machine Armature current	DC Machine Field current	Power (P) (Watts)	Power Angle (δ)

Discussion:

When load is applied to a synchronous machine, the machine poles fall back a certain angle δ 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

δ = 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 δ. To accomplish this, the rotor momentarily accelerates, but does not become stable at the approximate value of load angle (say δ_l), and travels further on account of its inertia, decreasing the load angle to a value lower than δ_l. 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 δ_l. 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 δ depends upon excitation. Further the maximum possible value of δ for which a cylindrical-rotor machine remains inherently stable is 90°. It is thus clear that an under-excited machine is less stable than an over-excited one.

Calculations:

Let synchronous machine induced emf per phase=$|E|\angle\delta$

Synchronous grid voltage per phase=$|V|\angle 0$

Synchronous impedance per phase=$|Z|\angle\alpha$

Active power and reactive power expressions written as

$$P = 3\left(\frac{|V| * |E|}{|Z|}cos(\delta - \alpha) - 3\frac{|V|^2}{|Z|}cos(\alpha)\right)$$

$$Q = 3\left(\frac{|V|^2}{|Z|}sin(\alpha) - \frac{|V| * |E|}{|Z|}sin(\delta - \alpha)\right)$$

Here P, Q, $|V|$ are obtained from the measurements and $|Z|, \alpha$ are obtained from the system data. Solve the above two equations for two unknowns ($|E|, \delta$). Calculate δ for each P and plot the p- δ curve.

Questions: -

1. State the conditions for synchronization of two alternators.
2. State the effect of wrong synchronization.
3. Explain the necessity of synchronization of alternators.
4. State the advantages of using number of small generating units instead of single large unit for supplying power.
5. Why the frequency of incoming alternator is kept slightly higher than bus-bar frequency?
6. For the given test set up how can you make the synchronous machine become a generator feeding power to the bus?
7. 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?