Determination of Synchronous Reactance from Open Circuit and Short Circut Tests

i- Open Circuit Test: The machine is run on no load and the induced e.m.f. per phase is measured corresponding to various values of field current and a curve between induced e.m.f. per phase, $\mathbf{E_0}$ and field current, I_f is drawn which is known as open circuit characteristic (O.C.C.) and has been illustrated in Fig 5.

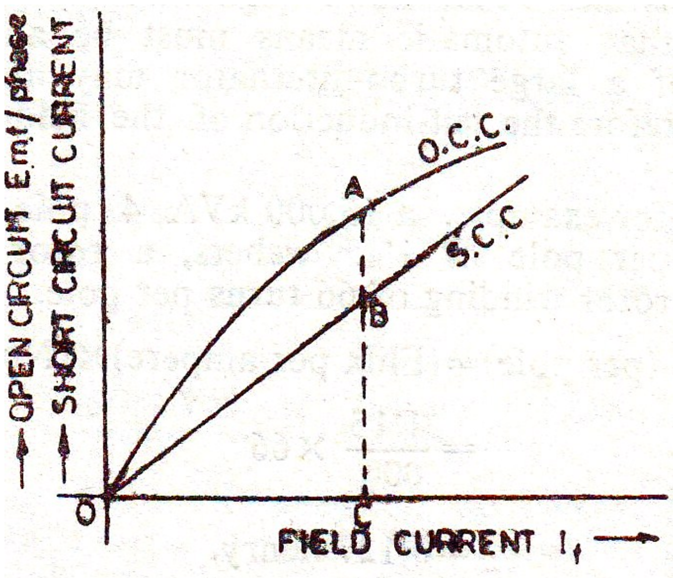

Fig 5 Open Circuit Characteristic

ii- Short Circuit Test: The armature winding is short-circuited through a low resistance ammeter. The speed is kept constant during this test and short-circuit current is measured corresponding to various values of field current. The field current or excitation is increased to give short-circuit current about twice the full load current. The short circuit characteristic (S.C.C.) is drawn by plotting a curve between short circuit current I_{sc} as ordinate and field current, I_f as abscissa, as shown in Fig. 5.

Consider **OC** the normal field current, then **BC** gives short circuit current, I_{sc} corresponding to this value of field current on the S.C.C. and **AB** gives the induced e.m.f. per phase on the O.C.C. for the same excitation. Since on short circuit for field current **OC**,the whole of the induced e.m.f. **AC** is utilized to create a short circuit current, I_{sc} given by **BC**.

Hence synchronous Impedance,

$$\mathbf{Z_s} = \mathbf{AC} \text{ (in volts) / } \mathbf{BC} \text{ (in amperes)}$$

And synchronous reactance,

$$\mathbf{X_s = \sqrt{(Z_s^2 - R_a^2)}}$$

Where $\mathbf{R_a}$ is the effective armature resistance per phase which can be measured directly by volt-meter and ammeter method or by using the wheat-stone bridge.
For normal working conditions the armature resistance measured so is increased by 60% or so. This is being done to allow for skin effect and thus effective armature resistance $\mathbf{R_a}$ is obtained.

Measurement of X_d and X_q

The d-axis synchronous reactance is determined from O.C. and S.C. tests, the q-axis synchronous reactance can be measured by many methods, one of these methods is the slip test method.

Slip test method:

From this test, the value of $\mathbf{X_d}$ and $\mathbf{X_q}$ can be determined. The synchronous machine is driven by a separate prime-mover (or motor) at a speed slightly different from synchronous speed. The field windings are left open and positive sequence balanced voltages of reduced magnitude (around 25% of rated value) and of rated frequency are impressed across the armature terminals. Under these conditions, the relative velocity between the field poles and the rotating armature m.m f. waves is equal to the difference between synchronous speed and the rotor speed,i.e. the slip speed. A small A.C.voltage across the open field winding indicates that the field poles and rotating m.m.f. wave, are revolving in the same direction,and this is what is required in slip test. if field poles revolve in a direction opposite to the rotating m.m.f. wave, negative sequence reactance would be measured.
At one instant, when the peak of armature m.m.f. wave is in line with the field pole or direct axis,the reluctance offered by the small air gap is minimum as shown in fig. 6 (a). At this instant the impressed terminal voltage per phase divided by the corresponding armature current per phase, gives d-axis synchronous reactance $\mathbf{X_d}$.
After one-quarter of slip cycle, the peak of armature m.m.f. wave acts on the interpolar or q-axis of the magnetic circuit, Fig. 6 (b). and the reluctance offered by long air-gap is maximum. At this instant, the ratio of armature terminal voltage per phase to the corresponding armature current per phase, gives q-axis synchronous reac[t]ance $\mathbf{X_q}$. Oscillograms of armature current, terminal voltage and the e.m.f. induced in the open-circuited field winding are shown in Fig.7. A much larger slip than would be used in practice, has been shown in Fig.7, merely for the sake of clarity.

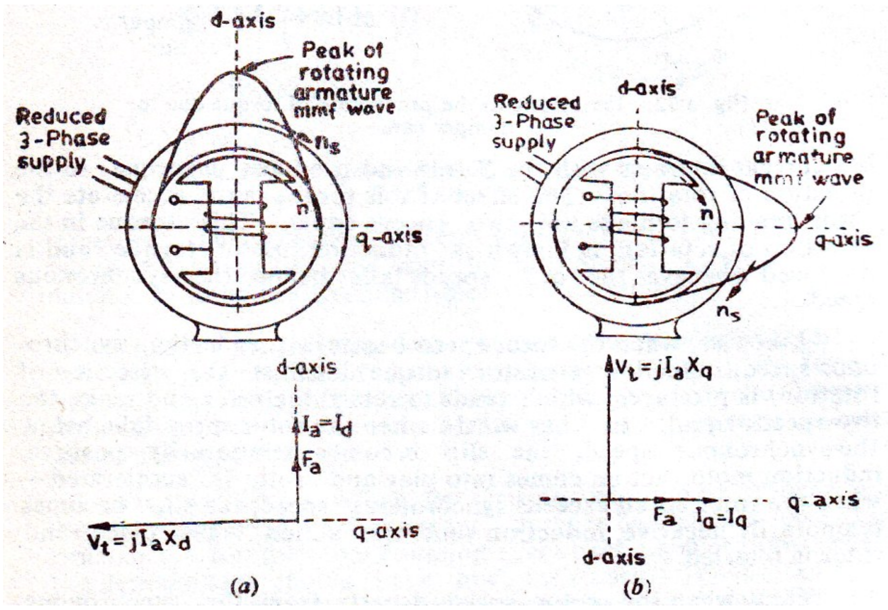

Fig. 6 pertaining to the physical concepts of (a) X_d , (b) X_q

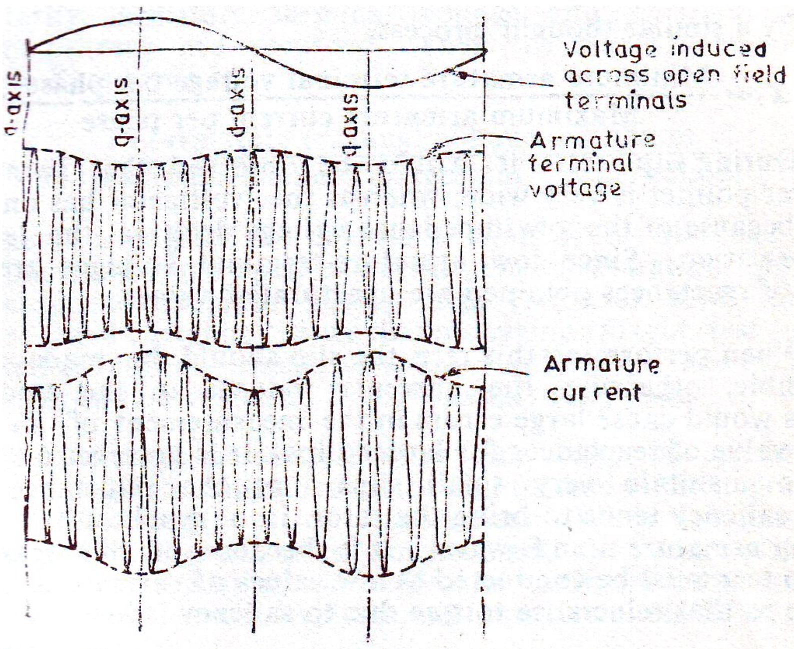

Fig. 7 Typical oscillograms in slip test

When the armature m.m.f. wave is along the direct axis, the armature flux passing through open field winding is maximum, therefore, the induced field e.m.f., i.e. $d\phi_a/dt$ is zero. The d-axis can, therefore, be located on the oscillogram of Fig.7 where the induced field e.m.f. is zero. When armature m.m.f. wave is along q-axis, the armature flux linking the field winding is zero, therefore, the induced field e.m.f. $d\phi_a/dt$ is maximum. Thus the q-axis can also be located on the oscillogram. If oscillograms can't be taken, then an ammeter and a voltmeter are used as shown in the connection diagram of Fig.8. The prime-mover (or d.c. motor) speed is adjusted till ammeter and voltmeter pointers swing slowly between maximum and minimum positions. Under this condition, maximum and minimum readings of both ammeter and voltmeter are recorded in order to determined $\mathbf{X_d}$ and $\mathbf{X_q}$.

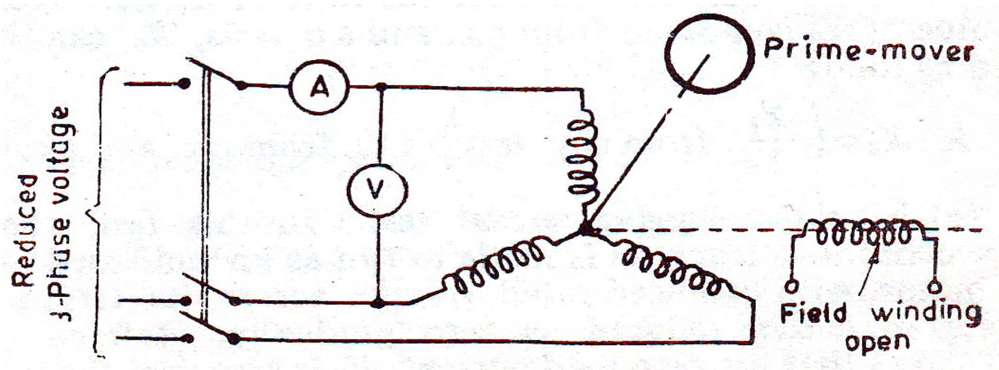

Fig 8 Slip-test connection diagram for obtaining X_d and X_q

Since the applied voltage is constant, the air-gap flux would be constant. When crest of the rotating m.m.f. wave is in line with the field-pole axis, Fig. 6 (a), minimum air-gap offers minimum reluctance, consequently the armature current, required for the establishment of constant air-gap flux, must be minimum. Constant applied voltage minus the minimum impedance voltage drop (armature current being minimum) in the leads and 3-phase variac gives maximum armature-terminal voltage. Thus the d-axis, synchronous reactance is given by

$\mathbf{X_d}$ = (Max. armature terminal voltage per phase) / (Min. armature current per phase)

By a similar thought process

$\mathbf{X_q}$ = (Min. armature terminal voltage per phase) / (Max. armature current per phase)

During slip test, it would be observed that swing of the ammeter pointer is very wide, whereas the voltmeter has only small swing because of the low impedance voltage drop in the leads and 3-phase variac. Since low armature-terminal voltages are used, values of reactances obtained are unsaturated values.

When performing this test, the slip should be made as small as possible, otherwise the currents induced in the amortisseur circuits would cause large errors in the measurement of $\mathbf{X_d}$ and $\mathbf{X_q}$ (lower value of reactances for larger slips). It is however quite difficult to maintain very small slips, as the reluctance torque due to saliency tends to bring the rotor into synchronism with the rotating armature m.m.f. wave. It is because of this reason that the slip test must be conducted at low values of armature terminal voltage so that reluctance torque due to saliency is low.

The advantages of oscillographic method over voltmeter-ammeter methods are

i- elimination of the inertia effects of voltmeter and ammeter

ii- the possibility of large slip-speed, which in turn allows higher armature-terminal voltages to be applied.

In practice, there may be error in reading the oscillograms. At the same time. voltmeter ammeter readings are not very reliable because of their inertia effect. In view of these shortcomings, slip test is conducted only to determine the ratio of $\mathbf{X_d / X_q}$.

Now, using the value of $\mathbf{X_d}$ computed from o.c. and s.c. tests, $\mathbf{X_q}$ can be determined as follow :

$\mathbf{X_q} = \mathbf{X_d / X_q}$ (from slip test) * $\mathbf{X_d}$ (from O.C. and S.C. tests)

Ex1: A Three-phase Star-Connected Salient pole Synchronous Generator is driven at a Speed Slightly less the Synchronous Speed with open Circuited field Winding. its Stator is Supplied from a balanced three-phase Supply. A Voltmeter Connected across the line gave minimum and maximum reading of 2810 and 2830 Volt. The line Current varies between 365 and 280 Ampere. find the direct and quadrature axis Synchronous reactances per phase. Neglect armature resistance.

Sol/

Maximum Voltage = 2830 V
Minimum Voltage = 2810 V
Maximum Current = 365 A
Minimum Current = 280 A

$$\text{Direct-axis Synchronous reactance} = \frac{\text{Maximum Voltage / phase}}{\text{Minimum Current}}$$

$$X_d = \frac{2830}{\sqrt{3} * 280} = 5.83 \ \Omega/ph$$

$$\text{Quadrature-axis Synchronous reactance} = \frac{\text{Minimum Voltage / phase}}{\text{Maximum Current}}$$

$$X_q = \frac{2810}{\sqrt{3} * 365} = 4.44 \ \Omega/ph$$

Ex2: A Three-phase, 3300 V, 50 Hz, Star-Connected alternator has an effective resistance of 0.5 Ω/phase. A field Current of 30 A produces full-load Current of 180 A on Short-Circuit and a line e.m.f. of 1000 V on open-Circuit. Determine:

1- The Synchronous Reactance of alternator per phase
2- The developed power due to field excitation if Power angle = 11.17°

Sol/ 1-

Synchronous impedance per phase, $Z_s = \frac{\text{O.C. phase Voltage}}{\text{S.C. phase Current}}$ for I_f

$$Z_s = \frac{1000/\sqrt{3}}{180} = 3.21 \ \Omega/ph$$

Synchronous reactance per phase, $X_s = \sqrt{Z_s^2 - R_a^2}$

$$X_s = \sqrt{3.21^2 - 0.5^2} = 3.17 \ \Omega/ph$$

2- Open Circuit Voltage per phase $= \sqrt{(V\cos\theta + I_a R_a)^2 + (V\sin\theta + I_a X_a)^2}$

$$E = \sqrt{(1905*0.8 + 180*0.5)^2 + (1905*0.6 + 180*3.17)^2}$$

$$E = 2354 \ V$$

Power developed of alternator $= \frac{3EV}{X_s} \sin\delta$

$$P_d = \frac{3*2354*1905}{3.17} * \sin 11.17$$

$$P_d = 822128 \ \text{Watt}$$

Ex3: A 2000 KVA, 2200 V, 60 Hz, Star-Connected, has a resistance of 0.25 Ω/ph. An excitation current of 80 A produces a short Circuit Current equal the full load Value, the Same excitation Current produces an e.m.f. of 800 V on open-Circuit. Determine the Synchronous reactance per phase and the developed power due to field excitation at rated Current and 0.8 P.f lagging loading Condition with Power Angle of 45° ?

Sol/ Synchronous impedance, $Z_s = \frac{\text{O.C. phase Voltage}}{\text{S.C. phase Current}}$ for I_f (5)

$$Z_s = \frac{800/\sqrt{3}}{80} = 5.78\ \Omega/ph$$

Synchronous reactance, $X_s = \sqrt{Z_s^2 - Ra^2}$

$$X_s = \sqrt{5.78^2 - 0.25^2} = 5.77\ \Omega/ph$$

$$\text{Rated Current} = \frac{2000\ K}{\sqrt{3} * 2200} = 524.8\ A$$

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

$$= \sqrt{(1270*0.8 + 524.8*0.25)^2 + (1270*0.6 + 524.8*5.77)^2}$$

$$E = 3960\ V$$

$$P_d = \frac{3EV}{X_s}\sin\delta = \frac{3*3960*1270}{5.77} * \sin 45$$

$$P_d = 1848968\ \text{Watt}$$