AC Machines: Synchronous Machine

Voltage Regulation

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Voltage Regulation

$$\%R = \frac{|E_0| - |V|}{|V|} \times 100$$

- The voltage regulation of an alternator or synchronous generator is defined as the rise in the terminal voltage when the load is decreased from full-load rated value to zero. The speed and field current of the alternator remain constant.
- The voltage regulation is like the figure-of-merit of an alternator.
- The smaller the value of the voltage regulation of a synchronous generator or alternator, the better is the performance of the alternator.
- For an ideal alternator, the value of the voltage regulation is zero.
- The voltage regulation of an alternator depends upon the power factor of the load.

✓ An alternator operating at a unity power factor has a small positive voltage regulation.

✓ An alternator operating at a lagging power factor has a large positive voltage regulation.

✓ An alternator operating at lower leading power factors, the voltage rises with increase of the load and hence, the voltage regulation is negative.

✓ For a certain leading power factor, the full-load voltage regulation is zero. In this case, both the full-load and no-load terminal voltages are the same.

Determination of Voltage Regulation

Direct Loading: Suitable for small generators

- In the direct load test, the alternator is run at synchronous speed and its terminal voltage is adjusted to its rated value (V). Now, the load is varied until the ammeter and wattmeter connected in the test circuit indicate the rated values at the given power factor. Then, the load is removed and the speed and the field excitation of the alternator are kept constant and the no-load voltage (E_0) of the alternator is recorded.

$$\%R = \frac{|E_0| - |V|}{|V|} \times 100$$

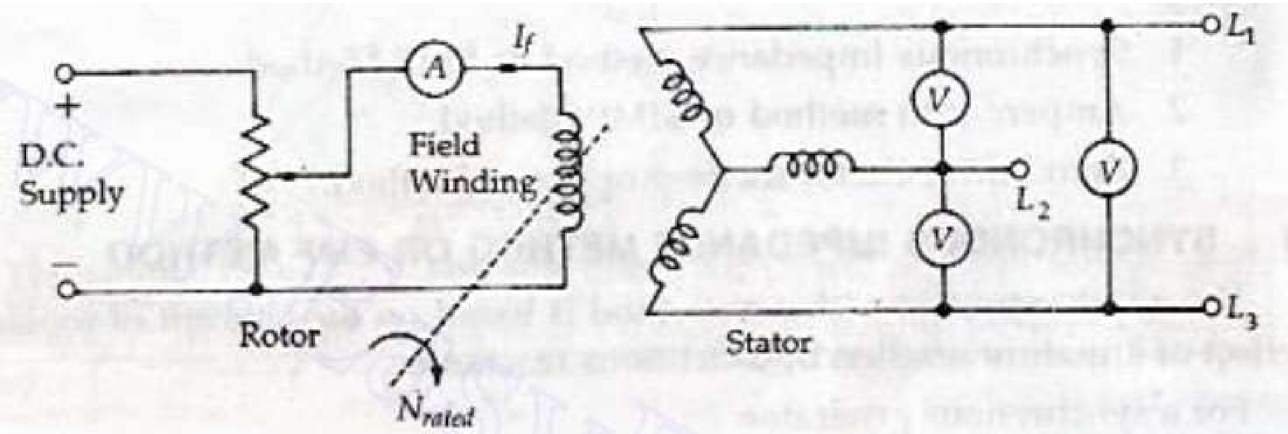
Indirect Methods: Suitable for large generators due to economical reasons. For cylindrical rotor type alternators, the methods are:

- Synchronous impedance method or EMF method
- Ampere-turn method or MMF method & Modified MMF method
- Zero power factor method or Potier method or ZPF method .

Synchronous impedance method or EMF method

- In this method, we should first determine the synchronous impedance (synchronous reactance and armature resistance) of the alternator.
- For this an open-circuit and a short circuit tests are to be performed on the alternator.

Open circuit test or Open circuit characteristics (OCC)



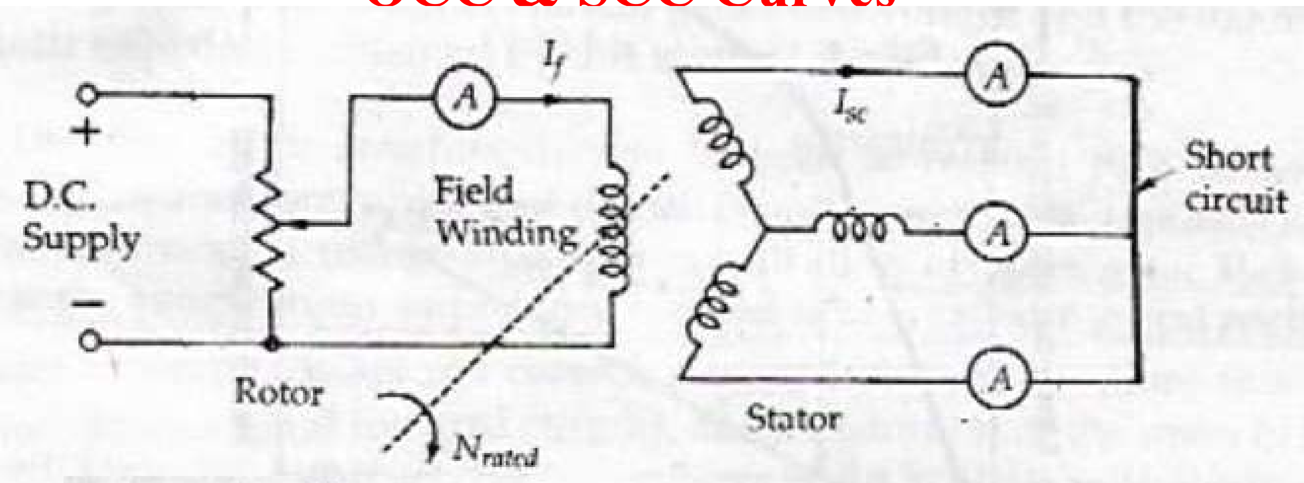
Open circuit characteristics (OCC)

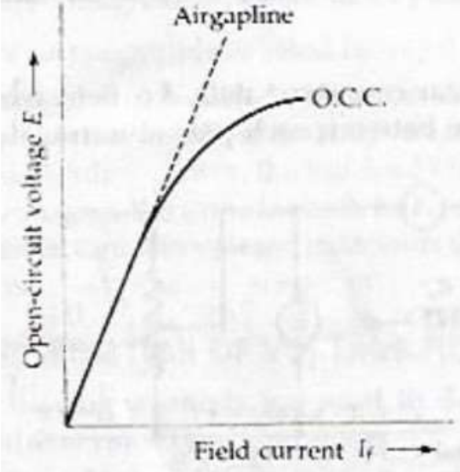
- In this test the machine is run by a primemover at synchronous speed Ns to generate voltage at the rated frequency, while the armature terminals are open-circuited with switch S open.
- The readings of the open-circuit line-to-line armature voltage (E_L) are taken for various values rotor field current I_f.
- I_f is representative of the net mmf/pole acting on the magnetic circuit of machine.
- These data are plotted as OCC.
- The OCC exhibits the saturation phenomenon of the iron in machine.
- At low values of I_f when iron is in the unsaturated state, the OCC is almost linear and the mmf applied is mainly consumed in establishing flux in the air-gap, the reluctance of the iron path being almost negligible.

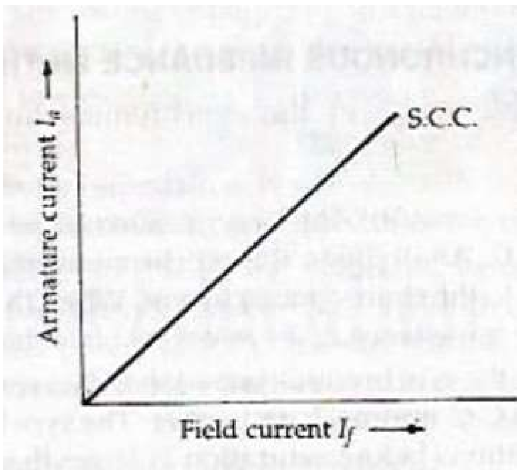
Short circuit characteristics (SCC)

- The short-circuit characteristic of the machine is obtained by means of the short -circuit test.
- While the rotor is run at synchronous speed Ns, the rotor field is kept unexcited to begin with.
- The field excitation is then gradually increased till the armature current equals about 150% of its rated value.
- It is to be noted that the machine must not be short-circuited under excited conditions with a near about rated voltage.
- This can give rise to intolerably large transient currents in the machine.
- Armature current is limited by Ra & Xs (X_L +Xa)
- Resistance is very less compared to reactance.
- Armature current is nearly purely inductive.
- Since the armature circuit is assumed purely inductive, the short-circuit current lags the air-gap voltage E_0 by 90° so that the armature reaction is fully demagnetizing in effect.
- Machine is operating under the unsaturated magnetization condition,

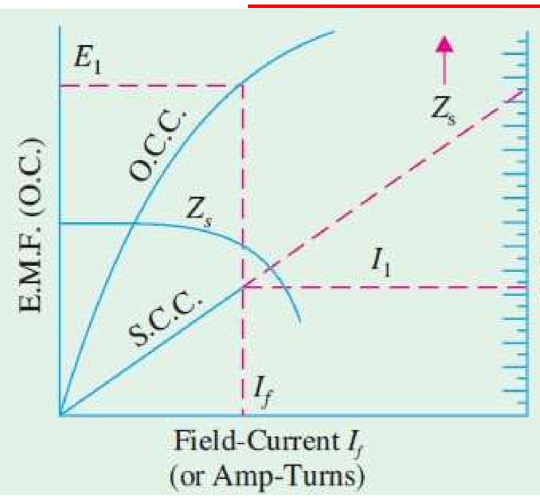
OCC & SCC Curves

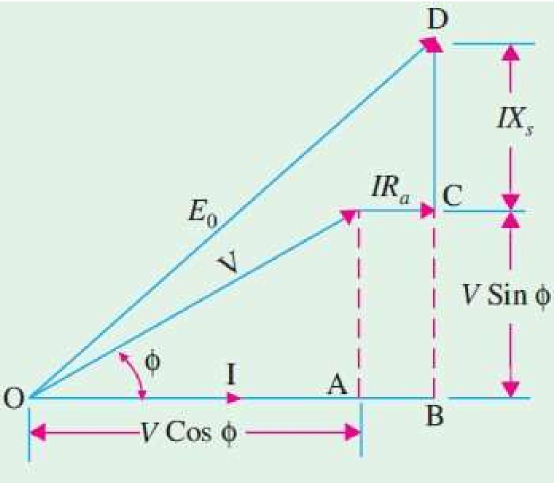






OCC & SCC



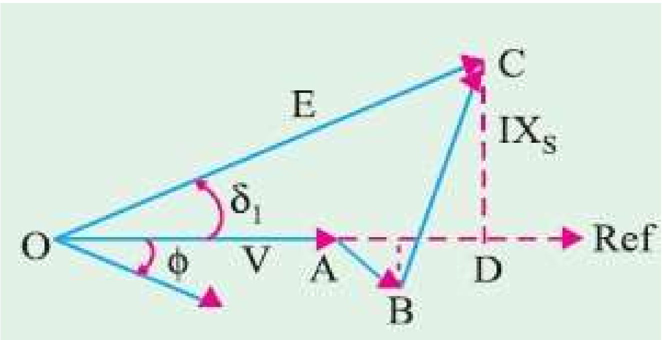


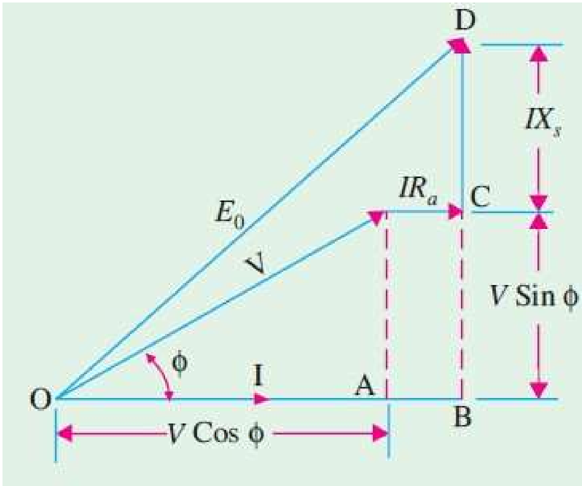
$$OD = E_0 \qquad \therefore\ E_0 = \sqrt{(OB^2 + BD^2)}$$

$$E_0 = \sqrt{[(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2]}$$

Consider a field current I_f. The O.C. voltage corresponding to this field current is E_1. When winding is short-circuited, the terminal voltage is zero. Hence, it may be assumed that the whole of this voltage E_1 is being used to circulate the armature short-circuit current I_1 against the synchronous impedance Z_S.

$$E_1 = I_1 Z_S \qquad \therefore\ Z_S = \frac{E_1 \text{ (open-circuit)}}{I_1 \text{ (short-circuit)}}$$





$OC = E = \sqrt{OD^2 + DC^2}$

$OD = OA + AB \cos\phi + BC \sin\phi$

$CD = -AB \sin\phi + BC \cos\phi$

$OD = E_0 \quad \therefore E_0 = \sqrt{(OB^2 + BD^2)}$

OB=OA+AB, OA=Vcosφ, AB=IRa

BD= BC+CD, BC=Vsinφ, CD=IXs

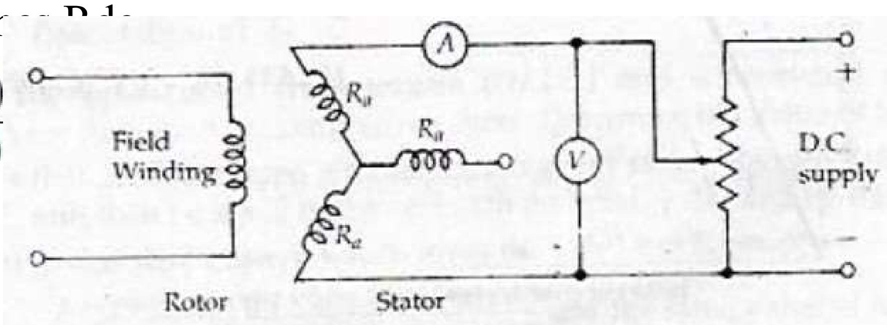
$$E_0 = \sqrt{[(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_S)^2]}$$

Armature Resistance

- To determine the value of synchronous reactance, the actual value of the per phase armature resistance is calculated by voltmeter–ammeter method.
- Since the value of armature resistance is very small, a low DC supply voltage is connected across the terminals of any two-phases of the three-phase alternator
- The value of armature resistance is:
- Measured Resistance = Vdc / Idc
- Rdc = Measured Resistance / 2 (Y-Connected)
- Then, the actual AC resistance of the armature of an alternator is 1.25 to 1.75 times to that of DC resistance.
- Ra = 1.25 to 1.75 tim

$$Z_S = \frac{E_1 \text{ (open-circuit)}}{I_1 \text{ (short-circuit)}}$$

$$, X_S = \sqrt{(Z_S^2 - R_a^2)}$$



Voltage Regulation: Problems on EMF Method

Problem-1: A three-phase star connected 1200 kVA, 3300 V, 50 Hz, alternator has armature resistance of 0·25 Ω per phase. A field current of 40 A produces a short circuit current of 200 A and an open circuit emf of 1100 V between lines. Calculate regulation on full load 0·8 power factor lagging.

Sol:

Rated power = **1200 kVA = 1200 × 10^3 VA**

Terminal voltage (line value), **V_L = 3300 V**

Armature resistance per phase, **R = 0·25 Ω**

Short circuit current, **Isc = 200 A**

Open circuit emf (phase value), **E = 1100 / Sqrt (3) = 635 V**

Synchronous impedance/phase, **Zs = E / Isc = 635 /200= 3.175 Ω**

Synchronous reactance/phase, **Xs = Sqrt [$(Zs)^2$ – $(R)^2$]**

= Sqrt [3.1752 – 0.252] = **3.165 Ω**

Full load current, **I = 1200 kVA / (Sqrt (3) * 3300) = 210 A**

Voltage Regulation: Problems on EMF Method

Terminal voltage/phase, **$V = V_L$ / Sqrt (3) = 3300 /Sqrt (3) = 1905 V**
Load power factor, **cos θ = 0·8; sin θ = sin (cos–1 0·8) = 0·6**
No-load voltage/phase,
$Eo = Sqrt\ [(V \cos\theta + IR)^2 + (V \sin\theta + IXs)^2]$
$Eo = Sqrt\ [(1905 * 0.8 + 210 * 0.25)^2 + (1905 * 0.6 + 210 * 3.165)^2] =$
Eo = 2399 V
Percentage Regulation =**(Vno load – Vfull load) / Vfull load * 100%**
V.R. = (Eo – Vt) / Vt *100% = (2399 – 1905) / 1905*100% = 25.9%

Problem-2: A three-phase, star connected, 20 MVA, 11 kV, 50 Hz alternator produces a short-circuit current equal to full-load current when a field current of 70 A passes through its field winding. The same field current produces an emf of 1820 V (line to line) on open circuit. If the alternator has a resistance between each pair of terminals as measured by DC is 0.16 Ω and the effective resistance is 1.5 times the ohmic resistance, what will be its full-load regulation at : (i) 0.707 pf lagging (ii) 0.8 pf leading.

$$\%R = \frac{|E_0| - |V|}{|V|} \times 100$$

Rated power = **20000 kVA**
Terminal voltage (line value), **V_L = 11000 V, V (phase value) = 6351 V**
Open circuit emf (line value), **E_L = 1820 V**
Open circuit emf (phase value), E = 1820 / Sqrt (3) = **1050.8 V**
Resistance between two terminals = 0·16 Ω
Resistance measured/phase = 0.16 / 2 = 0.8 Ω
Effective resistance/phase, R = 1·5 * 0·8 = **0·12 Ω**
Full load current, **I = 20000 kVA / (Sqrt (3) * 11000) = 1049.7 A**
Short circuit current, **Isc = 1049.7 A**
Synchronous impedance/phase, **Zs = E / Isc = 1050.8 /1049.7= 1.001 Ω**
Synchronous reactance/phase, **Xs = Sqrt [$(Zs)^2 - (R)^2$]**
= Sqrt [$1.001^2 - 0.12^2$] = **0.994 Ω**
At 0.707 p.f. lagging: **Eo=Sqrt[$(V\cos\theta+IR)^2+(V\sin\theta + IXs)^2$]= 7206 V**
% R=**(Vno load – Vfull load) / Vfull load * 100%** = **13.46 %**
At 0.8 p.f. leading: **Eo= Sqrt[$(V\cos\theta+IR)^2 + (V\sin\theta - IXs)^2$]** = **5896 V**
% R=**(Vno load – Vfull load) / Vfull load * 100%** = **– 7.15 %**

Voltage Regulation: Problems on EMF Method

EXAMPLE 3.14. *A 550 V, 55 kVA, single-phase alternator has an effective resistance of 0.2 Ω. A field current of 10 A produces an armature current of 200 A on short circuit and an emf of 450 V on open circuit. Calculate the synchronous reactance and voltage regulation at full load with power factor 0.8 lagging.*

SOLUTION. $S_{1\phi} = V I_a$

$$55 \times 10^3 = 550\, I_a$$

$$I_a = \frac{55 \times 10^3}{550} = 100\text{ A}$$

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

Synchronous impedance

$$Z_s = \frac{\text{open–circuit phase voltage}}{\text{short–circuit armature current}}$$

$$= \frac{450}{200} = 2.25\ \Omega$$

Synchronous reactance

$$X_s = \sqrt{Z_s^2 - R_a^2} = \sqrt{(2.25)^2 - (0.2)^2} = 2.24\ \Omega$$

Generated armature voltage per phase for lagging *pf*

$$E_a = \sqrt{(V\cos\phi + I_a R_a)^2 + (V\sin\phi + I_a X_s)^2}$$

$$= \sqrt{(550 \times 0.8 + 100 \times 0.2)^2 + (550 \times 0.6 + 100 \times 2.24)^2}$$

$$= \sqrt{460^2 + 554^2} = 720 \text{ V}$$

Voltage regulation

$$= \frac{E_a - \mathbf{V}}{\mathbf{V}} \times 100 = \frac{720 - 550}{550} \times 100 = 30.91\%$$

Alternative method of calculating E_a

Let **V** be taken as reference phasor.

$\therefore \quad \mathbf{V} = V \angle 0° = 550 \angle 0° = 550 + j0 \text{ V}$

For lagging *pf* $\cos\phi$

$$\mathbf{I}_a = I_a \angle -\phi° = I_a \angle -\cos^{-1} 0.8° = 100 \angle -36.87° \text{ A}$$

$$\mathbf{Z}_s = R_a + j\,X_s = 0.2 + j\,2.24 = 2.25 \angle 84.9° \ \Omega$$

$$\mathbf{E}_a = \mathbf{V} + \mathbf{I}_a \mathbf{Z}_s$$

$$= 550 + j\,0 + (100 \angle -36.87°)(2.25 \angle 84.9°)$$

$$= 550 + 225 \angle 48.03°$$

$$= 550 + 150.47 + j\,167.3 = 720 \angle 13.4° \text{ V}$$

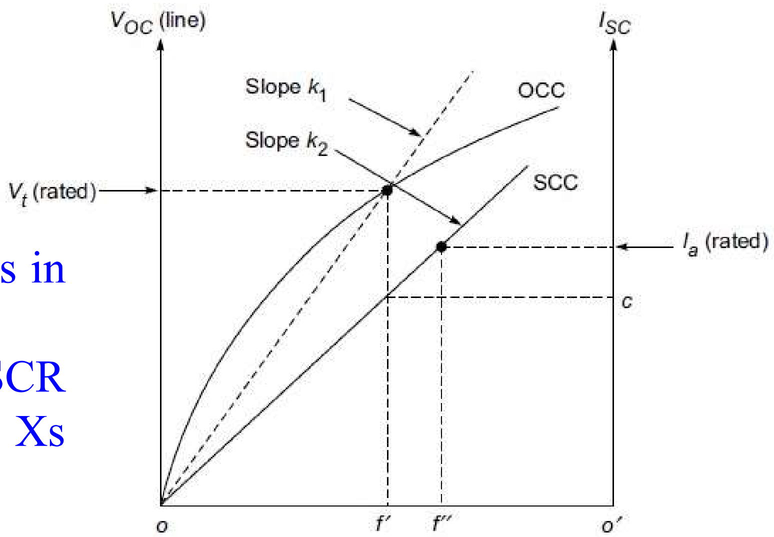
Advantages and Disadvantages of EMF method

- The main advantage of this method is that the value of synchronous impedance Zs for any load condition can be calculated.
- Regulation of the alternator at any load condition and load power factor can be determined.
- Actual load need not be connected to the alternator (only OCC & SCC is required) and the calculation procedure is much simpler
- This method is not accurate because the value of Z_S so found is always more than its value under normal voltage conditions and saturation.
- Hence, the value of regulation so obtained is always more than that found from an actual test.
- That is why it is called pessimistic method.
- The value of Z_S is not constant but varies with saturation.
- At low saturation, its value is larger because then the effect of a given armature ampere-turns is much more than at high saturation.
- Now, under short-circuit conditions, saturation is very low, because armature m.m.f. is directly demagnetising.

Short Circuit Ratio (SCR)

- The short-circuit ratio (SCR) is defined as the ratio of the field current required to produce rated voltage on open-circuit to the field current required to produce rated armature current with the armature terminals shorted while the machine is mechanically run at synchronous speed.

$$SCR = \frac{of'}{of''}$$



- SCR is the reciprocal of Xs in pu.
- Therefore, a low value of SCR implies a large value of Xs (pu) and vice versa.

Significance of SCR

- The SCR affects the physical size, operating characteristics and cost of the synchronous machine.
- With a low value of SCR, the synchronous machine is very sensitive to the load variations.
- an alternator with a low SCR is less stable when operating in parallel with other alternators.
- The armature current of the synchronous machine under short-circuit conditions is small for a low value of SCR
- With a high value of SCR, a synchronous machine has a better voltage regulation and improved steady-state stability limit, but the armature current under short-circuit conditions is high.

Ampere-turn method or MMF method

- ❖ Change in terminal Voltage:
- ✓ Due to armature resistance: Voltage Drop (IR_a)
- ✓ Armature leakage reactance: Voltage Drop (IX_L)
- ✓ Armature reaction: Change in flux (demagnetizing/magnetizing)
- ❖ In EMF, armature reaction effect is replaced by a voltage drop in Xa
- ❖ In ampere-turn method the effect of armature leakage reactance is replaced by an equivalent additional armature reaction MMF so that this MMF can be combined with the armature reaction MMF.
- ❖ Field current If is a measure of MMF
- ❖ MMF method requires mmf (product of field current (If) and turns (N) of field winding) for two separate purposes.

Ampere-turn method or MMF method

- It must have an mmf which is necessary to induce the rated terminal voltage on open circuit condition.
- It must have an mmf to circulate the full load current equal and opposite to that of armature reaction mmf.
- The field mmf (I_{f1}) required to induce the rated terminal voltage is obtained by conducting open circuit test.
- I_{f2} is the field current required to circulate the full load armature current by balancing or overcoming the armature reaction, which is obtained by conducting the short circuit test.
- Then the resultant MMF is determined by vector addition of I_{f1} & I_{f2}
- No load voltage is found from OCC corresponding to resultant MMF

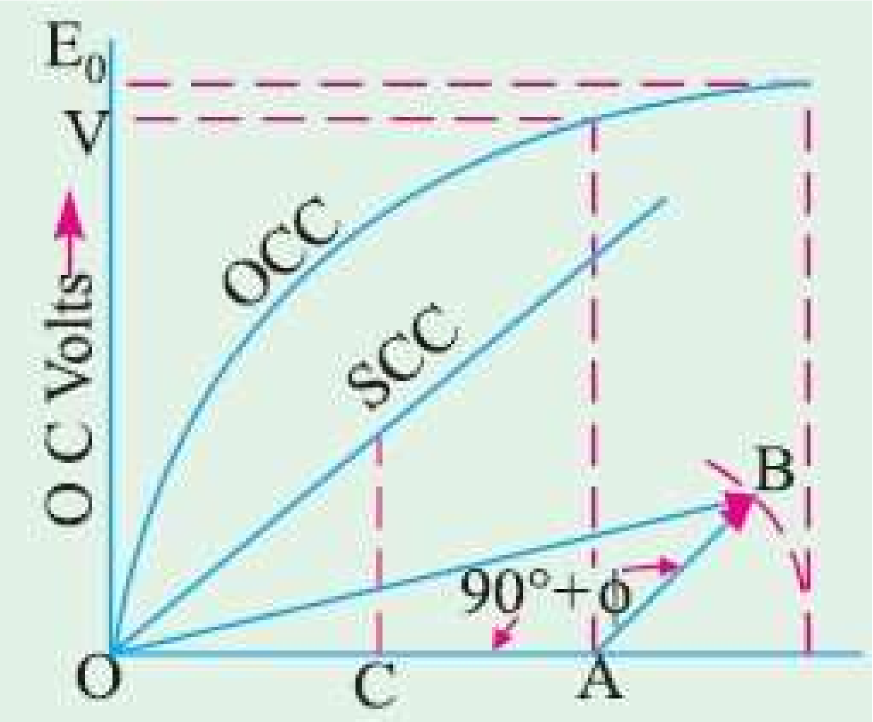
Ampere-turn method or MMF method

OA= Field current required to induce the rated terminal voltage V.
AB=OC= Field current required to overcoming the armature reaction

Vector sum of OA & AB=OB

No load voltage corresponding to OB $=E_0$

$$\%R = \frac{|E_0| - |V|}{|V|} \times 100$$



Example 37.30. *A 3.5-MVA, Y-connected alternator rated at 4160 volts at 50-Hz has the open-circuit characteristic given by the following data :*

Field Current (Amps)	*50*	*100*	*150*	*200*	*250*	*300*	*350*	*400*	*450*
E.M.F. (Volts)	*1620*	*3150*	*4160*	*4750*	*5130*	*5370*	*5550*	*5650*	*5750*

A field current of 200 A is found necessary to circulate full-load current on short-circuit of the alternator. Calculate by ***(i)*** *synchronous impedance method and* ***(ii)*** *ampere-turn method the full-load voltage regulation at 0.8 p.f. lagging. Neglect resistance. Comment on the results obtained.*

Solution. (*i*) As seen from the given data, a field current of 200 A produces O.C. voltage of 4750 (line value) and full-load current on short-circuit which is

$$= 3.5 \times 10^6 / \sqrt{3} \times 4160 = 486 \text{ A}$$

$$Z_S = \frac{\text{O.C. volt/phase}}{\text{S.C. current/phase}} = \frac{4750/\sqrt{3}}{486} = \frac{2740}{486} = 5.64\ \Omega/\text{phase}$$

Since $R_a = 0, X_S = Z_S \quad \therefore \quad IR_a = 0, IX_S = IZ_S = 486 \times 5.64 = 2740 \text{ V}$

F.L. Voltage/phase $= 4160/\sqrt{3} = 2400 \text{ V}, \cos\phi = 0.8, \sin\phi = 0.6$

$$E_0 = (V\cos\phi + IR_a)^2 + (V\sin\phi + I, X_S)^2]^{1/2}$$

$$= [(2400 \times 0.8 + 0)^2 + (2400 \times 0.6 + 2740)^2]^{1/2} = 4600 \text{ V}$$

$$\%\text{ regn. up} = \frac{4600 - 2400}{2400} \times 100 = \mathbf{92.5\%}$$

(*ii*) It is seen from the given data that for normal voltage of 4160 V, field current needed is 150 A. Field current necessary to circulate F.L. current on short-circuit is 200 A.

In Fig. 37.48, *OA* represents 150 A. The vector *AB* which represents 200 A is vectorially added to *OA* at $(90° + \phi) = (90° + 36°52') = 126°52'$. Vector *OB* represents excitation necessary to produce a terminal p.d. of 4160 *V* at 0.8 p.f. lagging at *full-load*.

$$OB = [150^2 + 200^2 + 2 \times 150 \times 200 \times \cos(180° - 126°52')]^{1/2}$$
$$= 313.8 \text{ A}$$

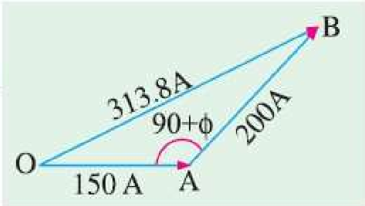


Fig. 37.48

The generated phase e.m.f. E_0, corresponding to this excitation as found from *OCC* (if drawn) is 3140 V. Line value is $3140 \times \sqrt{3} = 5440$ V.

$$\% \text{ regn.} = \frac{5440 - 4160}{4160} \times 100 = \mathbf{30.7\%}$$

The two value of regulation, found by the two methods, are found to differ widely from each other.
The first method gives somewhat higher value, while the other method gives a lower value.
However, the second value is more likely to be nearer the actual value, because the first method (EMF method) employs Z_S, *which does not have a constant value. Its value depends* on the field excitation.

MMF Method Problem

EXAMPLE 3.16. *A 3-phase, star-connected, 1000 kVA, 2000 V, 50 Hz alternator gave the following open-circuit and short-circuit test readings :*

Field current	A	10	20	25	30	40	50
O.C. voltage	V	800	1500	1760	2000	2350	2600
S.C. armature current	A		200	250	300		

The armature effective resistance per phase is 0.2 Ω.

Draw the characteristic curves and determine the full-load percentage regulation at (a) 0.8 power factor lagging, (b) 0.8 power factor leading.

SOLUTION. The O.C.C. and S.C.C. are shown in Fig. 3.22.

The phase voltage in volts are

$$\frac{800}{\sqrt{3}}, \quad \frac{1500}{\sqrt{3}}, \quad \frac{1760}{\sqrt{3}}, \quad \frac{2000}{\sqrt{3}}, \quad \frac{2350}{\sqrt{3}}, \quad \frac{2600}{\sqrt{3}};$$

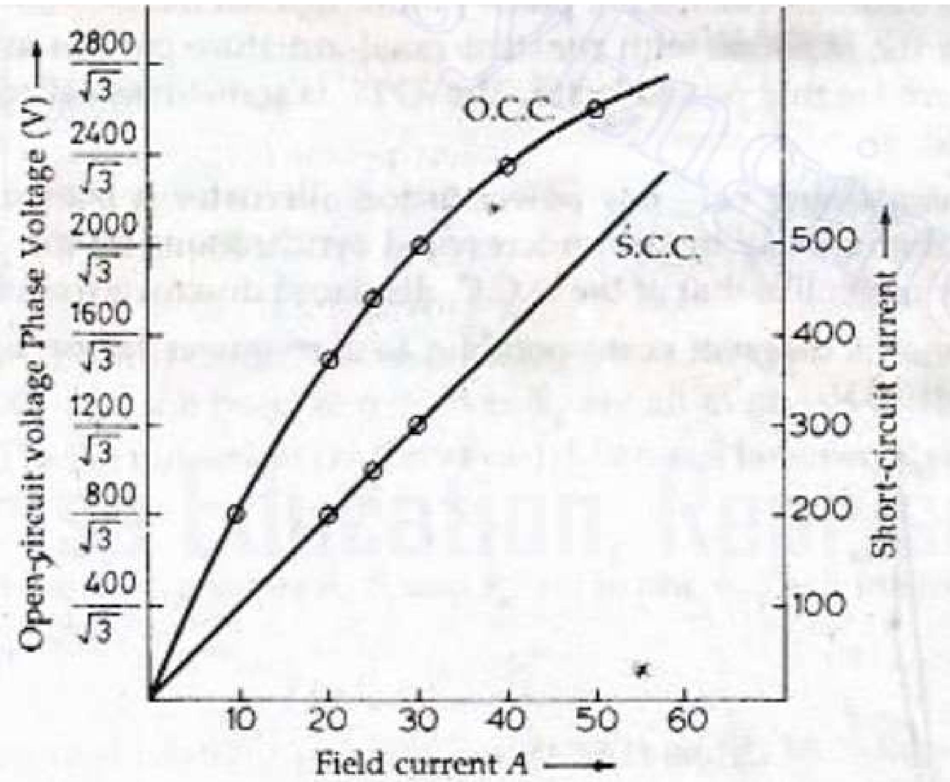
or 462, 866, 1016, 1155, 1357, 1501.

Full-load phase voltage $V_p = \frac{2000}{\sqrt{3}} = 1155 \text{ V}$

$$\text{kVA} = \frac{\sqrt{3}\, V_L I_{fl}}{1000}$$

$$1000 = \frac{\sqrt{3} \times 2000 \times I_{fl}}{1000}, \; I_{fl} = I_a = 288.7 \text{ A}$$

MMF Method Problem



MMF Method Problem

(a) Lagging power factor of 0.8

$$\mathbf{E}' = \mathbf{V}_p + \mathbf{I}_a R_a = 1155 + (288.7 \angle -\cos^{-1} 0.8) \times 0.2$$
$$= 1155 + (57.74 \times 0.8 - j\,57.74 \times 0.6)$$
$$= 1155 + 46.2 - j\,34.44$$
$$= 1201.2 - j\,34.44 = 1201.7 \angle -1.6^\circ \text{ V}$$

Here $\alpha = -1.6^\circ$

From the O.C.C., the field current required to produce the voltage of 1201.7 V is 32 A. Therefore $I'_f = 32$ A.

From the S.C.C., the field current required to produce full-load current of 288.7 is 29 A. Therefore $I_{f_2} = 29$ A. For $\cos\phi = 0.8$, $\phi = 36.87^\circ$

From the phasor diagram

$$\mathbf{I}_{f_2} = I_{f_2} \angle 180^\circ - \phi$$
$$= 29 \angle 180^\circ - 36.87^\circ = 29 \angle 143.13^\circ \text{ A}$$
$$= -23.2 + j\,17.4$$

MMF Method Problem

$$\mathbf{I'}_f = I'_f \angle 90^\circ - \alpha$$
$$= 32 \angle 90^\circ - 1.6^\circ = 32 \angle 88.4^\circ \text{ A}$$
$$= 0.89 + j\,31.98$$
$$\mathbf{I}_f = \mathbf{I}_{f_2} + \mathbf{I'}_f$$
$$= -23.2 + j\,17.4 + 0.89 + j\,31.98$$
$$= -22.31 + j\,44.38 = 54.18 \angle 114.3^\circ \text{ A}$$

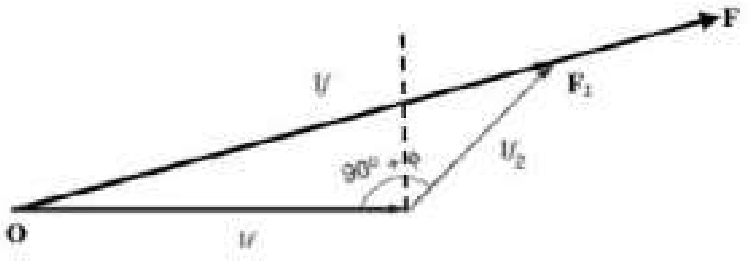
From the O.C.C., the open circuit phase voltage corresponding to the field current of 54.18 A is 1559 V.

∴ percentage voltage regulation

$$= \frac{E_{op} - V_p}{V_p} \times 100 = \frac{1559 - 1155}{1155} \times 100 = 34.97\%$$

ASA or Modified MMF method

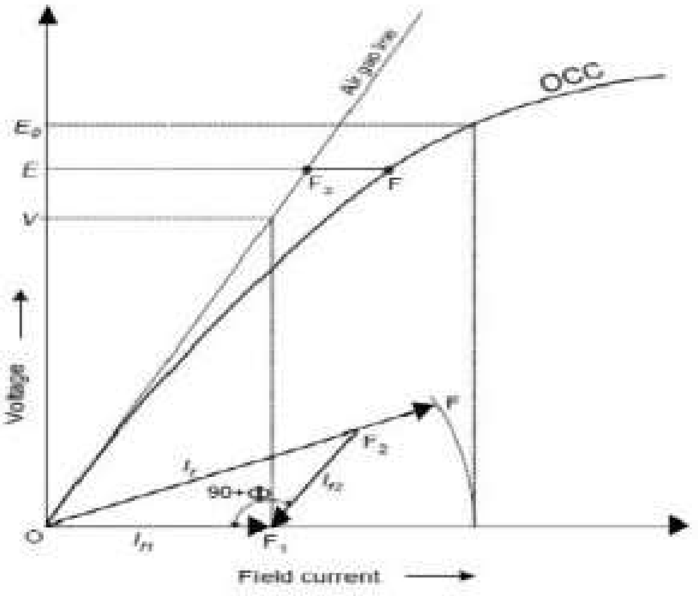
- ASA or modified mmf method consider saturation effect for calculation of regulation.
- In the mmf method the total mmf F computed is based on the assumption of unsaturated magnetic circuit which is unrealistic.
- In order to account for the partial saturation of the magnetic circuit it must be increased by a certain amount F_2F which can be computed from OCC, SCC and air gap lines as explained below referring to Fig: (i) and (ii).



(i)

ASA or Modified MMF method

- ❖ 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.
- ❖ The resultant of If1 and If2 gives If. (OF2 in figure). Extend OF2 upto 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 (V+IRa)
- ❖ Project total field current OF to the field current axis and find corresponding voltage E0 using OCC. Hence regulation can found by ASA method which is more realistic.



(ii)

ASA or Modified MMF method

1. By conducting OC and SC test plot OCC and SCC.

2. From the OCC find the field current *If1* required to produce the voltage, $E1= (V + IR_a)$.

3. From SCC find the magnitude of field current *If2* ($\approx F_a+F_{al}$) to produce the required armature current. F_a+F_{al} can also found from ZPF characteristics.

4. Draw *If2* at angle (90+Φ) from *If1*, where Φ is the phase angle of current w. r. t voltage. If current is leading, take the angle of *If2* as (90-Φ).

5. Determine the resultant field current, *If* and mark its magnitude on the field current axis.

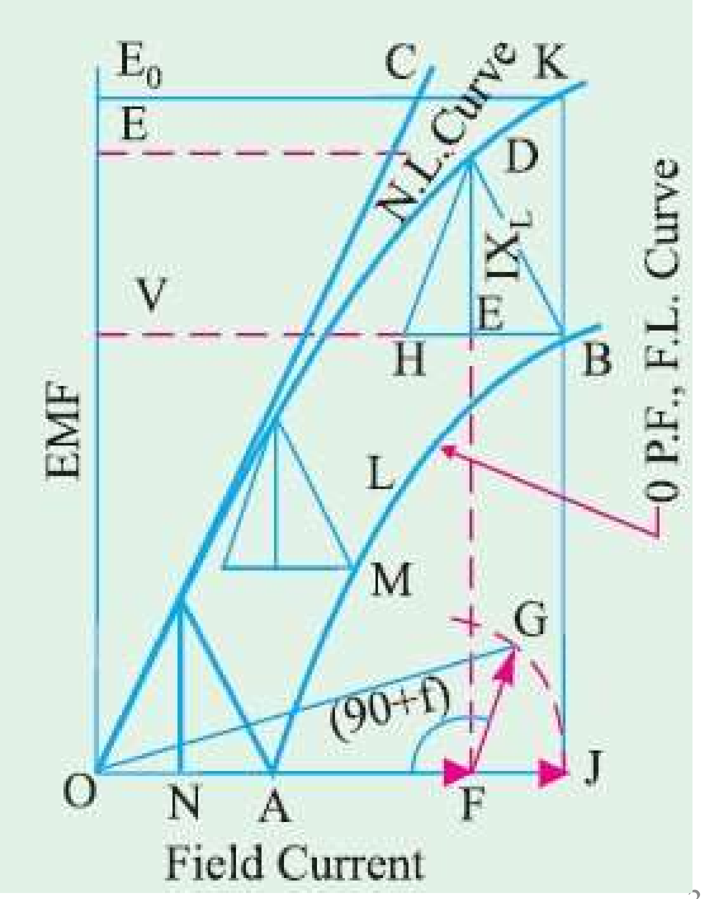
6. From OCC. find the voltage corresponding to *If*, which will be *E0* and hence find the regulation.

Zero Power Factor Method or Potier Method

- ❖ This method is based on the separation of armature-leakage reactance drop and the armature reaction effects.
- ❖ This method gives more accurate results.
- ❖ The experimental data required is
- ✓ (i) no-load curve and (ii) full-load zero power factor curve (not the short-circuit characteristic) also called wattless load characteristic. It is the curve of terminal volts against excitation when armature is delivering F.L. current at zero p.f.
- ✓ 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.
- ❖ If we vectorially add to V the drop due to resistance Ra and leakage reactance X_L, we get E.
- ❖ If to E is further added the drop due to armature reaction (assuming lagging p.f.), then we get E_0.

Zero Power Factor Method or Potier Method

- ❖ Point B was obtained when wattmeter was reading zero.
- ❖ Point A is obtained from a short-circuit test with full-load armature current.
- ❖ OA represents field current which is equal and opposite to the demagnetising armature reaction and for balancing leakage reactance drop at full-load.
- ❖ Knowing these two points, full-load zero p.f. curve AB can be drawn



Zero Power Factor Method or Potier Method

- From B, BH is drawn equal to and parallel to OA.
- From H, HD is drawn parallel to initial straight part of N-L curve i.e. parallel to OC, which is tangential to N-L curve.
- Hence, we get point D on no-load curve, which corresponds to point B on full-load zero p.f. curve.
- The triangle BHD is known as Potier triangle.
- This triangle is constant for a given armature current and hence can be transferred to give us other points like M, L etc.
- Draw DE perpendicular to BH. The length DE represents the drop in voltage due to armature leakage reactance X_L i.e. $I.X_L$.
- BE gives field current necessary to overcome demagnetising effect of armature reaction at full load
- EH field current necessary for balancing the armature leakage reactance drop DE.

Zero Power Factor Method or Potier Method

- Let V be the terminal voltage on full-load.
- If we add to it vectorially the voltage drop due to armature leakage reactance alone (neglecting Ra), then we get voltage E = DF (and not E0).
- Field excitation corresponding to E is given by OF.
- NA (= BE) represents the field current needed to overcome armature reaction.
- Hence, if we add NA vectorially to OF (as in MMF method) to reach point K, we get excitation for E_0 whose value can be read from N-L curve.
- FG (= NA) is drawn at an angle of (90° + φ) for a lagging p.f. (or it is drawn at an angle of 90° − φ for a leading p.f.).
- The voltage corresponding to this excitation is JK = E_0

$$\%R = \frac{|E_0| - |V|}{|V|} \times 100$$

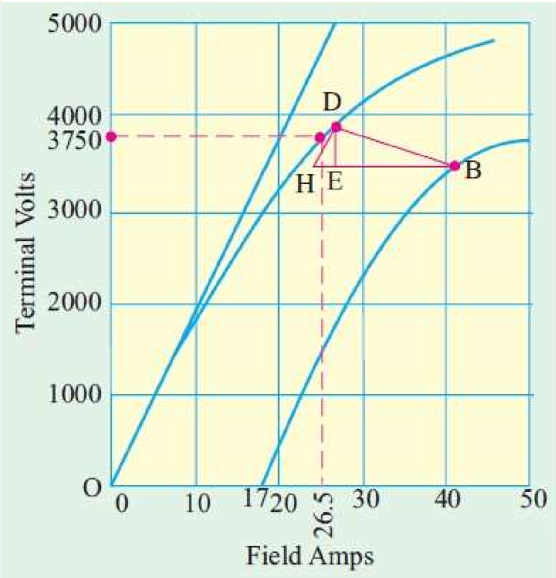
Example 37.34. *A 3-phase, 6,00-V alternator has the following O.C.C. at normal speed :*

Field amperes :	*14*	*18*	*23*	*30*	*43*
Terminal volts :	*4000*	*5000*	*6000*	*7000*	*8000*

With armature short-circuited and full-load current flowing the field current is 17 A and when the machine is supplying full-load of 2,000 kVA at zero power factor, the field current is 42.5 A and the terminal voltage is 6,000 V.

Determine the field current required when the machine is supplying the full-load at 0.8 p.f. lagging.

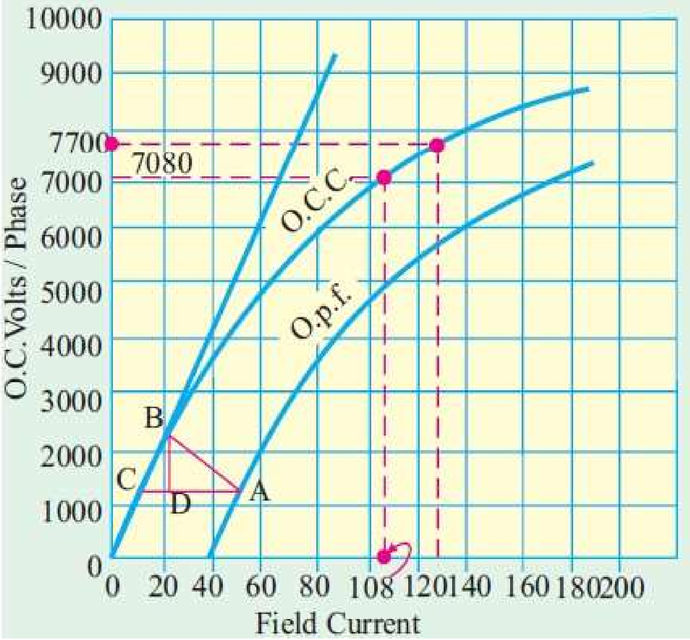
- ✓The O.C.C. is drawn with phase voltages which are 2310, 2828, 3465 4042 4620
- ✓The full-load zero p.f. characteristic can be drawn because two points are known *i.e. (17, 0) and (42.5,* 3465).
- ✓In the Potier ΔBDH, line DE represents the leakage reactance drop (= IX_L) and is (by measurement) equal to 450 V.
- ✓*E* = 3750 V
- ✓From O.C.C. it is found that field amperes required for this voltage = 26.5 A.
- ✓Field amperes required for balancing armature reaction = BE = 14.5 A (from Potier triangle BDH).



Resultant field current is $= \sqrt{26.5^2 + 14.5^2 + 2 \times 26.5 \times 14.4 \cos 53°8'} = $ **37.2 A**

An 11-kV, 1000-kVA, 3-phase, Y-connected alternator has a resistance of 2 Ω per phase. The open-circuit and full-load zero power factor characteristics are given below. Find the voltage regulation of the alternator for full load current at 0.8 p.f. lagging by all the 4 methods

Field current (A)	:	*40*	*50*	*110*	*140*	*180*
O.C.C. line voltage	:	*5,800*	*7,000*	*12,500*	*13,750*	*15,000*
Line volts zero p.f.		*0*	*1500*	*8500*	*10,500*	*12,500*



AC Machines: Synchronous Machine

Theory of salient pole machine: Blondel's two reaction theory

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Rotor Construction

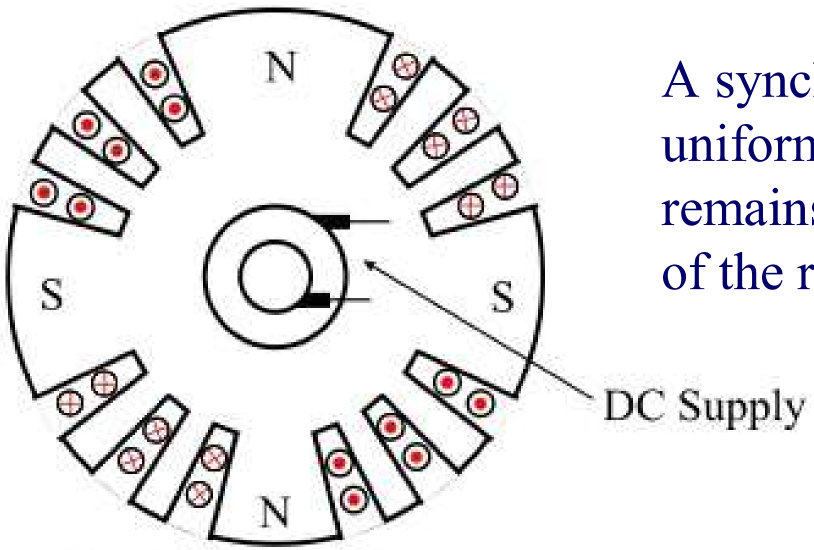


Fig. - Cylindrical Rotor

A synchronous machine with cylindrical rotor has a uniform air-gap, because of which its reactance remains the same, irrespective of the spatial position of the rotor.

A cylindrical rotor machine possesses one axis of symmetry

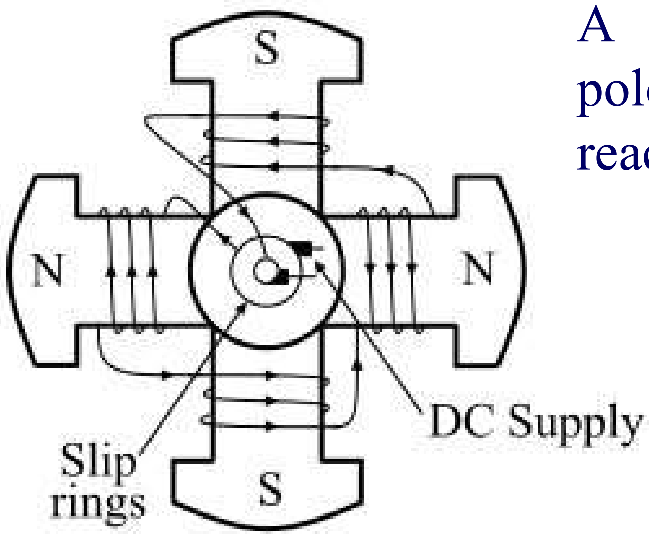


Fig. - Salient Pole Rotor

A synchronous machine with salient or projecting poles has non-uniform air-gap due to which its reactance varies with the rotor position.

Salient-pole machine possesses two axes of geometric symmetry ***(i)*** field poles axis, called direct axis or *d-axis and* ***(ii) axis passing through*** the centre of the interpolar space, called the quadrature axis or *qaxis*

Two Reaction Theory of Salient Pole Machine

- In a salient-pole rotor synchronous machine, the air-gap is highly non-uniform.
- The axis shown along the axis of the rotor is known as *direct axis or d-axis* and the axis perpendicular to the d-axis is called *quadrature axis or q-axis*.
- Small air-gaps are involved in the path of d-axis flux (φd), thus the reluctance of the path is minimum
- The q-axis flux (φq) path has large air-gaps and it is the path of maximum reluctance.

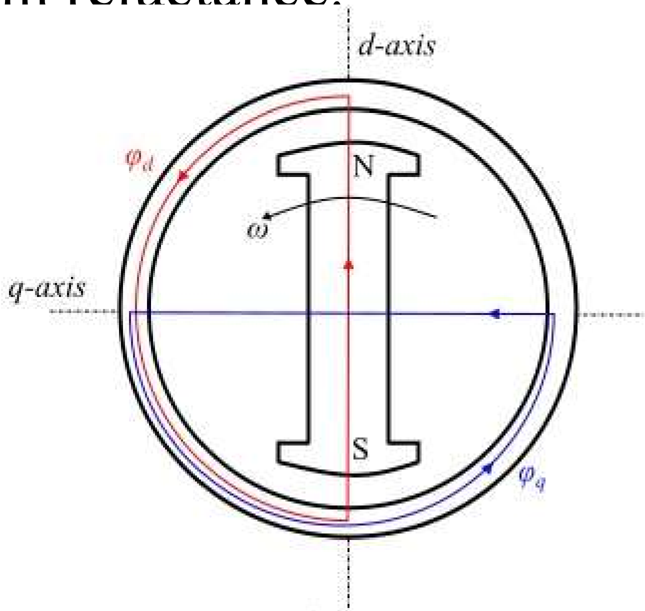


Figure-1

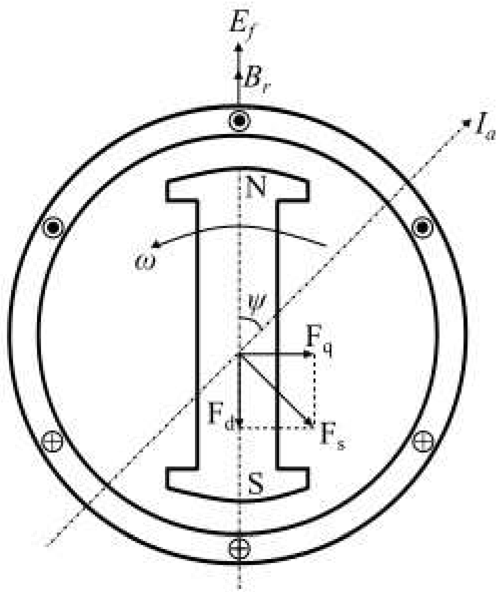


Figure-2

Two Reaction Theory of Salient Pole Machine

- Two mmfs act on the d-axis of a salient-pole synchronous machine i.e. field m.m.f. and armature m.m.f. whereas only one m.m.f., i.e. armature mmf acts on the q-axis, because field mmf has no component in the q-axis.
- The magnetic reluctance is low along the poles and high between the poles. The above facts form the basis of the two-reaction theory proposed by Blondel

  (i) armature current I_a can be resolved into two components i.e. I_d perpendicular to E and I_q along E

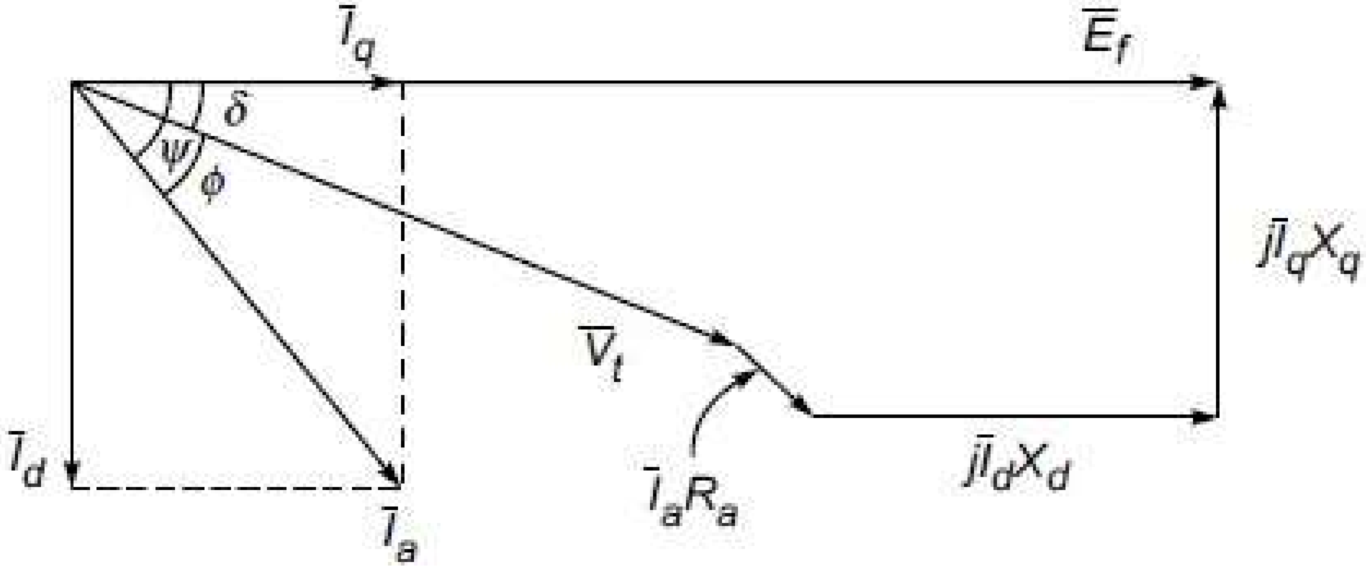
  (ii) armature reactance has two components i.e. d-axis armature reactance X_{ad} associated with I_d and q-axis armature reactance X_{aq} linked with I_q.

If we include the armature leakage reactance Xl which is the same on both axes, we get: Direct axis synchronous reactance $X_d = X_{ad} + Xl$
and Quadrature axis synchronous reactance $Xq = Xaq + Xl$

Since reluctance on the q-axis is higher, owing to the larger air-gap, hence,

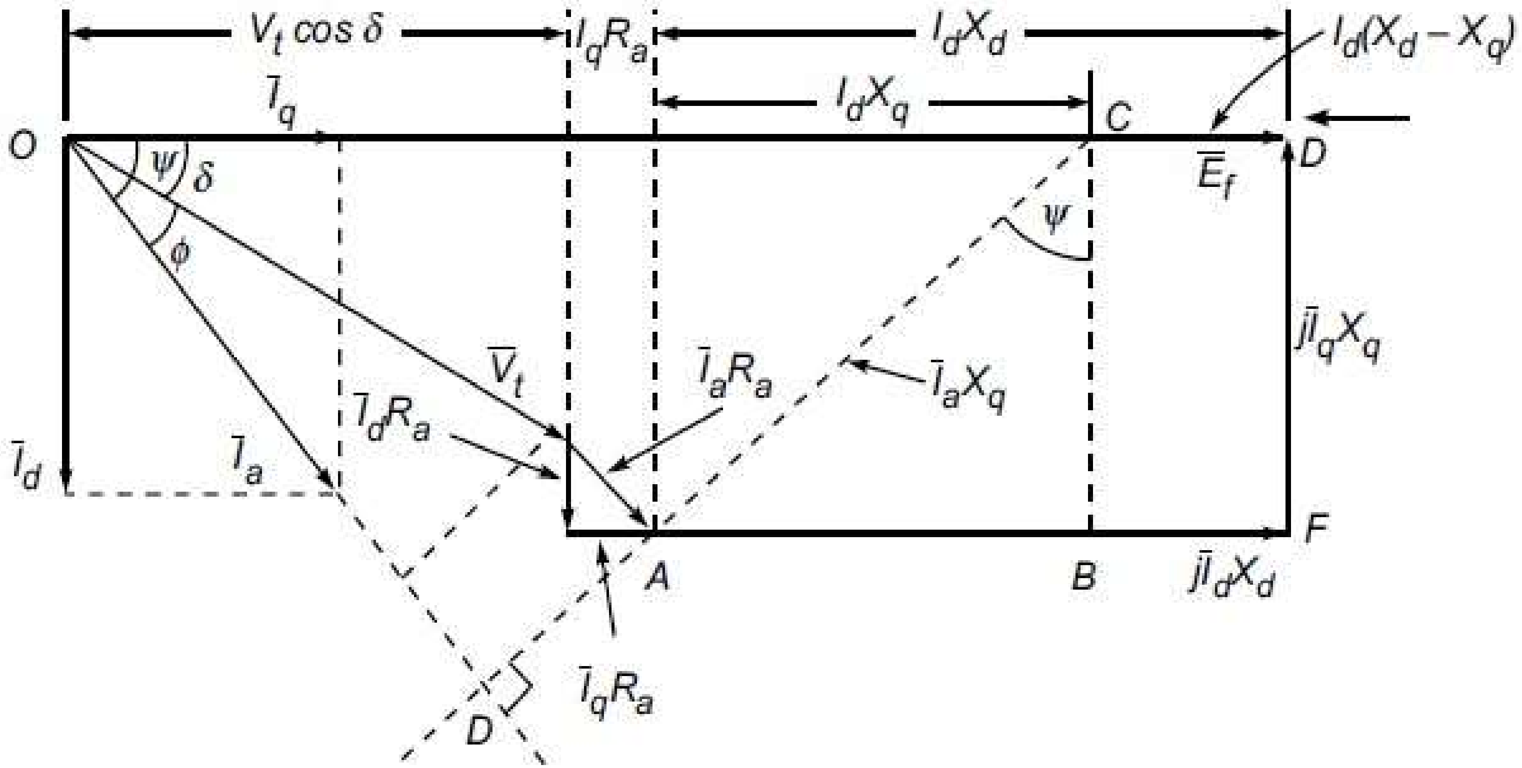
$$X_{aq} < X_{ad} \text{ or } X_q < X_d \text{ or } X_d > X_q$$

Phasor Diagram of Salient Pole Machine



- Armature current I_a is resolved into two components i.e. I_d and I_q
- Currents I_d and I_q causes voltage drops $jI_d\ X_d$ and $jI_q\ X_q$
- $jI_d\ X_d$ and $jI_q\ X_q$ leads I_d and I_q by 90^0
- Armature resistance drop Ia Ra is drawn parallel to Ia
- Vector for the drop IdXd is drawn perpendicular to Id whereas that for IqXq is drawn perpendicular to Iq. (Id = Ia sin ψ ; Iq = Ia cos ψ)
- $E0 = V + IaRa + jId\ Xd + jIq\ Xq$
- The angle $\Psi = \varphi + \delta$ is not known for a given Vt, Ia and φ.
- I_d and I_q cannot be found which are needed to draw the phasor diagram.

Calculation for Phasor Diagram



AC is drawn at 90° to the current phasor Ia and CB is drawn at 90° to Ef .

In Δ ODC: ∟OCD=90^0- ψ, ∟OCB=90^0, ∟OCB=90^0 , ∟ACB=90^0-(90^0- ψ)= ψ

Id = Ia sin ψ ; Iq = Ia cos ψ ; hence, Ia = Iq/cos ψ, IaRa cos ψ =IqRa

In Δ ABC: $\cos\psi = \frac{BC}{AC} = \frac{I_q X_q}{AC}$ $AC = \frac{I_q X_q}{\cos\psi} = I_a X_q$ $AB = I_a X_q \sin\psi = I_d X_q$

$CD = BF = I_d(X_d - X_q)$

$$E_f = V_t \cos\delta + I_q R_a + I_d X_q + I_d(X_d - X_q) = V_t \cos\delta + I_q R_a + I_d X_d$$

A synchronous generator has Xd = 0.8 pu and Xq = 0.5 pu. It is supplying full-load at rated voltage at 0.8 lagging pf. Draw the phasor diagram and calculate the excitation emf. Also calculate power angle.
Repeat the problem by ignoring Xq and assuming Xs=Xd.

$$\bar{V}_t = 1\angle 0^\circ \text{ pu}, I_a = 1 \text{ pu } 0.8 \text{ lagging},$$

$$\bar{I}_a = 1\angle -36.9^\circ \text{ pu}$$

$$\bar{E}'_f = \bar{V}_t + j\bar{I}_a X_q$$

$$= 1 + j1\angle -36.9^\circ \times 0.5 = 1 + 0.5\angle 53.1^\circ$$

$$= 1.30 + j\,0.40 = 1.30\angle 17.1^\circ \text{ pu}$$

$$\delta = 17.1^\circ$$

$$\psi = \phi + \delta = 36.9^\circ + 17.1^\circ = 54^\circ$$

$$I_d = I_a \sin\psi = 1 \times \sin 54^\circ = 0.81$$

$$CD = I_d(X_d - X_q)$$

$$= 0.81\,(0.8 - 0.5) = 0.243$$

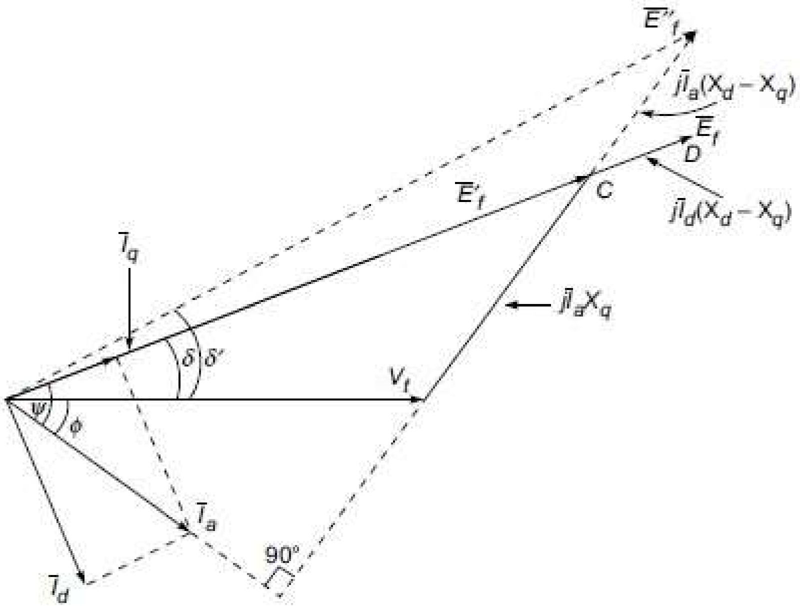
$$\bar{E}_f = \bar{E}'_f + CD = 1.36 + 0.243 = 1.60 \text{ pu}$$

$$\bar{E}''_f = \bar{V}_t + j\bar{I}_a X_d$$

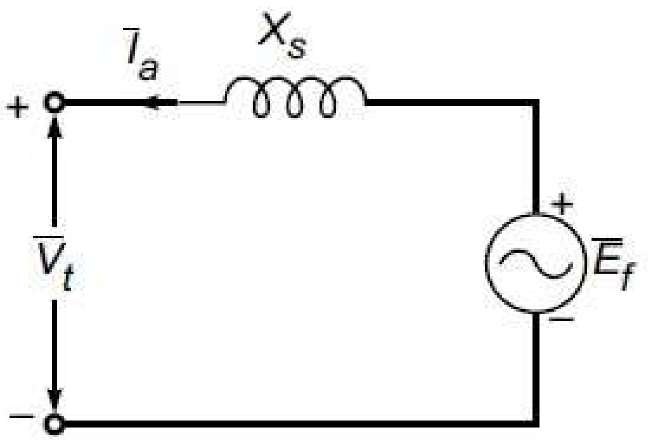
$$= 1 + j\,1\angle -36.9^\circ \times 0.8$$

$$= 1.48 + j\,0.64 = 1.61\angle 23.4^\circ$$

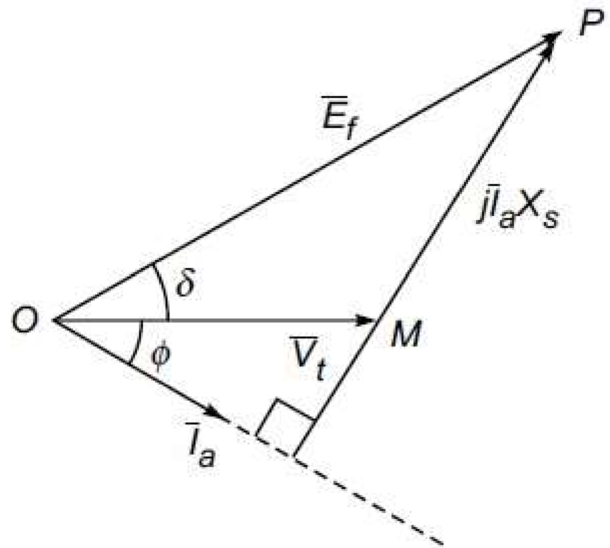
$$E''_f = 1.61 \text{ pu}, \delta' = 23.4^\circ$$



Power Angle Characteristics (P vs δ): Non-salient Pole



Generating mode $\bar{E}_f = \bar{V}_t + j\bar{I}_a X_s$



- ❖ Fig. above shows the circuit diagrams and phasor diagrams of a synchronous machine in generating mode
- ❖ The machine is connected to infinite bus-bars of voltage Vt.
- ❖ It is easily observed from the phasor diagrams that in generating mode, the excitation emf E_f leads V_t by angle δ.
- ❖ $\llcorner OMP = 180-(90-\Phi) = 90+\Phi$
- ❖ From the phasor triangle OMP: $OP/(\sin \llcorner OMP) = MP/(\sin \llcorner MOP)$

$$\frac{E_f}{\sin(90 \pm \phi)} = \frac{I_a X_s}{\sin\delta}; \quad \begin{matrix} (90^\circ + \phi), \text{ generating} \\ (90^\circ - \phi), \text{ motoring} \end{matrix}$$

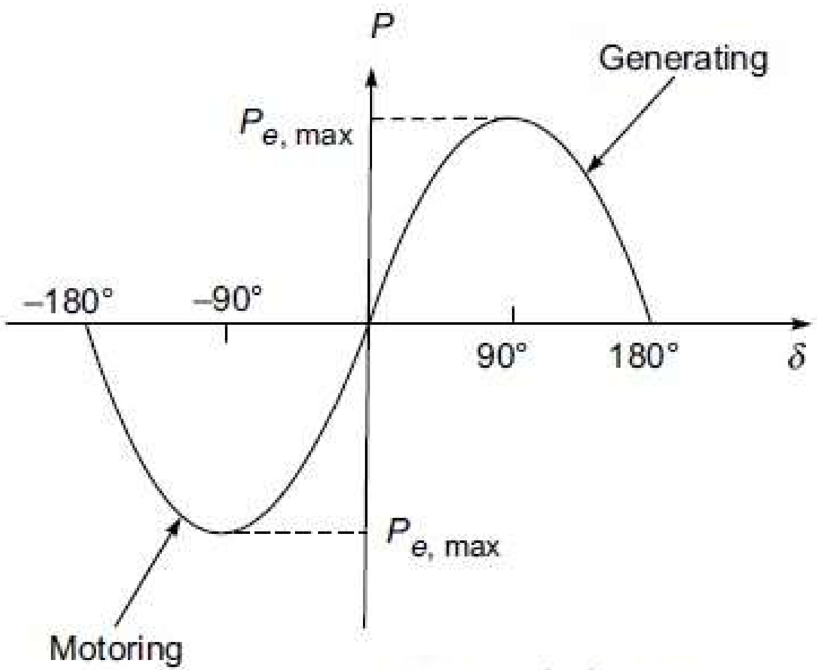
$$I_a \cos\phi = \frac{E_f}{X_s} \sin\delta$$

Power Angle Characteristics (P vs δ): Non-salient Pole

❖ Multiplying both sides by V_t :

$$V_t I_a \cos\phi = \frac{V_t E_f}{X_s} \sin\delta$$

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



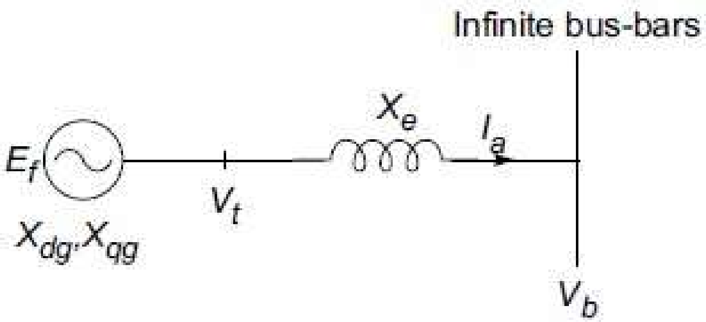
Power-angle characteristic

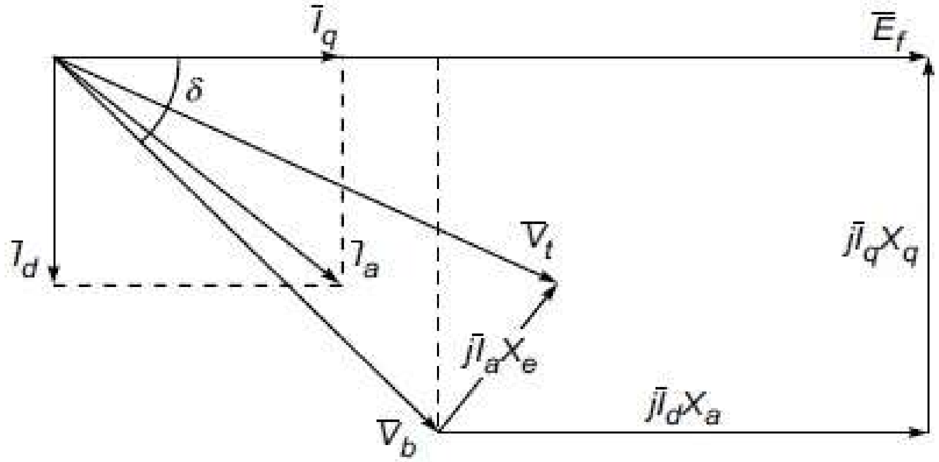
❖ $P_e = V_t I_a \cos\varphi$ = electrical power exchanged with the bus-bars

❖ δ = Angle between Ef and Vt and is called the power angle

❖ The relationship of Pe vs δ is known as the power-angle characteristic of the machine and is plotted for given V_t and E_f.

Power Angle Characteristics (P vs δ): Salient Pole





- Fig. above shows the one-line diagram of a salient pole synchronous machine connected to infinite bus bar of voltage Vb through a line of series reactance Xe.
- The total d- and q-axis reactance are: Xd = Xdg + Xe & Xq = Xqg + Xe
- From phasor diagram

$$P_e = I_d V_b \sin\delta + I_q V_b \cos\delta$$

$$I_d = \frac{E_f - V_b \cos\delta}{X_d}$$

$$I_q = \frac{V_b \sin\delta}{X_q}$$

Power Angle Characteristics (P vs δ): Salient Pole

$$P_e = \frac{E_f V_b}{X_d}\sin\delta + \underbrace{V_b^2 \frac{X_d - X_q}{2X_d X_q}\sin 2\delta}_{\text{Reluctance power}}$$

✓The second term in above Eq. is known as the reluctance power.

✓The reluctance power varies as sin 2 δ with a maximum value at δ = 45° .

✓This term is independent of field excitation and would be present even if the field is unexcited