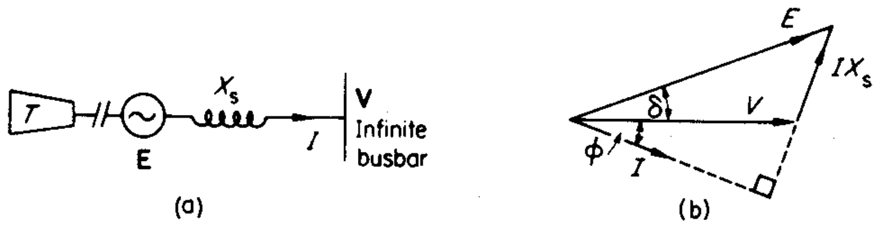
The Operation of a Generator on Infinite Busbars

In order to simplify the ideas as much as possible the resistance of the generator will be neglected; in practice this assumption is usually reasonable. Figure 1 (a) shows the schematic diagram of a machine connected to an infinite busbar along with the corresponding phasor diagram.



(a) **Synchronous machine connected to an infinite busbar. (b) Corresponding phasor diagram.**

Figure 1.

If losses are neglected the power output from the turbine is equal to the power output from the generator. The angle δ between the E and V phasors is known as the load angle is dependent on the power input from the turbine shaft. With an isolated machine supplying its own load the latter dictates the power required and hence the load angle; when connected to an infinite-busbar system, however, the load delivered by the machine is no longer directly dependent on the connected load. By changing the turbine output and hence δ the generator can be made to take on any load the operator desires, subject to economic and technical limits.

From the phasor diagram in Figure 1 (b), the power delivered to the infinite busbar $= VI\cos\phi$ per phase but,

$$\frac{E}{\sin(90+\phi)} = \frac{IX_s}{\sin\delta}$$

hence

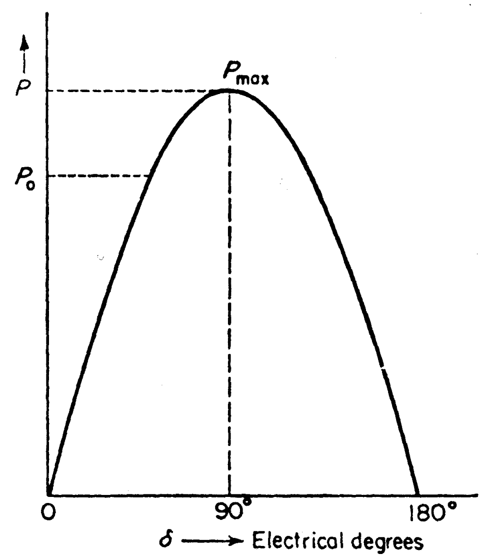
$$I\cos\phi = \frac{E}{X_s}\sin\delta$$

$$\therefore \text{ power delivered } = \frac{VE}{X_s}\sin\delta$$

(1.1)

This expression is of extreme importance as it governs to a large extent the operation of a power system.

Equation 1.1 is shown plotted in Figure 2. The maximum power is obtained at $\delta = 90^o$. If δ becomes larger than 90^o due to an attempt to obtain more than P_{max}, increase in δ results in less power output and the machine becomes unstable and loses synchronism. Loss of synchronism results in the interchange of current surges between the generator and network as the poles of the machine pull into synchronism and then out again.

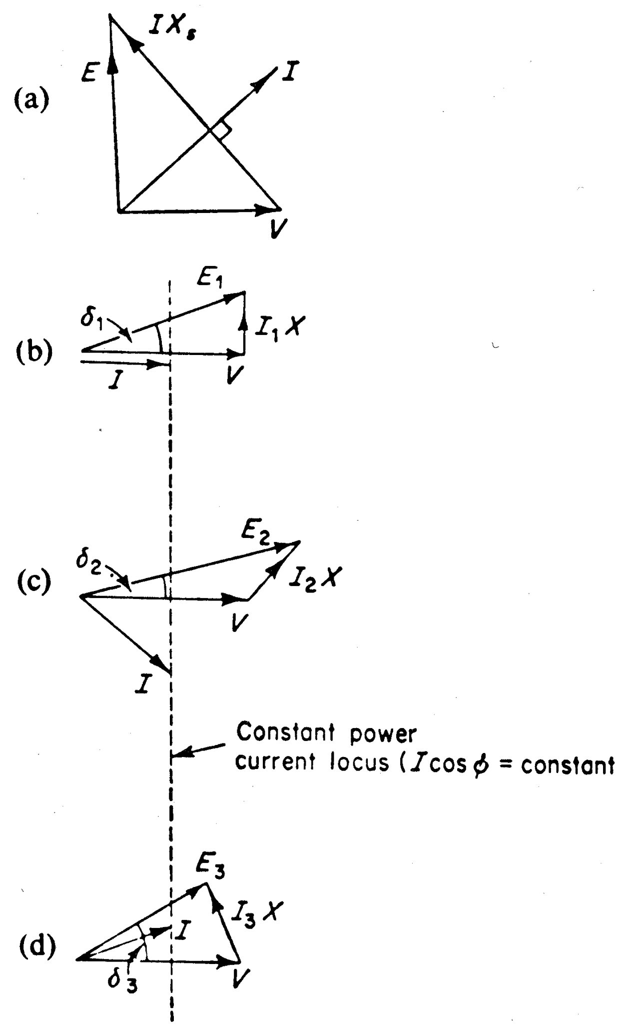


Power-angle curve of a synchronous machine. Resistance and saliency neglected.

Figure 2.

If the power output of the generator is increased by small increments with the no-load voltage kept constant, the limited of stability occurs at $\delta = 90^o$ and is known as the *steady-state stability limit.* There is another limit of stability due to a sudden large change in conditions such as caused by a fault, known as the *transient stability limit,* and it is possible for the rotor to oscillate beyond 90^o a number of times. If these oscillations diminish, the machine is stable. The load angle δ has a physical significance; it is the angle between like radial marks on the end of the rotor shaft of the machine and on an imaginary rotor representing the system. The marks are in identical physical positions when the machine is on no-load. The synchronizing power coefficient = $dP/d\delta$ watts per radian and the synchronizing torque coefficient = $(1/_{ws})/(dP/d\delta)$.

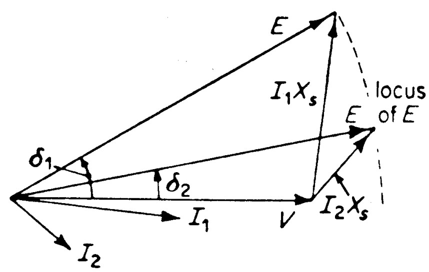
In figure 3(a) the phasor diagram for the limiting steady-state condition is shown. It should be noted that in this condition current is always leading. The following figures, 3(b), (c) and (d), show the phasor diagrams for various operational conditions.



(a) Phasor diagram for generator at limit of steady-state state stability. (c) and (d) Phasor diagrams for generator delivering constant power to the infinite busbar system but with different excitations. As V is constant the in-phase component of I must be constant. As $EV/X \sin\delta$ is constant as E changes, δ must change and $\delta_3 > \delta_1 > \delta_2$.

Figure 3.

Another interesting operating condition is variable power and constant excitation. This is shown in Figure 4. In this case as V and E are constant when the power from the turbine is increased δ must increase and the power factor changes.



Operation at variable power and constant excitation.

Figure 4.

It is convenient to summarize the above types of an operation in a single diagram or chart which will enable an operator to see immediately whether the machine is operating within the limits of stability and rating.

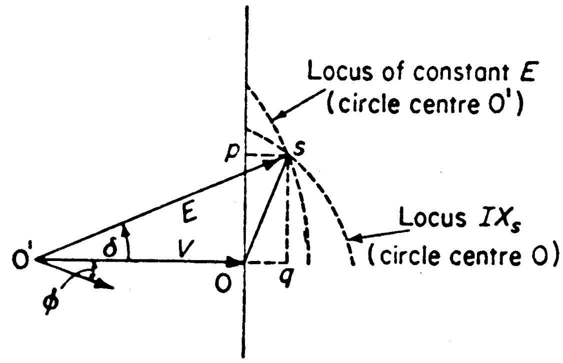
The performance chart of a synchronous generator

Consider figure 5(a), the phasor diagram for a round-rotor machine ignoring resistance. The locus of constant IX_s,I, and hence MVA is a circle and the locus of constant E a circle. Hence,

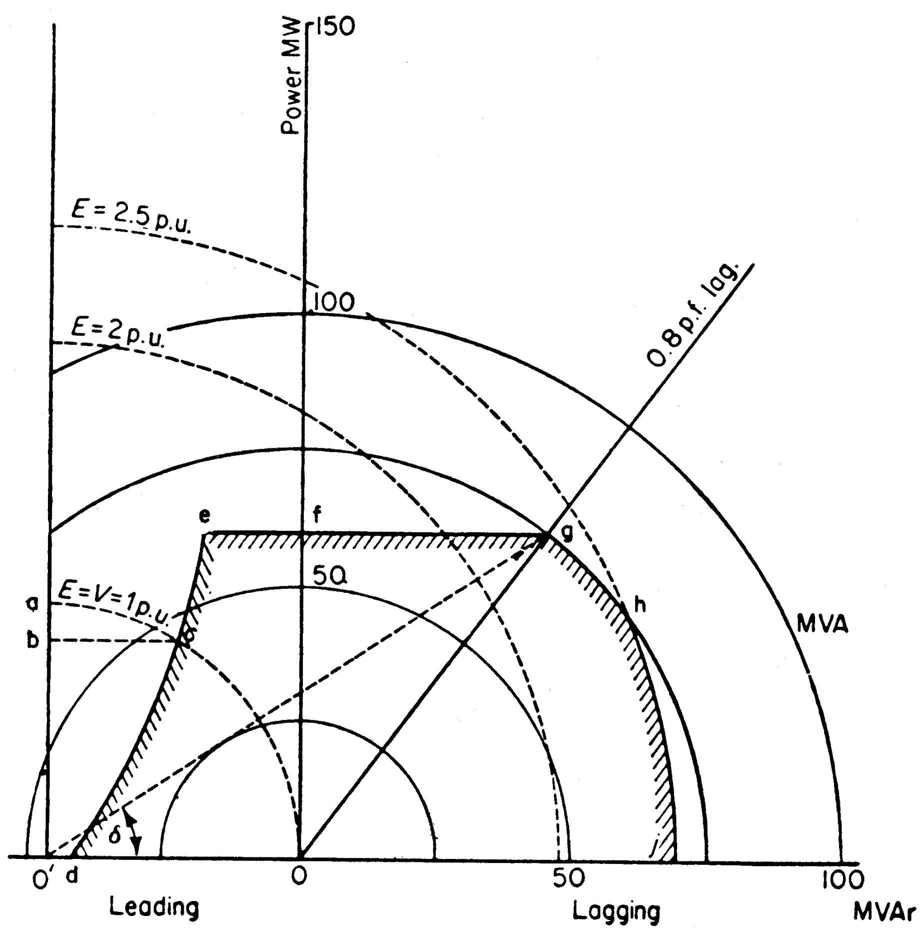
0s is proportional to VI or MVA
ps is proportional to VI sin ϕ or MVAr
sq is proportional to VI cos ϕ or MW

To obtain the scaling factor for MVA, MVAr and MW the fact that at zero excitation, E = 0 and IX_s = V, is used, from which I is V/X_s at 90^o leading to 00', corresponding to VAr/phase.

Figure 5(b) represents the construction of a chart for a 60 MW machine.



(a)



(b)

Performance chart of a synchronous generator.

Figure 5

Machine data 60 MW, 0.8 pf, 75 MVA
11.8 kV, SCR 0.63, 3000 rev/min
Maximum exciter current 500 A

$$X_s = \frac{1}{0.63} pu = 2.94\Omega / phase$$

The chart will refer to complete three-phase values of MW and MAVr. When the excitation and hence *E* are reduced to zero, the current leads *V* by 90^o and is equal to (V/X_s), ie 11,800/√3 x 2.94. The leading vars correspond to this = 11,800^2/2.94 = 47 MVAr.

With centre 0 a number of semicircles are drawn of radii equal to various MVA loadings, the most important being the 75 MVA circle. Arcs with 0' as centre are drawn with various multiples of 00' (or *V*) as radii to give the loci for constant excitation. Lines may also be drawn from 0 corresponding to various power factors, but for clarity only 0.8 pf lagging is shown.

The operational limits are fixed as follows. The rated turbine output gives a 60 MW limit which is drawn as shown, ie line efg, which meets the 75 MVA line in g. The MVA arc governs the thermal loading of the machine, ie the stator temperature rise, so that over portion gh the output is decided by the MVA rating. At point h the rotor heating becomes more decisive and the arc hj is decided by the maximum excitation current allowable, in this case assumed to be 2.5 p.u. The remaining limit is that governed by loss of synchronism at leading power factors. The theoretical limit is the line perpendicular to 00''at 0''(ie $\delta = 90^o$), but in practice a safety margin is introduced to allow a further increase in load of either 10 or 20 per cent before instability.

In Figure 5 a 10 per cent margin is used and is represented by ecd: it is constructed in the following manner. Considering point 'a' on the theoretical limit on the *E* = 1 p.u. arc, the power 0'a is reduced by 10 per cent of the rated power (ie by 6MW) to 0'b; the operating point must, however, still be on the same *E* arc and b is projected to c which is a point on the new limiting curve. This is repeated for several excitations giving finnaly the curve ecd.

The complete operating limit is shown shaded and the operator should normally work within the area bounded by this line.

As an example of the use of the chart, the full-load operating point g (60 MW, 0.8 p.f.lagging) will require an excitation *E* of 2.3 p.u. and the measured load angle δ is 33^o. This can be checked by using, power = VE/X_s sin δ, ie

$$60x10^6 = \frac{11{,}800^2\, x2.3}{2.94`}\sin\delta$$

from which

$$\delta = 33.4^o$$