Voltage regulation of alternator by EMF, MMF, ZPF method

Voltage Regulation

When an alternator is subjected to a varying load, the voltage at the armature terminals varies to a certain extent, and the amount of this variation determines the regulation of the machine. When the alternator is loaded the terminal voltage decreases as the drops in the machine stars increasing and hence it will always be different than the induced emf.

Voltage regulation of an alternator is defined as the change in terminal voltage from no load to full load expressed as a percentage of rated voltage when the load at a given power factor is removed without change in speed and excitation. Or the numerical value of the regulation is defined as the percentage rise in voltage when full load at the specified power-factor is switched off with speed and field current remaining unchanged expressed as a percentage of rated voltage.

Hence regulation can be expressed as

% Regulation = (E-V)/V*100

where E0 = No-load induced emf /phase, Vt = Rated terminal voltage/phase at load

Methods of finding Voltage Regulation:

The voltage regulation of an alternator can be determined by different methods. In case of small generators it can be determined by direct loading whereas in case of large generators it cannot determined by direct loading but will be usually predetermined by different methods. Following are the different methods used for predetermination of regulation of alternators.

1. Direct loading method
2. EMF method or Synchronous impedance method
3. MMF method or Ampere turns method
4. ASA modified MMF method
5. ZPF method or Potier triangle method

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All the above methods other than direct loading are valid for non-salient pole machines only. As the alternators are manufactured in large capacity direct loading of alternators is not employed for determination of regulation. Other methods can be employed for predetermination of regulation. Hence the other methods of determination of regulations will be discussed in the following sections.

1. EMF method:

This method is also known as synchronous impedance method. Here the magnetic circuit is assumed to be unsaturated. In this method the MMFs (fluxes) produced by rotor and stator are replaced by their equivalent emf, and hence called emf method.

To predetermine the regulation by this method the following informations are to be determined. Armature resistance /phase of the alternator, open circuit and short circuit characteristics of the alternator.

Determination of synchronous impedance $Z_s$

As the terminals of the stator are short circuited in SC test, the short circuit current is circulated against the impedance of the stator called the synchronous impedance. This impedance can be estimated form the oc and sc characteristics.

The ratio of open circuit voltage to the short circuit current at a particular field current, or at a field current responsible for circulating the rated current is called the synchronous impedance.

$$Z_s = \frac{V_{oc}}{I_{sc}}$$ for same $I_f$

Hence $Z_s = \frac{V_{oc}}{I_{sc}}$ for same $I_f$

From Fig: 1.16 synchronous impedance $Z_s = \frac{V}{I_{sc}}$

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Armature resistance Ra of the stator can be measured using Voltmeter - Ammeter method. Using synchronous impedance and armature resistance synchronous reactance and hence regulation can be calculated as follows using emf method.

\[ Z_s = \sqrt{(R_a^2 + (Xs)^2)} \] and Synchronous reactance \( X_s = \sqrt{(Z_a^2 - (R_a)^2)} \)

Hence induced emf per phase can be found as \( E_g = \sqrt{[(V_t \cos \delta) + I_a R_a]^2 + (V_t \sin \delta \pm I_a X_s)^2]} \)

where \( V_t \) = phase voltage per phase = \( V_{ph} \), \( I_a \) = load current per phase

**In the above expression in second term + sign is for lagging power factor and - sign is for leading power factor.**

\% Regulation = \[ \frac{E_g - V_t}{V_t} \]

where

\( E_g \) = no-load induced emf /phase,

\( V_t \) = rated terminal voltage/phase

Synchronous impedance method is easy but it gives approximate results. This method gives the value of regulation which is greater (poor) than the actual value and hence this method is called pessimistic method. The complete phasor diagram for the emf method is shown in Fig 1.18.
2. MMF method

This method is also known as amp-turns method. In this method the all the emfs produced by rotor and stator are replaced by their equivalent MMFs (fluxes), and hence called mmf method. In this method also it is assumed that the magnetic circuit is unsaturated. In this method both the reactance drops are replaced by their equivalent mmfs. Fig: 1.19 shows the complete phasor diagram for the mmf method. Similar to emf method OC and SC characteristics are used for the determination of regulation by mmf method. The details are shown in Fig: 1.19. Using the details it is possible determine the regulation at different power factors.

From the phasor diagram it can be seen that the mmf required to produce the emf $E_1 = (V + IR_a)$ is $F_{R1}$. In large machines resistance drop may neglected. The mmf required to overcome the reactance drops is $(F_a + F_{al})$ as shown in phasor diagram. The mmf $(F_a + F_{al})$ can be found from SC characteristic as under SC condition both reactance drops will be present.
Following procedure can be used for determination of regulation by mmf method.

1. By conducting OC and SC test plot OCC and SCC.
2. From the OCC find the field current $I_f$ required to produce the voltage, $E_l = (V + I_R)$. 
3. From SCC find the magnitude of field current $I_f^2 (= F_a + F_a)$ to produce the required armature current. $F_a + F_a$ can also found from ZPF characteristics. 
4. Draw $I_f^2$ at angle $(90+\Phi)$ from $I_f$, where \(\Phi\) is the phase angle of current w. r. t voltage. If current is leading, take the angle of $I_f$ as $(90-\Phi)$. 
5. Determine the resultant field current, $I_f$ and mark its magnitude on the field current axis. 
6. From OCC, find the voltage corresponding to $I_f$ which will be $E_0$ and hence find the regulation.

Because of the assumption of unsaturated magnetic circuit the regulation computed by this method will be less than the actual and hence this method of regulation is called optimistic method.

3. ASA Modified MMF Method:

ASA or modified mmf method consider saturation effect for calculation of regulation. In the mmf method the total mmf $F$ computed is based on the assumption of unsaturated magnetic circuit which is unrealistic. In order to account for the partial saturation of the magnetic circuit it must be increased by a certain amount $F_F^2$ which can be computed from occ, scc and air gap lines as explained below referring to Fig: 1.20 (i) and (ii).
If1 is the field current required to induce the rated voltage on open circuit. Draw If2 with length equal to field current required to circulate rated current during short circuit condition at an angle (90+) from If1. The resultant of If1 and If2 gives If (OF2 in figure). Extend OF2 up to F so that F2F accounts for the additional field current required for accounting the effect of partial saturation of magnetic circuit. F2F is found for voltage E (refer to phasor diagram of mmf method) as shown in Fig: 1.20. Project total field current OF to the field current axis and find corresponding voltage E0 using OCC. Hence regulation can be found by ASA method which is more realistic.

4. Zero Power Factor (ZPF) method or Potier Triangle Method:

During the operation of the alternator, resistance voltage drop IaRa and armature leakage reactance drop IaXL are actually emf quantities and the armature reaction reactance is a mmf quantity. To determine the regulation of the alternator by this method OCC, SCC and ZPF test details and characteristics are required. As explained earlier oc and sc tests are conducted and OCC and SCC are drawn. ZPF test is conducted by connecting the alternator to ZPF load and exciting the alternator in such way that the alternator supplies the rated current at rated voltage running at rated speed. To plot ZPF characteristics only two points are required. One point is corresponding to the zero voltage and rated current that can be obtained from scc and the other at rated voltage and rated current under zpf load. This zero power factor curve appears like OCC but shifted by a factor IaXL vertically and horizontally by armature reaction mmf as shown below in Fig: 1.21. Following are the steps to draw ZPF characteristics.
By suitable tests plot OCC and SCC. Draw air gap line. Conduct ZPF test at full load for rated voltage and fix the point B. Draw the line BH with length equal to field current required to produce full load current on short circuit. Draw HD parallel to the air gap line so as to cut the OCC. Draw DE perpendicular to HB or parallel to voltage axis. Now, DE represents voltage drop IXl and BE represents the field current required to overcome the effect of armature reaction.

Triangle BDE is called Potier triangle and XL is the Potier reactance. Find E from \( V, IRa, IXL \) and \( \Phi \).
Use the expression
\[
E = \sqrt{\left(V \cdot \cos\Phi + IrRa\right)^2 + \left(V \cdot \sin\Phi + IXL\right)^2}
\]
to compute E. Find field current corresponding to E. Draw FG with magnitude equal to BE at angle \( (90+\Psi) \) from field current axis, where \( \Psi \) is the phase angle of current from voltage vector E (internal phase angle).

The resultant field current is given by OG. Mark this length on field current axis. From OCC find the corresponding \( E_0 \). Find the regulation.

This method is based on the separation of armature leakage reactance drop and the armature reaction effect. This is more accurate than the emf and mmf methods. The experimental data required is No load curve (or) O.C.C, S.C.C, Armature resistance, full load zero power factor curve (or) wattles load characteristics. The ZPF lagging characteristics is a reaction between terminal voltage and excitation when armature is delivering F.L. current at zero power factor.

The reduction in voltage due to armature reaction is found from above and (ii) voltage drop due to armature leakage reactance XL (also called potier reactance) is found from both. By combining these two, \( E_0 \) can be calculated. It should be noted that if we vectorially add to V the drop due to resistance and leakage reactance XL, we get E. If E is further added the drop
due to armature reaction (assuming lagging power factor), then we get $E_0$. The zero power factor lagging curve can be obtained if a similar machine is available which may be driven at no-load as a synchronous motor at practically zero power factor (or) by loading the alternator with pure reactors. By connecting the alternator to a 3Φ line with ammeter and watt meters connected for measuring current and power and by so adjusting the field current that we get full-load armature current with zero wattmeter reading.

**CIRCUIT DIAGRAM: O.C & S.C TEST ON ALTERNATOR**

![Circuit Diagram](image)

**PROCEDURE:**

**A. OPEN CIRCUIT TEST**

1) The Electrical connections are made as shown in the circuit diagram.
2) Keeping the field rheostat of the motor (R1) in cut-out position, the rheostat connected in series with armature of the motor (R2) in cut in position, the rheostat in the field circuit of alternator (R3) in cut in position and keeping the TPST and field switch of the alternator open, the supply switch is closed.
3) The motor is brought to its rated speed by gradually cutting out R2 and if necessary by cutting in R1.
4) Now close the supply switch S2 for the field of Alternator.
5) Note down the initial set of readings of field current and induced EMF.
6) Vary the field rheostat R3 in steps and at each step see that the speed is kept constant and take down the readings of If and induced EMF.
7) Repeat the same steps (6) until the field excitation becomes 20% more than the rated value.
8) Bring back the field rheostat R3 to its original position and supply switch S2 is opened.

**SHORT CIRCUIT TEST:**

1) Connections are made as shown in the circuit diagram.
2) The first three steps of the above procedure for O.C.C are common for this test.
3) Close the TPST switch shorting the stator of the Alternator
4) Close the supply switch S2 for the field of the Alternator keeping the Rheostat R3 in cut in position.
5) Adjust the field rheostat R3 if necessary and see the Ammeter will read the full load short circuit current.
6) Note down the field current required to produce full load short circuit current.

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7) Bring back the field rheostat R3 to its original position, open the D.C supply switch S2 and then the TPST and short circuit on the other side of TPST.

**CIRCUIT DIAGRAM: ZPF TEST ON ALTERNATOR**

**ZPF TEST:**
- a. Connections are made as shown in circuit diagram 2.
- b. The first three steps of the above procedure for O.C.C are common.
- c. Keeping the pure inductive load at its minimum position and close the TPST switch.
- d. Now close the field supply switch S2 and adjust for the full load current.
- e. Note down the voltage and the field current at that instant.
- f. Adjust the inductive load in steps and at each step maintain the full load current and note down the readings of field current and voltage.
- g. Bring back the rheostat R3 to its original position (cut in) and supply switch S2 is opened.
- h. Bring the rheostat R1 to cut out and R2 cut in and open the supply switch.

**MEASUREMENT OF STATOR RESISTANCE:**
1) Connections are made as shown in the circuit diagram.
2) Supply switch is closed.
3) Apply the load in steps
4) All the meter readings are noted down.
5) Stator resistance is calculated using the formula
   \[ \text{Stator resistance / phase} = 1.5 \times \frac{V}{I} \text{ ohms where } R_s = \frac{V}{I} \text{ ohms} \]

**TABULAR COLUMN:**
A. For Open Circuit test:

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### Short Circuit Ratio of a Synchronous Machine

The **Short Circuit Ratio (SCR)** of a synchronous machine is defined as the ratio of the field current required to generate rated voltage on an open circuit to the field current required to circulate rated armature current on short circuit. The short circuit ratio can be calculated from the **open circuit characteristic (O.C.C)** at rated speed and the **short circuit characteristic (S.C.C)** of a three-phase synchronous machine as shown in the figure below.

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**Graph and Vector Diagram**

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From the above figure, the short circuit ratio is given by the equation shown below.

\[
SCR = \frac{I_f \text{ for rated O.C. voltage}}{I_f \text{ for rated S.C. current}} = \frac{Oa}{Od} \ldots \ldots (1)
\]

Since the triangles Oab and Ode are similar. Therefore,

\[
SCR = \frac{Oa}{Od} = \frac{ab}{de} \ldots \ldots (2)
\]

The direct axis synchronous reactance \( X_d \) is defined as the ratio of open circuit voltage for a given field current to the armature short circuit current for the same field current.

For the field current equal to Oa, the direct axis synchronous reactance in ohms is given by the equation shown below.

\[
X_d \Omega = \frac{ac}{ab} \ldots \ldots (3)
\]

**Significance of Short Circuit Ratio (SCR)**

**Short Circuit Ratio** is an important factor of the synchronous machine. It affects the operating characteristics, physical size and cost of the machine. The large variation in the terminal voltage with a change in load takes place for the lower value of the short circuit ratio of a

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synchronous generator. To keep the terminal voltage constant, the field current ($I_f$) has to be varied over a wide range.

For the small value of the short circuit ratio (SCR), the synchronizing power is small. As the synchronizing power keeps the machine in synchronism, a lower value of the SCR has a low stability limit. In other words, a machine with a low SCR is less stable when operating in parallel with the other generators.

A synchronous machine with the high value of SCR had a better voltage regulation and improved steady state stability limit, but the short circuit fault current in the armature is high. It also affects the size and cost of the machine.

The excitation voltage of the synchronous machine is given by the equation.

$$E_f = 4.44 k_w f \phi T_{ph}$$

For the same value of $T_{ph}$, excitation voltage is directly proportional to the field flux per pole.

$$E_f \propto \frac{\text{field mmf per pole}}{\text{reluctance of air gap}}$$

The synchronous inductance is given as

$$L_s \propto \frac{1}{\text{reluctance of air gap}}$$

Therefore,

$$\text{SCR} \propto \frac{1}{L_s}$$

Hence, the short circuit ratio is directly proportional to the air gap reluctance or air gap length.

If the length of the air gap is increased, the SCR can be increased. With the increase in the air gap length, the field MMF is to be increased for the same value of excitation voltage ($E_f$). Hence, to increase the value of field MMF either field current or the number of field turns has to be increased. All this requires a greater height of field poles and, as a result, the overall diameter of the machine increases.
Thus, a conclusion is that the large value of SCR will increase the size, weight and the cost of the machine.

The typical values of the SCR for different types of machines are as follows:-

- For **cylindrical rotor** machine, the value of SCR lies between 0.5 to 0.9.
- In case of the **Salient-pole machine**, it lies between 1 to 1.5 and
- For **synchronous compensators**, it is 0.4.

**SLIP TEST ON ALTERNATOR**

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<th>Vmin(V)</th>
<th>Imax(A)</th>
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**PROCEDURE:**

1) The Electrical connections are made as shown in the circuit diagram.
2) Close the D.C supply switch, the motor is brought to rated speed by cutting out armature rheostat and cutting in field rheostat if necessary. Keep the DC machine and alternator speed at approximately 1450 rpm

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3) Keeping the autotransformer at zero output position, three phase supply switch is now closed.
4) Gradually increase the auto transformer voltage output so that the armature current injection reading is oscillating about a mean value.
5) Adjust the field rheostat of the D.C motor such that deflection is maximum and the readings are noted down around a mean value of 6.5 Amps at around 1425 rpm. Vmax, Vmin, Imax and Imin readings are taken accurately.
6) Reduce the armature current by bringing the autotransformer dial towards zero output position and then open the 3-phase supply switch.
7) To stop the machine, bring the DC motor rheostats to their original positions, remove the D.C supply switch.
8) Find the stator resistance of the alternator by A-V method.

Parallel Operation of Alternator

Alternator is really an AC generator. In alternator, an EMF is induced in the stator (stationary wire) with the influence of rotating magnetic field (rotor) due to Faraday's law of induction. Due to the synchronous speed of rotation of field poles, it is also known as synchronous generator.

Here, we can discuss about parallel operation of alternator. When the AC power systems are interconnected for efficiency, the alternators should also have to be connected in parallel. There will be more than two alternators connected in parallel in generating stations.

Condition for Parallel Operation of Alternator

There are some conditions to be satisfied for parallel operation of the alternator. Before entering into that, we should understand some terms which are as follows.

- The process of connecting two alternators or an alternator and an infinite bus bar system in parallel is known as synchronizing.
- Running machine is the machine which carries the load.
- Incoming machine is the alternator or machine which has to be connected in parallel with the system.

The conditions to be satisfied are

1. The phase sequence of the incoming machine voltage and the bus bar voltage should be identical.
2. The RMS line voltage (terminal voltage) of the bus bar or already running machine and the incoming machine should be the same.
3. The phase angle of the two systems should be equal.
4. The frequency of the two terminal voltages (incoming machine and the bus bar) should be nearly the same. Large power transients will occur when frequencies are not nearly equal.

Departure from the above conditions will result in the formation of power surges and current. It also results in unwanted electro-mechanical oscillation of rotor which leads to the damage of equipment.

General Procedure for Paralleling Alternators

The figure below shows an alternator (generator 2) being paralleled with a running power system (generator 1). These two machines are about to synchronize for supplying power to a load. Generator 2 is about to parallel with the help of a switch, S1. This switch should never
be closed without satisfying the above conditions.

1. To make the terminal voltages equal. This can be done by adjusting the terminal voltage of incoming machine by changing the field current and make it equal to the line voltage of running system using voltmeters.

2. There are two methods to check the phase sequence of the machines. They are as follows
   - First one is using a Synchroscope. It is not actually check the phase sequence but it is used to measure the difference in phase angles.
   - Second method is three lamp method (Figure 2). Here we can see three light bulbs are connected to the terminals of the switch, S1. Bulbs become bright if the phase difference is large. Bulbs become dim if the phase difference is small. The bulbs will show dim and bright all together if phase sequence is the same. The bulbs will get bright in progression if the phase sequence is opposite. This phase sequence can be made equal by swapping the connections on any two phases on one of the generators.
3. Next, we have to check and verify the incoming and running system frequency. It should be nearly the same. This can be done by inspecting the frequency of dimming and brightening of lamps.

4. When the frequencies are nearly equal, the two voltages (incoming alternator and running system) will alter the phase gradually. These changes can be observed and the switch, S1 can be made closed when the phase angles are equal.

**Advantages of Parallel Operating Alternators**

- When there is maintenance or an inspection, one machine can be taken out from service and the other alternators can keep up for the continuity of supply.
- Load supply can be increased.
- During light loads, more than one alternator can be shut down while the other will operate in nearly full load.
- High efficiency.
- The operating cost is reduced.
- Ensures the protection of supply and enables cost-effective generation.
- The generation cost is reduced.
- Breaking down of a generator does not cause any interruption in the supply.
- Reliability of the whole power system increases.

**Synchronization of alternator**

**Synchronization of alternator** means **connecting an alternator into grid** in parallel with many other alternators that is in a live system of constant voltage and constant frequency. Many alternators and loads are connected into a grid, and all the alternators in grid are having same output voltage and frequency (whatever may be the power). It is also said that the alternator is connected to infinite bus-bar. A stationary alternator is never connected to live bus-bars, because it will result in short circuit in the stator winding (since there is no generated emf yet). Before **connecting an alternator into grid**, following conditions must be satisfied:

1. Equal voltage: The terminal voltage of incoming alternator must be equal to the bus-bar voltage.
2. Similar frequency: The frequency of generated voltage must be equal to the frequency of the bus-bar voltage.
3. Phase sequence: The phase sequence of the three phases of alternator must be similar to that of the grid or bus-bars.
4. Phase angle: The phase angle between the generated voltage and the voltage of grid must be zero.

The first condition of voltage equality can be satisfied by a voltmeter. To satisfy the conditions of equal frequency and identical phases, one of the following two methods can be used:

(i) Synchronization using incandescent lamp

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(ii) Synchronization using synchroscope.

Synchronization of alternator using incandescent lamp

Let, alternator 2 is to be synchronized in a grid and the alternator 1 is already in the grid as shown in above figure. The alternator 2 is connected to grid through three synchronizing lamps (L1, L2 and L3) as shown in above figure. If the speed of the alternator 2 is not such that the frequency of output voltage is equal to the frequency of the grid, there will also be a phase difference in the voltages, and in this case the lamps will flicker. Three lamps are connected asymmetrically, because if they were connected symmetrically, they would glow or dark out simultaneously (if the phase rotation is same as that of bus-bars). Asymmetrically connected lamps indicate whether the incoming machine is running slower or faster. If the alternator 2 is running slower, the phase rotation of alternator 2 will appear to be clockwise relative to the phase rotation of the grid and the lamps will light up in the order 3, 2, 1; 3, 2, 1.... If the alternator 2 is running faster, the phase rotation of alternator 2 will appear to be anticlockwise relative to the phase rotation of the grid and the lamps will light up in the order 1, 2, 3; 1, 2, 3....

When the speed of the alternator 2 reaches so that, the frequency and phase rotation of output voltage is similar to that of the grid voltage, lamp L1 will go dark and lamps L2 and L3 will dimly but equally glow (as they are connected between different phases and due to this there will be phase difference of 120 degree). The synchronization is done at this very moment. This method of synchronization is sometimes also known as 'two bright and one dark method'.

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Drawbacks of 'synchronization using incandescent lamps' method are:

- Synchronization by using incandescent lamps depends on the correct judgment of the operator.
- This method does not tell how slowly or fast the machine is.
- To use this method for high voltage alternators, extra step down transformers need to be added as ratings of lamps are normally low.

**Synchronization of alternator using synchroscope**

A **synchroscope** is a device which shows the correct instant of closing the synchronizing switch. **Synchroscope** has a pointer which rotates on the dial. The pointer rotates anticlockwise if the **machine** is running slower or it rotates clockwise if the machine is running fast. The correct instant of closing synchronizing switch is when the pointer is straight upwards.

**V and Inverted V curves of a Synchronous Motor**

V-curve of a synchronous machine shows its performance in terms of variation of armature current with field current when the load and input voltage to the machine is constant. When a synchronous machine is connected to an infinite bus, the current input to the stator depends upon the shaft-load and excitation (field current). At a constant load, if excitation is changed the power factor of the machine changes, i.e. when the field current is small (machine is under-excited) the P.F. is low and
as the excitation is increased the P.F. improves so that for a certain field current the P.F. will be unity and machine draws minimum armature current. This is known as normal excitation. If the excitation is further increased the machine will become overexcited and it will draw more line current and P.F. becomes leading and decreases. Therefore, if the field current is changed keeping load and input voltage constant, the armature current changes to make $V \cos \phi$ constant. Because of their shape graphs of variation of armature current with excitation are called ‘V’ curves. If the ‘V’ curves at different load conditions are plotted and points on different curves having same P.F. are connected the resulting curve is known as “compounding curves”.

**PROCEDURE:**

1) The Electrical connections are made as shown in the circuit diagram.
2) Keep the field switch (SPST) closed. Now keep load switch (SPST) switch in open position.
3) Keep the field rheostat of the Synchronous motor (R1) in cut in position, the field rheostat of the D.C generator (R2) in cut in position, the 3 phase autotransformer in zero output position. Close the AC switch. Then close the DC supply switch.
4) Apply the voltage gradually by varying the auto transformer output up to 100V. Allow the rotor of synch motor to accelerate. The armature current should not exceed 10Amps.
5) Switch ON the excitation of the Synchronous motor by opening the SPST switch. Apply the rated voltage for Synchronous motor. Bring the armature current to minimum by cutting out the 600 ohms field rheostat (R1)
6) Bring the sync motor’s field to UPF position, where it will draw the least $I_a$.
7) Note down the field current $I_f$ and corresponding $I_a$ for Leading PF and carry out the same for Lagging PF. Note $W_1$ and $W_2$ readings also. Bring the rheostat R1 to cut-in position.
8) After taking the two sets of readings we have to take two sets of readings by loading the synch motor by loading the DC machine by an external resistance bank.

**ON SOME CONSTANT LOAD (x% OF FULL LOAD)**

9) Keeping the SPST open, excite the DC generator to its rated voltage by cutting out the generator field rheostat R2.
10) Close SPST and load the generator such that $VL*IL/\eta_g = x\%$ of the rated output of motor.
11) $VLIL = x * KVA*\eta_g$ Where $VL = 230$ Volts (generator rated voltage
Assume $\eta_g = 85\%$

$IL = (x* KVA *\eta_g)/VL$ KVA from name plate details
12) Now vary the synchronous motor field rheostat (R1) in steps (cutting it out) and at each step note down the readings $W_1, W_2, I_1, I_2$ & $I_f$ to their maximum values and tabulate them.
13) To switch off the set, bring back R1 to its original position, R2 to cut in and open the motor field supply switch, bring back the 3 phase autotransformer dial to its zero position and open the main supply switches.
14) Plot the graph of pf v/s If both at no load and at a fixed load and also plot the graphs of $I_a$ v/s $I_f$ for both no load and fixed load

**CIRCUIT DIAGRAM:** V and Inverted V curves of Synchronous Motor.
**IDEAL GRAPH:** Plot the graph of pf v/s if both at no load and full load and also plot the graphs of Ia v/s Ir for both no load and full load.

**TABULAR COLUMN**

### Power factor Lag:

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<th>Sl. No</th>
<th>W1 (W)</th>
<th>W2 (W)</th>
<th>Ia (A)</th>
<th>Ir (A)</th>
<th>p.f= ( \cos \Phi )</th>
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### Power factor Lead:

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>W1 (W)</th>
<th>W2 (W)</th>
<th>Ia (A)</th>
<th>Ir (A)</th>
<th>p.f= ( \cos \Phi )</th>
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Prepared by Ganesha G C, DSCE Bangalore-78
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CALCULATION  \( \cos \phi = \cos \left\{ \tan^{-1} \left( \sqrt{3} \left( \frac{W_1 - W_2}{W_1 + W_2} \right) \right) \right\} / (W_1 + W_2) \)

ON SOME CONSTANT LOAD (x % OF FULL LOAD)

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<tr>
<th>Sl No</th>
<th>W1 (W)</th>
<th>W2 (W)</th>
<th>Ia (A)</th>
<th>If (A)</th>
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Different Methods of Starting Synchronous Motor

General Method to start synchronous motor:

As we already know that synchronous Motor is not self-starting and we already discussed why the synchronous motor is not self-starting. So here is a general method to start synchronous motor.

1. Three phase winding is given a three phase ac supply. Now a rotating magnetic field is produced which is rotating at synchronous speed \( N_s \) rpm.
2. Now make the rotor to rotate in the direction of the rotating magnetic field at a speed very near to that of synchronous speed using some external equipment like a diesel engine.
3. Now switch on the dc supply given to the rotor so that rotor poles are produced. Now there are two fields one is rotating magnetic field produced by stator while the other is produced by the rotor which is physically rotated almost at the same speed as that of rotating magnetic field.
4. At a particular instant, both the fields are magnetically locked. The stator field pulls rotor field into synchronism. Now we can remove external device used to rotate rotor can be removed. But rotor will continue to rotate at the same speed as that of rotating magnetic field i.e. \( N_s \) due to magnetic locking.

Key Point: So the main point of this discussion is to start the synchronous motor; it needs some device to rotate the rotor at a speed very near or equal to the synchronous speed.

Must Read:

Methods of starting Synchronous Motor:

- We have to think about an alternative to rotate the rotor at a speed almost equal that of synchronous speed. So this can be possible by employing various methods to start the synchronous motor. The following are the different methods to start a synchronous motor.
  1. Using Pony Motors
  2. Using Damper Winding
  3. as a slip ring Induction motor
  4. Using Small dc machine coupled to it
1. **Using pony Motors:**

   In this method, some external devices like small induction motor used to bring rotor near to synchronous motor. This external device is called **Pony motor**.

   When the rotor attains synchronous speed, dc excitation to the rotor is switched on. After some time synchronism is developed and then pony motor is decoupled. Due to synchronism promoter continues to rotate as a synchronous motor.

2. **Using damper winding:**

   In a synchronous motor, we have normal field winding and in addition to this additional winding consisting of copper bars is placed in the slots in the pole faces. These bars short-circuited with the help of end rings. This additional winding on the rotor is called **damper winding**. This winding as it is short-circuited, it acts like squirrel cage rotor winding of an induction motor. The schematic diagram of this damper winding is shown in the below figure.

   ![Schematic Diagram of Damper Winding](image)

   Once the stator is excited by a three phase supply, the motor starts rotating as an induction motor at sub-synchronous speed. Then d.c. supply is given to the **field winding**. At a particular instant, motor gets pulled into synchronism and starts rotating at a synchronous speed. As the rotor rotates at synchronous speed, the relative motion between damper winding and the rotating magnetic field is zero. Hence when the motor is running as a synchronous motor, there cannot be any induced emf in the damper winding.

   So damper winding is active only at the start, to run the motor as an induction motor at start. Afterwards, it is out of the circuit. As **damper winding** is short circuited and motor gets started as an induction motor, it draws high current at the start so induction motor starters like star-delta, autotransformer etc. used to **start the synchronous motor** as an induction motor.

3. **as a Slip Ring Induction Motor:**

   The above **method of starting synchronous motor** as a squirrel cage induction motor does not provide high starting torque. So to achieve this, instead of shorting the damper Winding, it is designed to form a three phase star or delta connected winding.

   The three ends of this winding are brought out through slip rings. An external rheostat then can be introduced in series with the rotor circuit. So when the stator is excited, the motor starts as a slip ring induction motor and due to resistance added in the rotor provides high starting torque.

   The resistance is then gradually cut off, as motor gathers speed. When motor attains speed near synchronous, d.c. excitation is provided to the rotor, then motor gets pulled into synchronism and starts rotating at **synchronous speed**. The **damper winding** is shorted by shorting the slip rings.

   The initial resistance added in the rotor not only provides high starting torque but also limits high inrush of starting current. Hence it acts as a rotor resistance starter.
The **synchronous motor started by this method** is called a slip ring induction motor is shown in the below figure.

It can be observed from the above figure that the same three phase rotor winding acts as a normal rotor **winding** by shorting two of the phases. From the positive terminal, current ‘I’ flows in one of the phases, which divides into two other phases at start point as 1/2 through each, when the switch is thrown on d.c. supply side.

### 4. Using Small D.C. Machine:

Many times, large **synchronous motors** are provided with a coupled dc machine. This machine is used as a dc motor to rotate the synchronous motor at asynchronous speed. Then the excitation to the rotor is provided. Once the motor starts running as a synchronous motor, the same dc machine acts as a dc generator called exciter. The field of the **synchronous motor** is then excited by this exciter itself.

**Effect of change in load and effect of change in excitation in synchronous motor**

#### 1) Effect of Changing Field Excitation at Constant Load

In a DC motor, the armature current \(I_a\) is determined by dividing the difference between \(V\) and \(E_b\) by the armature resistance \(R_a\) (i.e \(I_a = (V-E_b)/R_a\)). Similarly, in a synchronous motor, the stator current \((I_a)\) is determined by dividing voltage-phasor resultant \((Er)\) between \(V\) and \(E_b\) by the synchronous impedance \(Z_s\) (i.e \(I_a = (V-E_b)/Z_s\)). One of the most important features of a synchronous motor is that by changing the field excitation, it can be made to operate from lagging to leading power factor. Consider a synchronous motor having a fixed supply voltage and driving a constant mechanical load. Since the mechanical load as well as the speed is constant, the power input to the motor \((P=3V*I_a * \cos \phi)\) is also constant. This means that the in-phase component \(I_a \cos \phi\) drawn from the supply will remain constant. If the field excitation is changed, back e.m.f \(E_b\) also changes. This results in the change in phase position of \(I_a\) w.r.t. \(V\) and synchronous motor for different values of field excitation. Note that extremities of current phasor \(I_a\) lie on the straight line AB. hence the power factor \(\cos \phi\) of the motor changes.

**\(i\) Under excitation**

The motor is said to be under-excited if the field excitation is such that \(E_b < V\). Under such conditions, the current \(I_a\) lags behind \(V\) so that motor power factor is lagging as shown in Fig: (i). This can be easily explained. Since \(E_b < V\), the net voltage \(Er\) is decreased and turns clockwise. As angle \((\delta = 90^\circ)\) between \(Er\) and \(I_a\) is constant, therefore, phasor \(I_a\) also turns...
clockwise i.e., current Ia lags behind the supply voltage. Consequently, the motor has a lagging power factor.

**(ii) Normal excitation**

The motor is said to be normally excited if the field excitation is such that \( E_b = V \). This is shown in Fig: 2.28 (ii). Note that the effect of increasing excitation (i.e., increasing \( E_b \)) is to turn the phasor \( E_r \) and hence Ia in the anti-clockwise direction i.e., Ia phasor has come closer to phasor V. Therefore, p.f. increases though still lagging. Since input power \( P = V \times I_a \times \cos \phi \) is unchanged, the stator current \( I_a \) must decrease with increase in p.f.

Suppose the field excitation is increased until the current Ia is in phase with the applied voltage V, making the p.f. of the synchronous motor unity [See Fig: 2.28 (iii)]. For a given load, at unity p.f. the resultant \( E_r \) and, therefore, Ia are minimum.

**(iii) Over excitation**

![Diagram showing normal and over excitation](image)

The motor is said to be overexcited if the field excitation is such that \( E_b > V \). Under such conditions, current Ia leads V and the motor power factor is leading as shown in Fig: 2.28 (iv). Note that \( E_r \) and hence Ia further turn anti-clockwise from the normal excitation position. Consequently, Ia leads V. From the above discussion, it is concluded that if the synchronous motor is under-excited, it has a lagging power factor. As the excitation is increased, the power factor improves till it becomes unity at normal excitation. Under such conditions, the current drawn from the supply is minimum. If the excitation is further increased (i.e., over excitation), the motor power factor becomes leading.

**Note.** The armature current (Ia) is minimum at unity p.f and increases as the power factor becomes poor, either leading or lagging.
2) **Effect of Load on a Synchronous Motor**

A synchronous motor runs at constant synchronous speed, regardless of the load. Let us see the effect of the load change on the motor. Consider a synchronous motor operating initially with a leading power factor. The phasor diagram for leading power factor is shown below.

The load on the shaft is increased. The rotor slows down momentarily, as it required some time to take increased power from the line. In another word, it can be said that even if the rotor is rotating at synchronous speed, the rotor slips back in space because of the increase in the load. In this process, the torque angle $\delta$ becomes larger and, as a result, the induced torque increases.

The induced torque equation is given as

$$T_{\text{ind}} = \frac{V E_f \sin \delta}{\omega X_s}$$

Then increased torque increases the rotor speed, and the motor again regains the synchronous speed, but with the larger torque angle. The excitation voltage $E_f$ is proportional to $\phi \omega$, it depends upon the field current and the speed of the motor. Since the motor is moving at a synchronous speed, and the field current is also constant. Hence, the magnitude of the Voltage $|E_d|$ remains constant. We have,
From the above equations, it is clear, that if $P$ is increased the value of $(E_f \sin \delta)$ and $(I_a \cos \varphi)$ also increases. The figure below shows the Effect of increase in load on the operation of a synchronous motor.

It is seen from the above figure that with the increase in load, the quantity $jI_a X_s$ goes on increasing and the relation $V = E_f + jI_a X_s$ is satisfied. The armature current is also increased. The power factor angle also changes with the change in load. It becomes less and less leading and then becomes more and more lagging as shown in the figure above.

Thus, if the load on a synchronous motor is increased the following points are considered which are given below.

- The motor continues to run at synchronous speed.
- The torque angle $\delta$ increases.
- The excitation voltage $E_r$ remains constant.
- The armature current $I_a$ drawn from the supply increases.

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The phase angle $\phi$ increases in the lagging direction.

There is a limit to the mechanical load that can be applied to a synchronous motor. As the load is increased, the torque angle $\delta$ also increases until the condition arises when the rotor is pulled out of synchronism and the motor is stopped.

**Pull-out torque** is defined as the maximum value of the torque which a synchronous motor can develop at rated voltage and frequency without losing synchronism. It values varies from 1.5 to 3.5 times the full load torque.