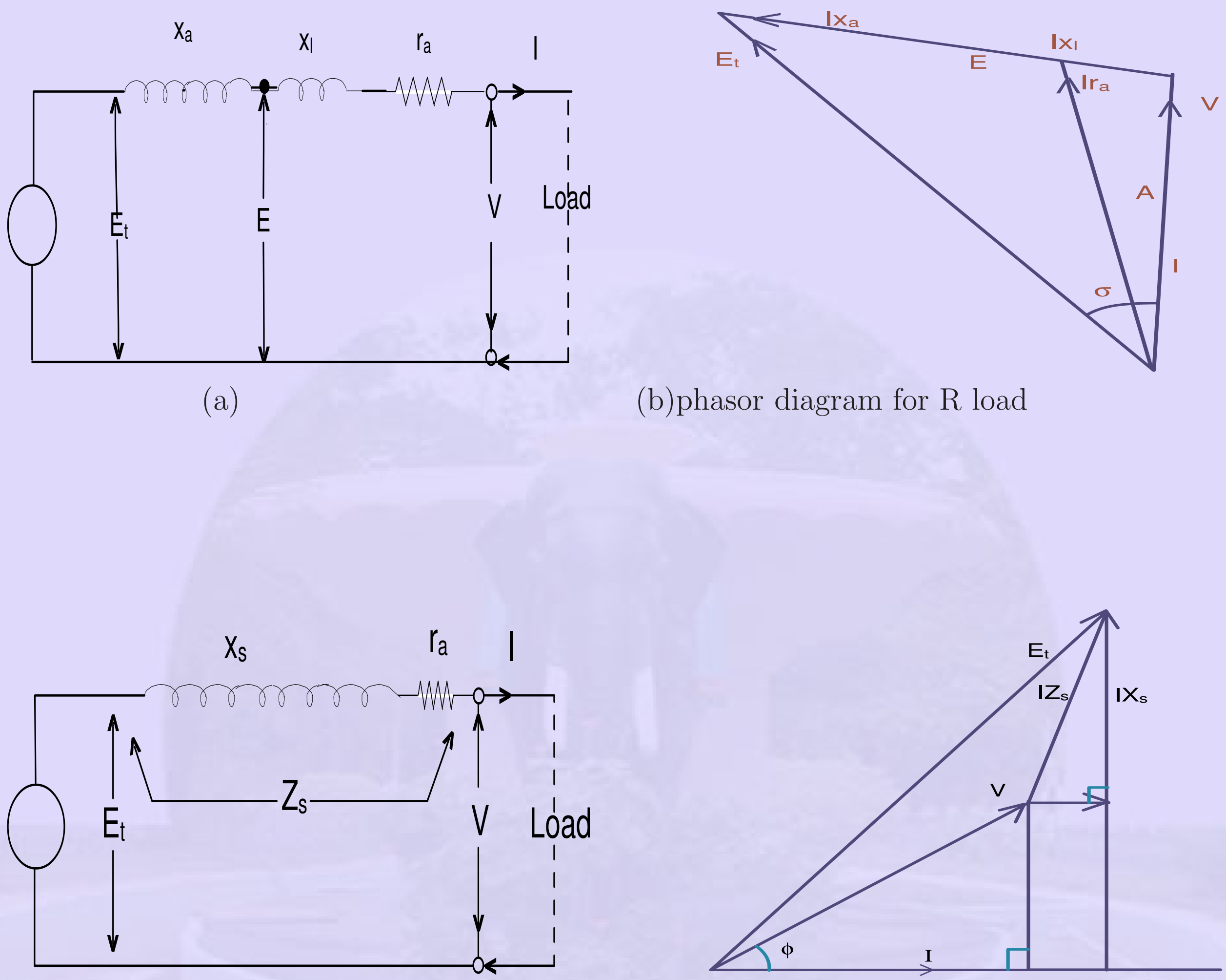
3 Synchronous Generator Operation

3.1 Cylindrical Rotor Machine



(a) (b)phasor diagram for R load

(c) (d)phasor diagram for R-L load

Figure 30: Equivalent circuits

The synchronous generator, under the assumption of constant synchronous reactance, may be considered as representable by an equivalent circuit comprising an ideal winding in which an e.m.f. E_t proportional to the field excitation is developed, the winding being connected to the terminals of the machine through a resistance r_a and reactance

$(X_l + X_a) = X_s$ all per phase. This is shown in Fig. 30. The principal characteristics of the synchronous generator will be obtained qualitatively from this circuit.

3.1.1 Generator Load Characteristics

Consider a synchronous generator driven at constant speed and with constant excitation. On open circuit the terminal voltage V is the same as the open circuit **e.m.f.** E_t. Suppose a unity-power-factor load be connected to the machine. The flow of load current produces a voltage drop IZ_s in the synchronous impedance, and terminal voltage V is reduced. Fig. 31 shows the complexor diagram for three types of load. It will be seen that the angle σ between E_t and V increases with load, indicating a shift of the flux across the pole faces due to cross- magnetization. The terminal voltage is obtained from the complex summation

$$V + Z_s = E_t$$
$$or\ V = E_t - IZ_s \tag{24}$$

Algebraically this can be written

$$V = \sqrt{(E_t^2 - I^2X_s^2)} - I_r \tag{25}$$

for non-reactive loads. Since normally r is small compared with X_s

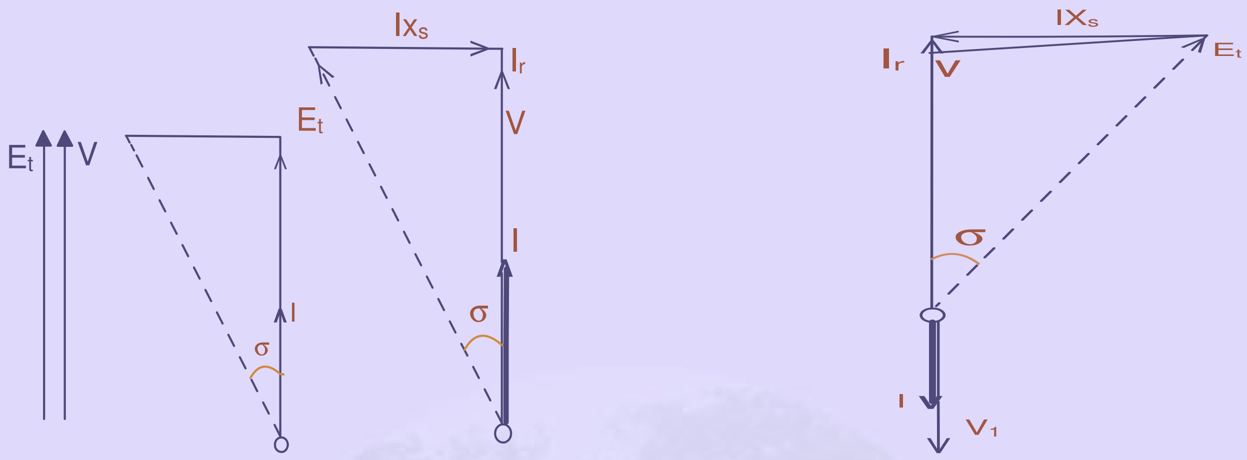
$$V^2 + I^2X_s^2 \approx E_t^2 = constant \tag{26}$$

so that the V/I curve, Fig. 32, is nearly an ellipse with semi-axes E_t and I_{sc}. The current I_{sc} is that which flows when the load resistance is reduced to zero. The voltage V falls to zero also and the machine is on short-circuit with V = 0 and

$$I = I_{sc} = E_t/Z_s \approx E_t/X_s \tag{27}$$

For a lagging load of zero power-factor, diagram is given in Fig. 31 The voltage is given as before and since the resistance in normal machines is small compared with the synchronous reactance, the voltage is given approximately by

$$V \approx E_t - IX_s \tag{28}$$



(a)phasor diagram for different R loads (b)

(c) (d)

Figure 31: Variation of voltage with load at constant Excitation

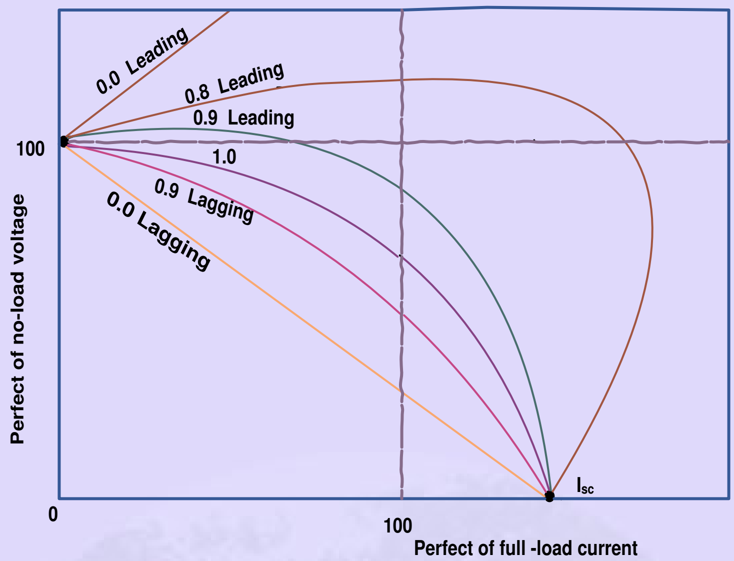


Figure 32: Generator Load characteristics

which is the straight line marked for $\cos\phi = 0$ lagging in Fig. 32. A leading load of zero power factor Fig. 31. will have the voltage

$$V \approx E_t + IX_s \tag{29}$$

another straight line for which, by reason of the direct magnetizing effect of leading currents, the voltage increases with load.

Intermediate load power factors produce voltage/current characteristics resembling those in Fig. 32. The voltage-drop with load (i.e. the regulation) is clearly dependent upon the power factor of the load. The short-circuit current I_{sc} at which the load terminal voltage falls to zero may be about 150 per cent (1.5 per unit) of normal current in large modern machines.

3.1.2 Generator Voltage-Regulation

The voltage-regulation of a synchronous generator is the voltage rise at the terminals when a given load is thrown off, the excitation and speed remaining constant. The voltage-rise is clearly the numerical difference between E_t and V, where V is the terminal voltage for a given load and E_t is the open-circuit voltage for the same field excitation. Expressed as a fraction, the regulation is

$$\varepsilon = (E_t - V)/V \ perunit \tag{30}$$

Comparing the voltages on full load (1.0 per unit normal current) in Fig. 32, it will be seen that much depends on the power factor of the load. For unity and lagging power factors there is always a voltage drop with increase of load, but for a certain leading power factor the full-load regulation is zero, i.e. the terminal voltage is the same for both full and no-load conditions. At lower leading power factors the voltage rises with increase of load, and the regulation is negative. From Fig. 30, the regulation for a load current I at power factor $\cos\phi$ is obtained from the equality

$$E_t^2 = (V\cos\phi + Ir)^2 + (V\sin\phi + IX_s)^2 \tag{31}$$

from which the regulation is calculated, when both E_t and V are known or found.

3.1.3 Generator excitation for constant voltage

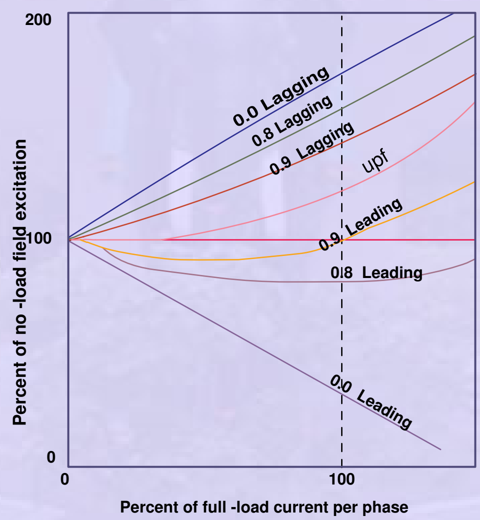


Figure 33: Generator Excitation for constant Voltage

Since the e.m.f. E_t is proportional to the excitation when the synchronous reactance is constant, the Eqn. 31 can be applied directly to obtain the excitation necessary to maintain constant output voltage for all loads. All unity-and lagging power-factor loads will require an increase of excitation with increase of load current, as a corollary of Fig. 32.

Low-leading-power-factor loads, on the other hand, will require the excitation to be reduced on account of the direct magnetizing effect of the zero- power-factor component. Fig. 33 shows typical e.m.f./current curves for a constant output voltage. The ordinates of Fig. 33 are marked in percentage of no-load field excitation, to which the e.m.f E_t exactly corresponds when saturation is neglected.

3.1.4 Generator input and output

For any load conditions as represented by Fig. 30, the output per phase is $P = VI\cos\phi$. The electrical power converted from mechanical power input is per phase

$$P_1 = E_t I\cos(\phi + \sigma) \tag{32}$$

Resolving E_t along I

$$P_1 = E_t I\cos(\phi + \sigma) = (V\cos\phi + Ir).I = VI\cos\phi + I^2R \tag{33}$$

The electrical input is thus the output plus the I^2R loss, as might be expected. The prime mover must naturally supply also the friction, windage and core losses, which do not appear in the phasor diagram.

In large machines the resistance is small compared with the synchronous reactance so that $\theta = arc\tan(x_s/r) \approx 90^\circ$, it can be shown that

$$\frac{V}{\sin(90 - \overline{\theta + \sigma})^2} = \frac{Z_s}{\sin\sigma} \tag{34}$$

and hence,

$$P = P_1 = E_t I\cos(\phi + \sigma) \approx (E_t/X_s).V\sin\sigma \tag{35}$$

Thus the power developed by a synchronous machine with given values of E_t V and Z_s is proportional to $sin\sigma$: or, for small angles, to σ, and the displacement angle σ representing the change in relative position between the rotor and resultant pole- axes is proportional to the load power. The term load-, power- or torque-angle may be applied to σ.

An obvious deduction from the above Eqn. 35is that the greater the field excitation (corresponding to E_t) the greater is the output per unit angle σ: that is, the more stable will be the operation.

3.2 Salient Pole Rotor Machine

As discussed earlier in Sec. 3.1 the behaviour of a synchronous machine on load can be determined by the use of synchronous reactance x_s which is nothing but the sum of x_a and x_l , where x_a is a fictitious reactance representing the effect of armature reaction while x_l is the leakage reactance. It was also mentioned that this method of representing the effect of armature reaction by a fictitious reactance x_a was applicable more aptly only for a cylindrical rotor (non-salient pole) machine. This was so as the procedure followed therein was valid only when both the armature and main field m.m.f.'s act upon the same magnetic circuit and saturation effects are absent.

3.2.1 Theory of Salient-pole machines (Blondel's Two-reaction Theory)

It was shown in Sec. **??** that the effect of armature reaction in the case of a salient pole synchronous machine can be taken as two components - one acting along the direct axis (coinciding with the main field pole axis) and the other acting along the quadrature axis (inter-polar region or magnetic neutral axis) - and as such the mmf components of armature-reaction in a salient-pole machine cannot be considered as acting on the same magnetic circuit. Hence the effect of the armature reaction cannot be taken into account by considering only the synchronous reactance, in the case of a salient pole synchronous machine.

In fact, the direct-axis component F_{ad} acts over a magnetic circuit identical with that of the main field system and produces a comparable effect while the quadrature-axis component F_{aq} acts along the interpolar space, resulting in an altogether smaller effect and, in addition, a flux distribution totally different from that of F_{ad} or the main field m.m.f. This explains why the application of cylindrical-rotor theory to salient-pole machines for predicting the performance gives results not conforming to the performance obtained from an actual test.

Blondel's two-reaction theory considers the effects of the quadrature and direct-axis components of the armature reaction separately. Neglecting saturation, their different effects are considered by assigning to each an appropriate value of armature-reaction "reactance," respectively x_{ad} and x_{aq} . The effects of armature resistance and true leakage reactance (x_l) may be treated separately, or may be added to the armature reaction coefficients on the assumption that they are the same, for either the direct-axis or quadrature-axis components of the armature current (which is almost true). Thus the combined reactance values can be expressed as :

$$x_{sd} = x_{ad} + x_l \text{ and } x_{sq} = x_{aq} + x_l \tag{36}$$

for the direct- and cross-reaction axes respectively. These values can be determined experimentally as described in Sec. 3.2.3

In a salient-pole machine, x_{aq}, the cross- or quadrature-axis reactance is smaller than x_{ad}, the direct-axis reactance, since the flux produced by a given current component in that axis is smaller as the reluctance of the magnetic path consists mostly of the interpolar spaces.

It is essential to clearly note the difference between the quadrature- and direct-axis components I_{aq}, and I_{ad} of the armature current I_a, and the reactive and active components I_{aa} and I_{ar}. Although both pairs are represented by phasors in phase quadrature, the former are related to the induced emf E_t while the latter are referred to the terminal voltage V. These phasors are clearly indicated with reference to the phasor diagram of a (salient pole) synchronous generator supplying a lagging power factor (pf) load, shown in Fig. **??**(a). We have

$$I_{aq} = I_a \cos(\delta + \phi); I_{ad} = I_a \sin(\delta + \phi); \text{and } I_a = \sqrt{(I_{aq}^2 + I_{ad}^2)} \tag{37}$$

$$I_{aa} = I_a \cos(\phi);\ I_{ar} = I_a \sin(\phi);\ \text{and } I_a = \sqrt{(I_{aa}^2 + I_{ar}^2)} \tag{38}$$

where σ = torque or power angle and ϕ = the p.f. angle of the load.

The phasor diagram Fig. 34 shows the two reactance voltage components $I_{aq} * x_{sq}$ and $I_{ad} * x_{sd}$ which are in quadrature with their respective components of the armature current. The resistance drop $\mathbf{I}_a * R_a$ is added in phase with I_a although we could take it as $I_{aq} * R_a$ and $I_{ad} * R_a$ separately, which is unnecessary as

$$\mathbf{I}_a = \mathbf{I}_{ad} + j\mathbf{I}_{aq}$$

Actually it is not possible to straight-away draw this phasor diagram as the power angle σ is unknown until the two reactance voltage components $I_{aq} * x_{sq}$ and $I_{ad} * x_{sd}$ are known. However this difficulty can be easily overcome by following the simple geometrical construction shown in Fig. 34(d), assuming that the values for terminal voltage V, the load power factor (pf) angle ϕ and the two synchronous reactances x_{sd} and x_{sq} are known to us.

The resistance drop $I_a * R_a$ (length AB) is added to the tip of the voltage phasor (OA) in phase with the current phasor (i.e. in a direction parallel to OQ). Then we draw line BC (of length equal to $I_a * x_{sq}$) and extend it to D such that BD will be (of length equal to $I_a * x_{sd}$) at the extremity B of $I_a * R_a$ and at right-angles to I_a . Draw OC and extend it (to F). From D draw the perpendicular DF on OC extended. Then OF represents the induced voltage E_t. The proof for this can be given as follows:. If DF is extended to G such that this line is perpendicular to BG drawn parallel to OF, we have :

$$BG = BD * \cos(90 - (\sigma + \phi)) = I_a * x_{sd} * \sin(\sigma + \phi) = I_{ad} * x_{sd} \text{ and} \quad (39)$$

$$GF = CH = BC * \sin(90 - (\sigma + \phi)) = I_a * x_{sq} * \cos(\sigma + \phi) = I_{aq} * x_{sq} \quad (40)$$

3.2.2 Power relations in a Salient Pole Synchronous Machine:

Neglecting the armature winding resistance, the power output of the generator is given by:

$$P = V * I_a * \cos\phi \quad (41)$$

This can be expressed in terms of σ, by noting from Fig. 34 that :

$$\begin{aligned} I_a * \cos\phi &= I_{aq} * \cos\sigma + I_{ad} * \sin\sigma \quad (42) \\ V * \cos\sigma &= E_o - I_{ad} * x_{sd} \\ \text{and } V * \sin\sigma &= I_{aq} * x_{sd} \end{aligned}$$

Substituting these in the expression for power, we have.

$$\begin{aligned} P &= V[(V * \sin\sigma / x_{sd}) * \cos\sigma + (E_o - V * \cos\sigma)/x_{sd} * \sin\sigma] \quad (43) \\ &= (V * E_o/x_{sd}) * \sin\sigma + V^2 * (x_{sd} - x_{sq})/(2 * x_{sq} * x_{sq}) * \sin 2\sigma \end{aligned}$$

It is clear from the above expression that the power is a little more than that for a cylindrical rotor synchronous machine, as the first term alone represents the power for a cylindrical rotor synchronous machine. A term in $(\sin 2\sigma)$ is added into the power - angle characteristic of a non-salient pole synchronous machine. This also shows that it is possible to generate an emf even if the excitation E_0 is zero. However this magnitude is quite less compared with that obtained with a finite E_0. Likewise we can show that the machine develops a torque - called the reluctance torque - as this torque is developed due to the variation of the reluctance in the magnetic circuit even if the excitation E_0 is zero.

3.2.3 Experimental Determination of x_d and x_q

The unsaturated values of x_d and x_q of a 3-Phase synchronous machine can be easily determined experimentally by conducting the following test known as slip test. The rotor of

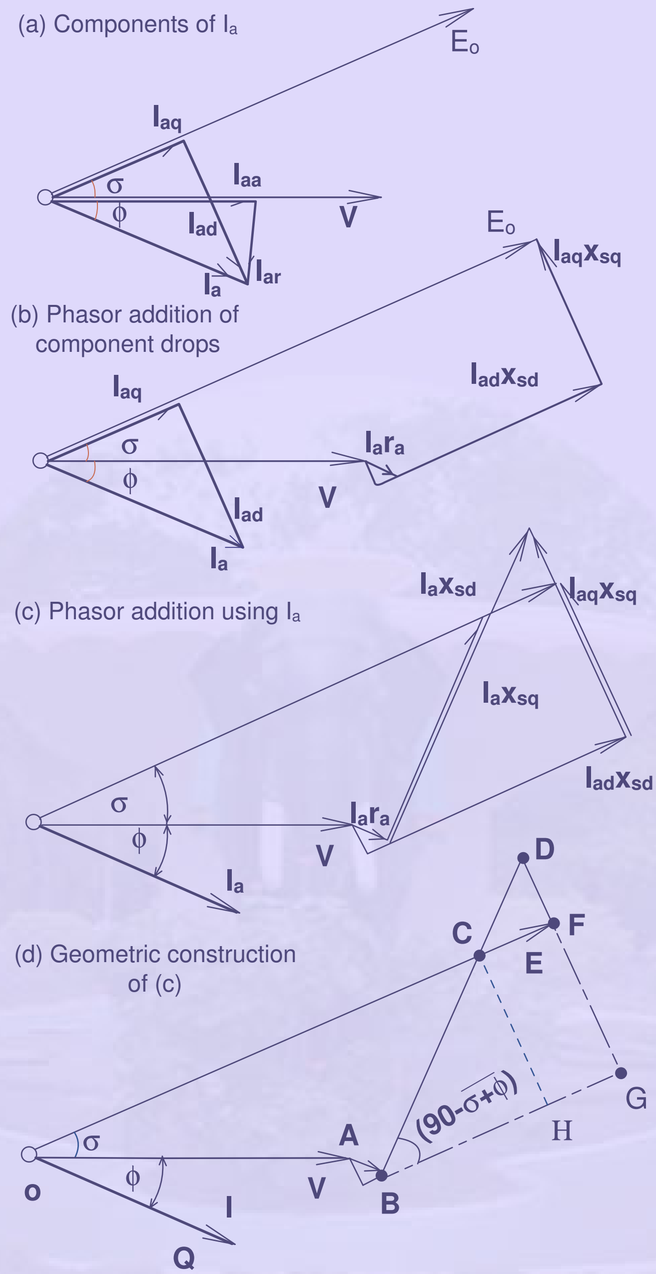


Figure 34: Phasor diagram of a generator-Two reaction theory

the synchronous machine is driven by means of a prime mover (usually a DC motor in the laboratory) at a speed close to the synchronous speed in the proper direction but not equal to it. The armature is supplied with a low voltage 3-Phase balanced supply through a variac, while the field circuit is kept open. The armature current varies between two limits since it moves through, since the synchronously rotating armature mmf acts through the varying magnetic reluctance paths as it goes from inter-polar axis to pole axis region. The values of x_{sd} and x_{sq} are determined based on the applied voltage and the armature current values. The ratio of applied voltage to the minimum value of the armature current gives the direct axis synchronous reactance x_{sd} which is usually the same as the synchronous reactance x_s that we usually determine from normal no-load and short-circuit tests as explained in Sec. **??** The ratio of applied voltage to the maximum value of the armature current gives the the quadrature-axis reactance x_{sq}. For more accurate determination of these values the oscillogram of the armature current and voltage can be recorded.

3.3 Losses and Efficiency

To calculate the efficiency of a synchronous generator, a procedure is to be followed for establishing the total losses when operating under load. For generators these losses are,

1. Rotational losses such as friction and windage.
2. Eddy current and hysteresis losses in the magnetic circuit
3. Copper losses in the armature winding and in the field coils
4. Load loss due to armature leakage flux causing eddy current and hysteresis losses in the armature-surrounding iron.

With regard to the losses, the following comments may be made,

1. The rotational losses, which include friction and windage losses, are constant, since the speed of a synchronous generator is constant. It may be determined from a no-load test.
2. The core loss includes eddy current and hysteresis losses as a result of normal flux density changes. It can be determined by measuring the power input to an auxiliary motor used to drive the generator at no load, with and without the field excited. The difference in power measured constitutes this loss.

3. The armature and field copper losses are obtained as $I_a^2 R_a$ and $V_f I_f$ Since per phase quantities are dealt with, the armature copper loss for the generator must be multiplied by the number of phases. The field winding loss is as a result of the excitation current flowing through the resistance of the field winding.

4. Load loss or stray losses result from eddy currents in the armature conductors and increased core losses due to distorted magnetic fields. Although it is possible to separate this loss by tests, in calculating the efficiency, it may be accounted for by taking the effective armature resistance rather than the dc resistance.

After all the foregoing losses have been determined, the efficiency η is calculated as,

$$\eta = \frac{kVA * PF}{kVA * PF + (total\ losses)} * 100\% \quad (44)$$

where η = efficiency,

kvA = load on the generator (output)

PF = power factor of the load

The quantity (kVA*PF) is, of course, the real power delivered to the load (in kW) by the synchronous generator. Thus, it could in general be stated as

$$\eta = \frac{P_{out}}{P_{in}} * 100 = \frac{P_{out}}{P_{out} + P_{losses}} * 100 \quad (45)$$

The input power $P_{in} = P_{out} + P_{losses}$ is the power required from the prime mover to drive the loaded generator.