J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

SYNCHRONOUS GENERATORS

Synchronous generators have long been used for converting mechanical to electrical energy in ac power systems. The great majority of these generators are three-phase machines operating at 50 Hz or 60 Hz. In some other applications, other frequencies are also used, such as 400 Hz in aerospace and marine electric power applications. For other special applications, single-phase generators and generators with more than three phases are built. In this article, three-phase synchronous generators operating at power frequency, (i.e. 60 Hz or 50 Hz) will be mainly considered.

A three-phase synchronous generator has essentially two elements: a three-phase armature winding and a magnetic field excitation winding or structure. For constructional convenience and economic reasons, the armature winding is commonly located in the stator (nonrotating part of the machine), and the rotor (rotating part of the machine) contains the magnetic field excitation winding or structure. In nearly all synchronous generators, a field winding carrying a dc current is used to establish the magnetic field. In some small synchronous generators, permanent magnets are utilized to establish this magnetic field.

A three-phase armature winding consists essentially of sets of coils equal to the number of pairs of poles symmetrically distributed around the stator, and each set consists of three groups of coils, which are symmetrically distributed under every pair of poles. Each one of these groups belongs to one of the phases, and all the groups belonging to one phase are connected together, usually in series but occasionally in parallel, to form the phase winding. For the availability of a neutral and because of insulation requirements, the three phase windings are connected in wye (star) for most synchronous generators.

When the rotor of a three-phase synchronous generator is driven by a prime mover, the magnetic flux linking the armature winding coils alternates and an alternating voltage is generated in them. The generated voltages in the three phase windings are similar, but are always 120° apart in phase. The frequency of these voltages will depend on the speed of the prime mover and the number of poles of the synchronous generator and is given by the following relationship (1,2):

$$f = \frac{pn}{120} \tag{1}$$

where f is the frequency of the generated voltage in hertz, p is the number of poles of the synchronous generator, and n is the speed of the rotor in revolutions per minute. For operation at a desired frequency, the choice of the number of poles of a synchronous generator will depend on the speed of the prime mover. For optimal operation, the speeds of the various prime movers depend on their types, and thus the number of poles and the form of construction of synchronous generators will essentially depend on their prime movers. The magnitude of the generated voltage depends on the rate of change of the magnetic flux linking the coils and, for the no-load situation, is given by the following relationship (1,2):

$$E_\mathrm{p} = 4.44\phi f N k_\mathrm{w} \tag{2}$$

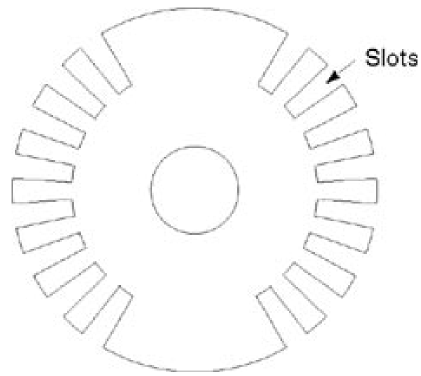

Fig. 1. Sketch showing the rotor construction of a two-pole cylindrical-rotor synchronous generator.

where E_p is the root-mean-square generated phase (line-to-neutral) voltage in volts and is usually called the open-circuit voltage, ϕ is the magnetic flux per pole in webers, f is the frequency in hertz, N is the number of turns in series per phase, and k_w is a winding factor that depends on the winding design (1,2). For the commonly used wye-connected armature windings, Eq. (2) gives the line-to-neutral generated voltage, and the generated voltage between the machine terminals (the line-to-line voltage) is given by the following relationship:

$$E_{LL} = \sqrt{3}E_p \tag{3}$$

The construction of synchronous generators may vary in several aspects. However, they are usually divided into two different basic types related to the form of their rotor construction:

Cylindrical-Rotor Generators. These generators have cylindrical rotors in which the field winding is embedded in axial slots (Fig. 1). The rotors usually have a length that is several times their diameter, and are made from a single steel forging or from several forgings. These types of synchronous generators are suitable when steam or gas turbines are used as prime movers. Such turbines operate best at high speeds, usually 3600 (3000) or 1800 (1500) revolutions per minute. At these speeds, the number of poles of a synchronous generator has to be either two or four for 60 (50) Hz operation.

Salient-Pole Generators. These types of synchronous generators have rotors of salient-pole construction (Fig. 2). The rotor has usually a diameter several times its length, and the field windings are wound around the poles and connected in series. These generators are used when the prime movers are hydraulic turbines or internal combustion engines. Such types of prime movers operate at best at relatively low speeds, in the range of 50 to 1000 revolutions per minute. At these speeds, the number of poles of a synchronous generator has to be larger than four for 60 or 50 Hz operation. In this case, it is more economical and convenient to construct the field structure in the salient-pole form.

GENERATED VOLTAGE WAVESHAPE

As mentioned before, the voltages are generated in the armature phase windings of a synchronous generator as a result of the relative motion between the magnetic field and the armature winding. The waveshape of these generated voltages will only be sinusoidal if the magnetic-flux-density waveshape is also sinusoidal.

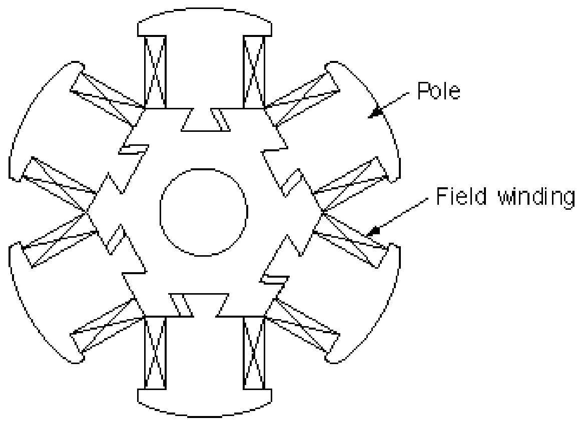

Fig. 2. Sketch showing the rotor construction of a six-pole salient-pole synchronous generator.

In practice, the magnetic-flux-density waveshape usually contains odd harmonic components, and as a result, corresponding odd harmonic components, though not of corresponding magnitudes, will appear in the generated phase voltages.

Usually, the most prominent harmonic components in the magnetic-flux-density waveshape are the third, fifth, and seventh. In general, the presence of such harmonic components can be treated in Eqs. (1) and (2) as if the synchronous machine, besides having the given number of poles, also had a number of harmonic poles equal to the harmonic order times the number of (fundamental) poles. With regard to the line-to-line generated voltage for the case of a wye-connected armature winding, Eq. (3) is also applicable to all odd harmonic components except the third harmonic and its multiples. In this case, these harmonic components do not appear between the line terminals of the synchronous machine, because they are in phase in all the three phase windings and hence will cancel each other in any line-to-line voltage calculation. However, some problems may still be caused by such harmonics in the generated line-to-neutral voltages.

With the proper design of the synchronous machine and particularly its armature winding, the magnitudes of the most prominent harmonic components of the generated voltages can be reduced and, in some cases, eliminated. Through this, the harmonic content of the generated voltage can be kept within the values specified by standards (345–6). It is worthy of mention here that the generated voltage waveshape specifications are usually limited to the open-circuit conditions, since the loading of synchronous generators affects the harmonic contents of their generated voltage in different ways that depend on the levels of saturation in the generator's magnetic circuit under load.

STEADY-STATE OPERATION

When the active power demand from a synchronous generator changes, small changes of speed cause a governor to adjust the input power of the prime mover accordingly. In this case, the prime-mover speed and the system frequency will be maintained as nearly as possible at the specified values. On the other hand, the effect of changing the field current of the synchronous generator will depend on the nature of the system connected at its terminals.

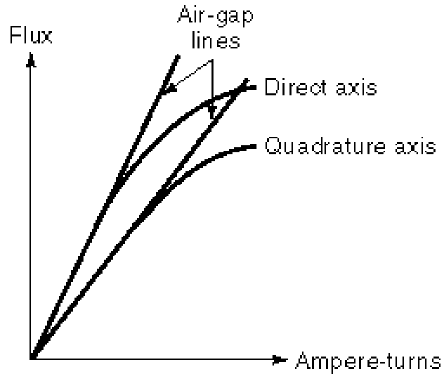

Fig. 3. The relationships between the air-gap flux and the magnetizing ampere-turns (saturation curves) along the direct and quadrature axes of a salient-pole synchronous generator.

If the synchronous generator runs alone to supply power to a load, the terminal voltage will depend on both the field current of the generator and the nature of the load. Thus, to keep the terminal voltage constant at a specified value, the field current has to be adjusted if the load changes.

If, however, the synchronous generator is connected to a large power system, as is usually the case, changing its field current does not affect the system voltage and only the reactive power supplied from the synchronous generator will change. In other words, it changes only the power factor of the power supplied by the generator. A synchronous generator is called *overexcited* if its field current is more than is needed to make it operate at unity power factor. In this case, the generator will operate at lagging power factor and is said to be supplying reactive power. If the field current of the generator is less than is needed to make it operate at unity power factor, the synchronous generator is called *underexcited*. In this case, the generator will operate at leading power factor and is said to be absorbing reactive power.

Phasor diagrams. For the analysis of a synchronous generator connected to a large power system, it is commonly assumed that the generator is connected to an infinite bus system. An *infinite bus system* is defined as a system that can absorb power without its voltage and frequency exhibiting any change. To carry out such an analysis, phasor diagrams are usually used and certain machine information is needed. These are the direct- and quadrature-axis open-circuit saturation curves (Fig. 3), the armature winding resistance R_a, the unsaturated direct- and quadrature-axis synchronous reactances X_d and X_q, and the leakage reactance X_l or Potier reactance X_p (1,2,7).

For a cylindrical-rotor synchronous generator, it can be assumed that the magnetic path is homogeneous around the rotor periphery, that is, all the saturation curves representing the magnetic relationship along all axes around the rotor periphery are similar. With this assumption, the direct- and quadrature-axis unsaturated synchronous reactances will be equal, and both are simply called the synchronous reactance. In this case, the equivalent circuit of Fig. 4 could represent the synchronous generator. In this figure, E_a is the generator terminal voltage per phase, E_G is the generated voltage per phase, I_a is the line current, R_a is the armature winding resistance per phase, and X_s is the synchronous reactance per phase. Usually, the effect of the armature winding resistance can be neglected. Figure 5 shows the phasor diagram for this equivalent circuit for the case of an overexcited generator supplying power at a lagging power factor. In this phasor diagram, ϕ is the power factor angle and δ is the angle between the generator terminal and generated voltages, which is usually called the load or power angle.

For a salient-pole synchronous generator, or when saliency is not neglected in the case of a cylindrical-rotor generator, account must be taken of the differing direct- and quadrature-axis synchronous reactances.

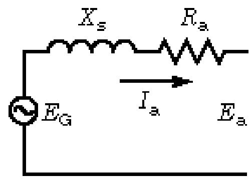

Fig. 4. The representation of a nonsalient-pole synchronous generator by an equivalent circuit.

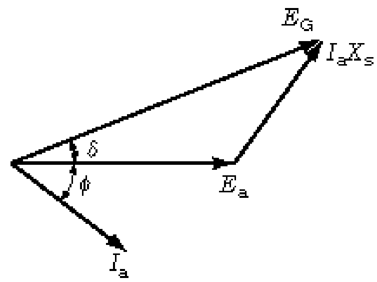

Fig. 5. Phasor diagram illustrating the relationship between the electrical quantities of an overexcited nonsalient-pole synchronous generator connected to an infinite bus system.

Figure 6 shows the phasor diagram for this case when the generator is overexcited and supplying power at a lagging power factor. In this phasor diagram, $I_{ad}X_d$ and $I_{aq}X_q$ are the voltage drops in the direct- and quadrature-axis synchronous reactances calculated by using the direct- and quadrature-axis components of the armature current, respectively. To obtain the values of these two components, a phasor equal to I_aX_q is added to the terminal voltage to obtain the phasor E_q. The direction of E_q gives the direction of the quadrature axis, and the direction of the direct axis will, as a result, be known. Knowing the directions of these two axes, the components of the armature current along the direct and quadrature axes will be known, and the voltage drops $I_{ad}X_d$ and $I_{aq}X_q$ can be calculated. It is clear from the phasor diagram that the phasor of the generated voltage E_G will be in the same direction as E_q, that is, it will be in the direction of the quadrature axis.

Effect of saturation on the steady-state performance. In the analysis of the steady-state performance of synchronous generators, the accurate calculation of their field excitation and load angle depends to a large extent on their saturation condition. In general, the effect of saturation will depend not only on the saturation curve in the axis (direction) of the resultant machine ampere-turns, but also on the phase angle between the resultant ampere-turns and the resultant magnetic flux. This phase angle depends on both the machine saliency and the different saturation levels along the different axes of the synchronous generator (8,9).

To take account of saturation in the synchronous-generator phasor diagrams, empirical methods, which in most of the cases seem to give fairly closer agreement to the measured values, are used. In these methods, the custom in the past was to use only one saturation factor or increment corresponding to the saturation along the direct axis. This has been replaced in present practice by the use of two different saturation factors corresponding to the saturation conditions along the direct and quadrature axes, since the saturation levels are very different along the two axes even in the case of the cylindrical-rotor synchronous generators. These saturation factors (or increments) are defined as the ratio of (or the difference between) the actual excitation and the excitation on the air-gap line of the saturation curves at the operating point. The internal voltage behind the leakage (or Potier) reactance is usually used to locate the operating point on the saturation curves. In using these two saturation factors, the magnetic coupling between the direct and the quadrature axes (the

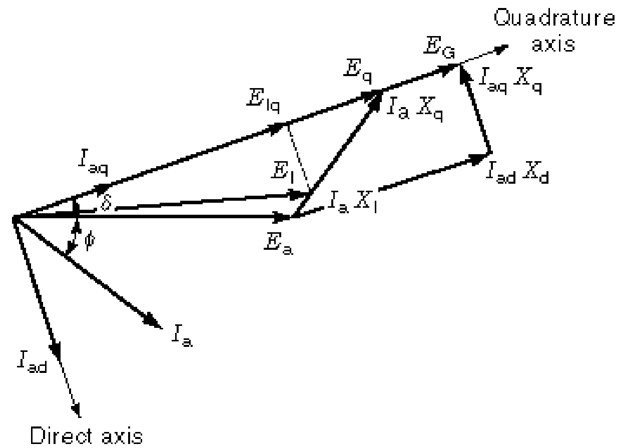

Fig. 6. Phasor diagram illustrating the relationship between the electrical quantities of an overexcited salient-pole synchronous generator connected to an infinite bus system.

cross-magnetizing phenomenon) is ignored. The importance of allowing for the cross-magnetizing phenomenon has, however, been recognized recently, and an accurate two-axis model of saturated synchronous generators should include it (8,9).

Use of one saturation factor (or increment). The use of one saturation factor or increment has been practiced both for salient-pole and for cylindrical-rotor synchronous machines, under different assumptions. In the case of salient-pole machines, saturation is assumed to occur only along the direct axis, and a saturation increment corresponding to the voltage behind the leakage (or Potier) reactance, E_l, or to the projection of this voltage on the quadrature axis, E_{lq}, is obtained from the direct-axis saturation curve (Fig. 3). The excitation, including the effect of saturation, will be equal to the sum of this saturation increment and the excitation from the air-gap line of the direct-axis saturation curve corresponding to the voltage E_G calculated using the unsaturated direct- and quadrature-axis synchronous reactances (Fig. 6).

In the case of cylindrical-rotor synchronous generators, saturation can be significant in both the direct and quadrature axes. However, the use of one saturation factor (or increment) is applied assuming the magnetic path is homogeneous around the rotor periphery. Thus, the direct-axis saturation curve will represent the magnetic relationship along any axis around the rotor periphery and can be used to find the saturation correction corresponding to the total air-gap flux (i.e., corresponding to the voltage behind the leakage or Potier reactance). Adding this saturation increment in phase with the voltage behind the leakage or Potier reactance to the voltage behind the unsaturated synchronous reactance, the total excitation including saturation is obtained (Fig. 7). In a second approach, the unsaturated synchronous reactance, X_{SU}, is broken into two components, and the larger component (X_{SU}–X_l or X_{SU}–X_p) is adjusted by the saturation factor to give, together with X_l or X_p, the saturated synchronous reactances. Thus,

$$X_{sat} = X_\ell + \frac{X_{SU} - X_\ell}{K_\ell} \quad \text{or} \quad X_{sat} = X_p + \frac{X_{SU} - X_p}{K_p}$$

An internal voltage E_{QD} is then obtained using this saturated reactance, as shown in Fig. 8. The total excitation is then obtained by multiplying this internal voltage by the saturation factor. On comparing Figs. 7 and 8, it is clear that the two approaches are similar.

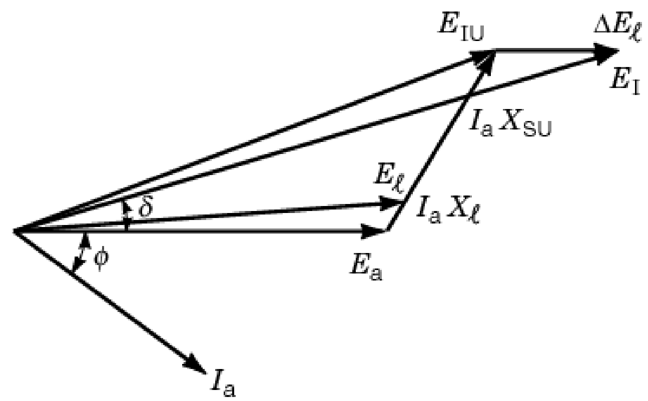

Fig. 7. The inclusion of the effect of saturation in the phasor diagram of a nonsalient-pole synchronous generator.

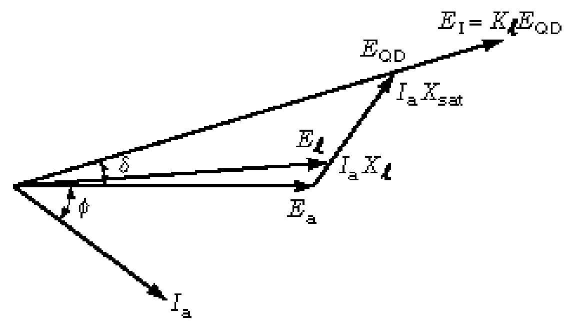

Fig. 8. The application of the saturated-synchronous-reactance method to include the effect of saturation in the phasor diagram of a nonsalient-pole synchronous generator.

Use of two saturation factors. In this approach, both the direct- and quadrature-axis saturation effects are represented by specifically adjusting the unsaturated direct- and quadrature-axis synchronous reactances by corresponding saturation factors K_d and K_q to obtain the saturated direct- and quadrature-axis synchronous reactances as discussed in the previous sub-subsection. In this case, K_d is calculated from the direct-axis saturation curve to give X_{dsat}, while K_q is calculated from the quadrature-axis saturation curve to give X_{qsat}. The internal voltage behind the leakage or Potier reactance is used to determine the operating point on both saturation curves. Using these saturated reactances X_{dsat} and X_{qsat} in Fig. 6, an internal voltage ($\equiv E_G$ in Fig. 6) is obtained. The total excitation is then obtained by multiplying this internal voltage by the saturation factor K_d. Empirically, the use of the two saturation factors seems to give, in some cases, an accurate representation of the effect of saturation along the intermediate axis of the total resultant ampere-turns, that is, the effect of both the saturation factor due to the total resultant ampere-turns using the saturation curve along the intermediate axis of the total resultant ampere-turns, and the phase angle between the resultant flux and the resultant ampere-turns.

Cross-magnetizing phenomenon. It has been recognized recently that the magnetic coupling between the direct and quadrature axes of saturated synchronous machines (cross-magnetizing phenomenon) plays an important role in their analysis (8,9). When the flux linkages along the direct and quadrature axes due to the components of the ampere-turns along these axes are handled separately, this magnetic coupling causes changes in these flux linkages. This can be represented in the phasor diagram of saturated synchronous generators

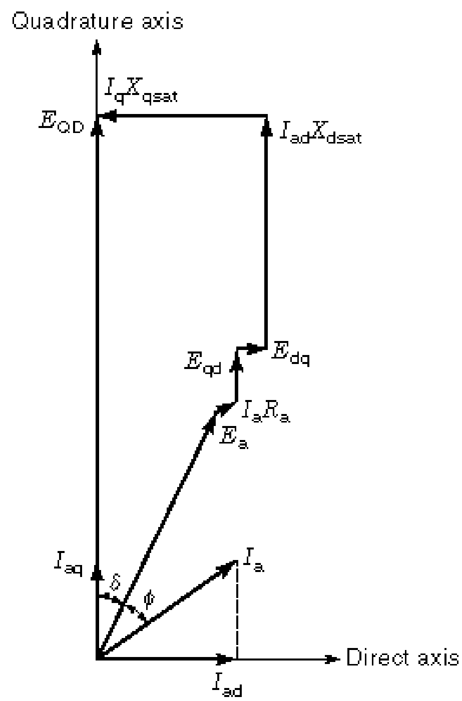

Fig. 9. The inclusion of the cross-magnetizing effect in the phasor diagram of a saturated synchronous generator.

in the form of separate direct- and quadrature-axis voltage drops, E_{dq} and E_{qd}, which are proportional to the changes in the quadrature- and direct-axis flux linkages, respectively, and which can be called the cross-magnetizing voltages (Fig. 9). The values of these cross-magnetizing voltages are functions of the components of the ampere-turns along both the direct and quadrature axes (8,9). In this case, the saturated synchronous reactances are calculated using saturation factors obtained from the direct- and quadrature-axis saturation curves using the projections of the voltage behind the leakage or Potier reactance on the direct and quadrature axes, respectively, as the operating points.

In a second approach, the effects of both the direct and quadrature saturation factors and the cross-magnetizing phenomenon are combined to give the values of saturated direct- and quadrature-axis synchronous reactances (10). In this case, the values of these saturated synchronous reactances are functions of the components of the ampere-turns along both the direct and quadrature axes and can be used as shown in the phasor diagram of Fig. 6.

Power–load-angle relationship. From the phasor diagram of Fig. 9, the power delivered by a synchronous generator connected to an infinite bus system, losses being neglected, can be derived as follows:

$$P = \frac{E_a E_{QD}}{X_{dsat}} \sin\delta + \frac{E_a^2}{2}\left(\frac{1}{X_{qsat}} - \frac{1}{X_{dsat}}\right)\sin 2\delta + \frac{E_{dq}E_a}{X_{qsat}}\cos\delta - \frac{E_{qd}E_a}{X_{dsat}}\sin\delta \qquad (4)$$

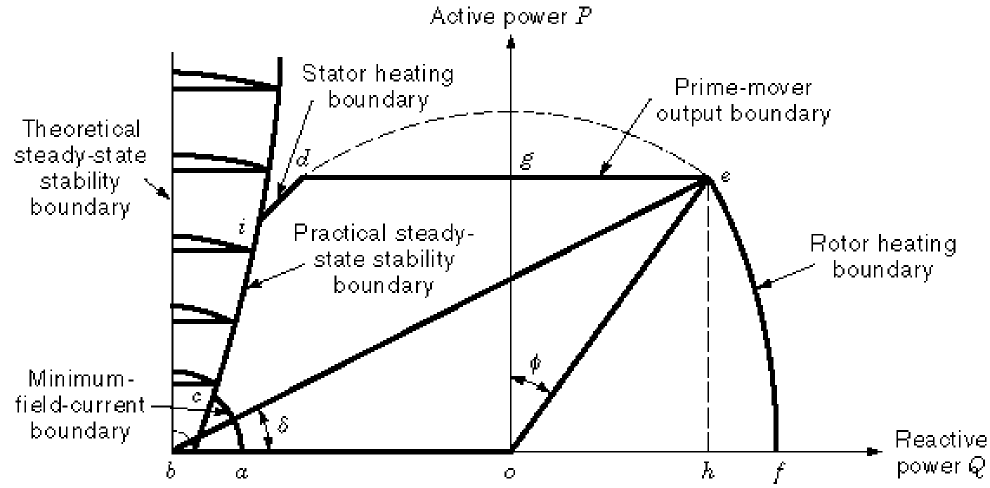

Fig. 10. A power capability diagram that shows the loading limitations imposed by heating, prime mover, excitation, and stability on a nonsalient-pole synchronous generator.

If the cross-magnetizing effect [the last two terms of Eq. (4)] and saliency [the second term of Eq. (4)] are neglected as represented in the phasor diagram of Fig. 8, the power–load-angle relationship becomes

$$P = \frac{E_a E_{QD}}{X_{sat}} \sin\delta \tag{5}$$

The maximum power that can be delivered by the synchronous generator is then $E_a E_{QD}/X_{sat}$ when δ equals 90°. This is the stability limit under steady-state conditions. However, if saliency is not neglected, the angle at which a maximum power can be delivered by the synchronous generator is less than 90°, and its value is dependent on the operating condition. In this case, the maximum power will be larger than $E_a E_{QD}/X_{sat}$.

Loading limitations. The loading limitations imposed by heating, prime mover, excitation, and stability on a synchronous generator connected to an infinite bus system can be evaluated by using power capability diagrams (11121314–15). Neglecting losses and saturation, Fig. 10 shows such a power capability diagram for the case of a nonsalient-pole synchronous generator connected to an infinite bus system. In this diagram, each point represents an operating condition. For example, point *e* represents the rated loading condition, the line *bo* represents the constant-phase voltage of the infinite bus system E_a, the line *oe* represents the rated stator current to a scale or the rated MVA to another scale at power-factor angle ϕ, the lines *og* and *oh* are the corresponding active and reactive powers, and the line *be* represents the phase generated voltage E_G.

The operation of this machine must be so controlled that the operating power remains within the boundaries set by:

(1) An arc *ef* of center *b* and radius *be* representing the rated field current, that is, the rotor heating limit
(2) An arc of center *o* and radius *oe* representing the rated stator current, that is, the stator heating limit
(3) The line *dge* representing the rated power output of the prime mover
(4) An arc *ac* that represents the minimum acceptable field current
(5) The curve *ci*, which represents the practical stability boundary beyond which instability at all loads occurs when the synchronous generator absorbs excessive reactive power, (i.e., is underexcited)

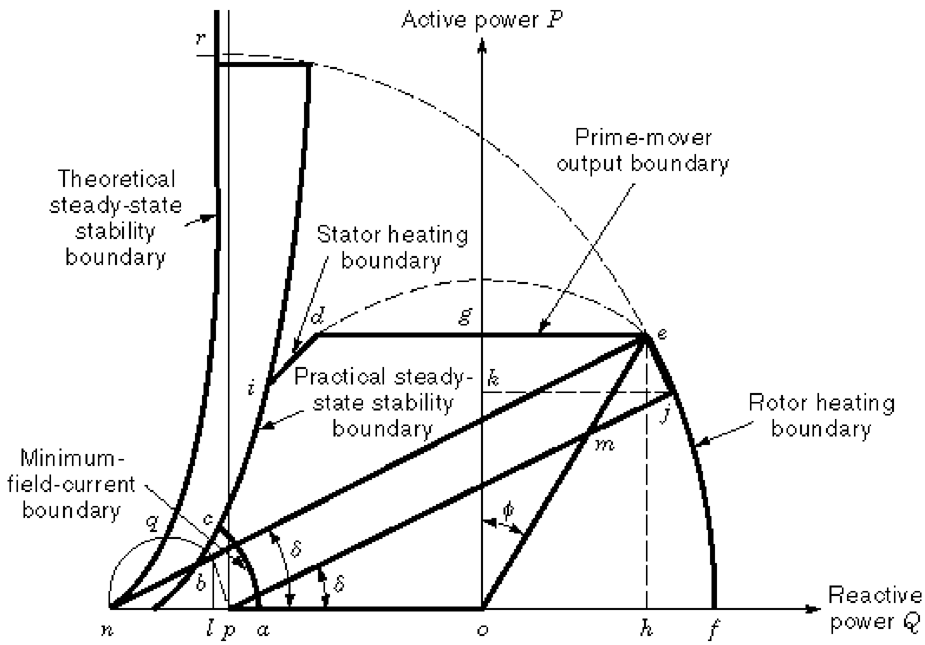

Fig. 11. A power capability diagram that shows the loading limitations imposed by heating, prime mover, excitation, and stability on a salient-pole synchronous generator.

For the case of salient-pole synchronous generators, the power capability diagrams can be drawn from the phasor diagram (Fig. 6) as illustrated in Fig. 11 when losses and saturation are ignored. As in the case of nonsalient-pole synchronous generators (Fig. 10), the lines *oe*, *og*, and *o*h are the rated MVA and the corresponding active and reactive powers, respectively. In Fig. 11, the ratio $om/oe = X_q/X_d$, the line $op = E_a{}^2/X_d$, the line $on = E_a{}^2/X_q$, the line *ej* is perpendicular to the line *pm*, and the line *pj* represents the generated voltage. At any loading condition, the length *be* on the line through point *n* represents also the generated voltage, since the angle *pbn* is always 90° and the point *b* moves on a semicircle constructed on the diameter *pn*. This semicircle represents the locus of the operating point *e* with zero excitation. For any other constant excitation, the locus of point *e* is not quite a circular arc; however, this becomes evident only with low excitation. In this figure, the active power represented by the line *og* is divided into two components: *ok*, which is the power contributed by the excitation, and *kg* (= *bl*), which is the reluctance power due to the saliency. The theoretical steady-state stability boundary *nqr* can be obtained by applying the expression $dP/d\delta = 0$. It should be noted that salient-pole synchronous generators can be operated with negative excitation (12,16).

SUDDEN THREE-PHASE SHORT CIRCUIT

If the three phases of a synchronous generator are suddenly short-circuited together, a high current of up to several times the full load value will flow in the stator. As shown in Fig. 12, this current have basically two components: a balanced three-phase alternating current component and an offset direct current.

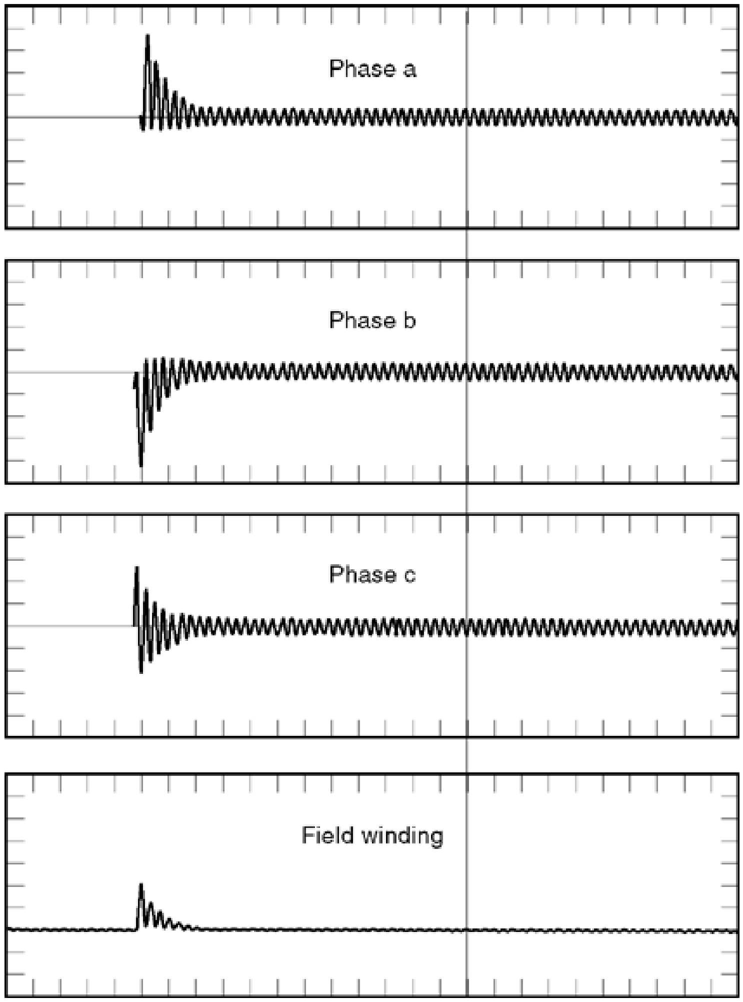

Fig. 12. Typical oscillograms of the stator and field currents of a synchronous generator on a sudden three-phase short circuit at its terminal.

In the case that the synchronous generator is initially unloaded, the balanced three-phase component of the short-circuit current can be expressed by the following equation (1, 2, 17–19):

$$I = \left(\frac{E}{X_d''} - \frac{E}{X_d'}\right)e^{-t/\tau_d''} + \left(\frac{E}{X_d'} - \frac{E}{X_d}\right)e^{-t/\tau_d'} + \frac{E}{X_d} \tag{6}$$

where I is the root-mean-square value of this balanced alternating current component, E is the root-mean-square value of the phase voltage prior to the short circuit, t is the time after the instant of the short circuit, X_d'' is the direct-axis subtransient reactance, X_d' is the direct-axis transient reactance, X_d is the direct-axis synchronous reactance, τ_d'' is the direct-axis short-circuit subtransient time constant, and τ_d' is the direct-axis short-circuit transient time constant. The magnitude of the second component, namely the offset direct current, depends on how near the instantaneous value of the phase voltage is to zero at the instant of the short circuit. For the instant corresponding to zero instantaneous phase voltage, the offset direct current will be at its maximum magnitude, and it will be zero for the instant corresponding to the peak of the phase voltage. The magnitude of the offset direct current in each phase will be equal and opposite to the instantaneous value of the balanced alternating current component at the instant of the short circuit, and thus it can be equal to zero in only one of the phases. In comparison with the alternating component, the offset direct current components decay at a rapid rate, with the armature short-circuit time constant τ_a.

The balanced three-phase component of the short-circuit stator current gives rise to a direct current component in the rotor circuits, namely the rotor damper circuits and the field winding. This is because the balanced three-phase component produces a magnetomotive force rotating synchronously with the rotor. In the case of the initially unloaded synchronous generator, the axis of this magnetomotive force lies along the pole axis and the magnetomotive force tends to reduce the flux linkages with the rotor circuits. Such changes of the flux linkages with the rotor circuits result in induced currents in the rotor damper circuits and field winding. The induced currents in the damper circuits decay with the direct-axis short-circuit subtransient time constant τ_d'', while the induced current in the field winding decays after the subtransient period with the direct-axis short-circuit transient time constant τ_d'.

On the other hand, the stator offset direct current components produce a stationary magnetomotive force that will induce a rotational-frequency current in the rotating rotor damper and field circuits. These rotor currents, like the stator offset direct current components, will decay with the armature short-circuit time constant τ_a.

Effect of sudden three-phase short-circuit on synchronous generators. As a result of the large currents flowing in the stator windings of a synchronous generator on a sudden three-phase short-circuit, electromagnetic forces much larger than normal will result on the end windings of the stator coils (18,19). These forces can produce severe mechanical strains on the end windings and cause insulation failure. These end windings must, therefore, be adequately braced.

Besides the forces on the end windings of the stator coils, a sudden three-phase short-circuit of a synchronous generator results also in pulsating torques, which can be many times the magnitude of the rated torque (17,19). The casing, the shaft, and the foundation of the synchronous generator must be designed to withstand the stress developed as a result of these torques.

DYNAMIC PERFORMANCE

Although a synchronous generator normally operates in parallel with others at a constant speed corresponding to the system frequency and number of poles, variation in the rotor speed about its average value can occur because of variations in the terminal voltage, field current, load, or driving torque. These changes in angular velocity are associated with changes in the load angle δ and usually occur in an oscillatory form. For the proper operation of the system, such oscillations should damp as quickly as possible.

Synchronizing procedure. The operation of synchronous generators in parallel with others raises the problem of switching a generator into service (synchronizing) and ensuring that it subsequently remains in synchronism. In connecting a synchronous generator in parallel with another machine or to an electrical system, certain conditions must be satisfied by the incoming generator with respect to the bus bars of the other machine or of the system. These conditions can be summarized as follows:

(1) The phase sequence of the incoming synchronous generator should be the same as that of the bus bars.
(2) The frequency of the incoming synchronous generator should be close to that of the bus bars.

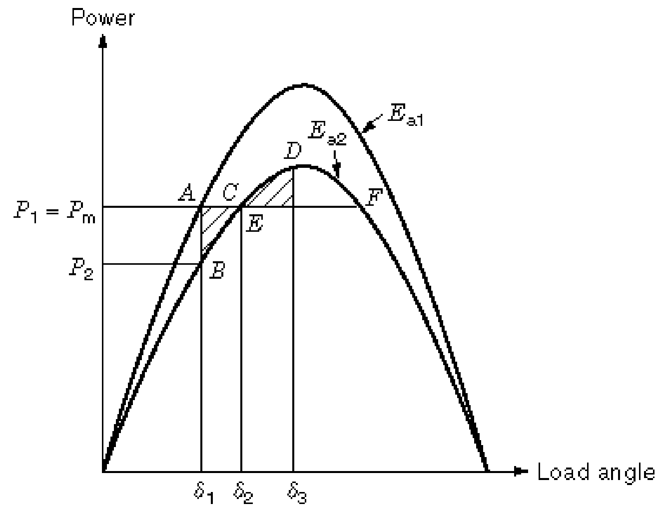

Fig. 13. The application of the equal-area criterion to illustrate the dynamic performance of a synchronous generator.

(3) The root-mean-square voltage of the incoming synchronous generator should be close to that of the bus bars.
(4) The incoming synchronous generator and the bus-bars' voltages must be momentarily in phase at the instant of connecting the incoming generator to the system.

In the cases of synchronizing synchronous generators manually, a synchroscope is usually used to satisfy condition 4 and indicate the right instant to close the switch between the incoming synchronous generator and the bus bars. The synchronizing process can also be carried out by automatic means that monitor the incoming synchronous generator and bus bars' frequencies and voltages and the phase angle between these voltages and initiate the switch closure at the right instant.

Synchronizing power. If a synchronous generator connected to an electrical system is disturbed from its steady state, for example by a change in the system voltage, the generator electrical output power will no longer balance the mechanical input power (presumed constant, and the losses are neglected). In this case, the generator rotor swings from load angle δ_1 to a new load angle δ_2 at which the balance will be restored. The change from δ_1 to δ_2 occurs usually in an oscillatory form, as illustrated for the case of a single synchronous generator connected to an infinite bus by the equal-area criterion in Fig. 13. In this figure, the initial operating point A moves to B as the infinite bus voltage drops from E_{a1} to E_{a2}, reducing the electrical output power of the synchronous generator from P_1 to P_2. The difference between the mechanical power input P_m (equal to P_1 and presumed to be kept constant) and the new electrical output power P_2 will accelerate the rotor, and the operating point moves from B to C on the power–load-angle curve of E_{a2}. At point C, the rotor speed is higher than the synchronous speed, and thus the operating point continues to move till point D. From C to D, the electric output power is larger than the mechanical input power, and thus the rotor will decelerate till its speed reaches the synchronous speed at point D. Since the rotor continues to decelerate, the operating point moves back to point C and then to point B to complete one swing. The areas ABC and CDE represent the energy interchanged between the rotor kinetic energy and the electric energy, and if there were no damping in the system, these two areas would be equal and the generator rotor would continue to oscillate between δ_1 and δ_3. However, due to the existence of damping, these oscillations will damp and the operating point will settle at the point C at which the electric output power is again equal to the mechanical input power. In the case that the mechanical input power is too close to the peak of the power–load-angle curve E_{a2}, the area *CDF* will be less than the area *ABC* and the rotor can never be slowed to the synchronous speed before reaching point *F*. In this case, the generator rotor starts to accelerate beyond point *F* and the generator falls out of synchronism.

If the change in the load angle ($\Delta\delta$) around an operating point is small, the accelerating or decelerating power (synchronizing power) can be expressed as follows:

$$\text{Synchronizing power} = P_s\,\Delta\delta \tag{7}$$

where P_s is the synchronizing-power coefficient. If the rotor oscillations were very slow, the appropriate power–load-angle curve for calculating this coefficient would be the steady-state curve as in Fig. 13, and the synchronizing power coefficient could be expressed (for the case of neglecting losses and the cross-magnetizing effect) as follows:

$$P_s = \frac{dP}{d\delta} = \frac{E_a E_{QD}}{X_{dsat}}\cos\delta + E_a^2\left(\frac{1}{X_{qsat}} - \frac{1}{X_{dsat}}\right)\cos 2\delta \tag{8}$$

If the assumption that the rotor oscillations are very slow is invalid, the use of Eq. (7) will result in inaccurate values for the synchronizing-power coefficients. References 2021–22 give some of the methods for calculating the synchronizing power coefficients for such cases.

Damping power. As mentioned above, the change of the operating condition due to a disturbance occurs usually in an oscillatory form that damps to a final new operating condition. The damping of these oscillations depends mainly on the damping power, which is often considered to vary linearly with the deviation of speed from synchronous speed. Thus the damping power can be expressed as follows:

$$\text{Damping power} = P_d\frac{d\delta}{dt} \tag{9}$$

where P_d is the damping-power coefficient. This coefficient depends greatly on the rotor construction, the frequency of oscillations, the field excitation system, and the load type. References 2021–22 give some of the methods for calculating these coefficients.

The natural frequency of oscillations. The oscillations of the synchronous generator rotor due to a disturbance occur with a frequency equal approximately to its natural frequency. This natural frequency of oscillations can be calculated by assuming that only the synchronizing power is acting on the oscillatory system, which is constituted by the inertia of the coupled rotors of the synchronous generator and its prime mover. In this case, the natural frequency of oscillations is expressed as follows:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{P_s}{2H}} \tag{10}$$

where H is the inertia constant (23).

DETERMINATION OF SYNCHRONOUS-GENERATOR PARAMETERS

Experimental methods. Most of the parameters of synchronous generators can be determined experimentally. Reference 7 describes in detail the various methods for doing this. In the following, a summary of the commonly applied methods for determining the parameters used in this article is given.

Synchronous reactances. The unsaturated direct-axis synchronous reactance can be obtained from the open-circuit and short-circuit tests (7). On the other hand, the unsaturated quadrature-axis synchronous reactance can be measured by the slip test (7) or by using the maximum-lagging-current method (7).

In the slip test, the synchronous generator is rotated at slightly below or above the synchronous speed while its armature windings are connected to a three-phase supply with no field current. On measuring the maximum and minimum values of the current and the corresponding values of the terminal voltage, the quadrature-axis synchronous reactance is found as the ratio of the minimum voltage to the maximum current. The direct-axis synchronous reactance can also be calculated from this test as the ratio of the maximum voltage to the minimum current.

In the maximum-lagging-current method, the synchronous generator is connected to an infinite bus system through a tap-changing transformer. For a certain terminal voltage, the synchronous generator's field current is reduced from its approximately rated no-load excitation to zero, reversed in polarity, and gradually increased in the opposite polarity. This will cause the rotor of the synchronous generator to slip one pole. If the negative excitation increases in small increments until instability occurs, the armature current at the stability limit will equal approximately its quadrature-axis component while the direct-axis component equals approximately zero. Neglecting the effect of the armature resistance, the terminal voltage E_a will thus be equal to the reactance voltage drop $I_a X_q$, and thus the quadrature-axis synchronous reactance X_q can be determined.

The quadrature-axis open-circuit characteristic curve, which is needed to calculate the quadrature-axis saturation factors, can also be obtained by applying this method. At the stability limit determined as explained above, the terminal voltage can thus be written as follows:

$$\begin{aligned} E_a &= X_q I_a \\ &= (X_{mq} + X_1) I_a \\ &= E_G + X_1 I_a \end{aligned} \tag{11}$$

where E_G is the internal electromotive force that represents the air-gap flux along the quadrature axis. Measuring the terminal voltage E_a and the armature current I_a at the stability limit and subtracting the armature leakage voltage drop $X_l I_a$ from E_a, the relationship between the electromotive force E_G and the armature current I_a can be obtained and can be used to represent the relationship between the air-gap flux and the excitation current along the quadrature axis, that is, the quadrature-axis open-circuit characteristic curve.

Leakage reactance. For determining the value of the leakage reactance, the Potier reactance X_p measured at rated terminal voltage is usually used as an approximation. This reactance can be determined with the help of the open-circuit and zero-power-factor characteristic curves (7). However, it has been found that the value of the Potier reactance measured at rated terminal voltage may not be a good approximation of the value of the armature leakage reactance. To obtain a more accurate value, the Potier reactance has to be determined in the highly saturated region of the open-circuit characteristic curve (24). This may however be difficult, since the synchronous generator may not be able to stand the values of the field current needed to obtain the open-circuit and zero-power-factor characteristics in the highly saturated region. Reference 24 has proposed an alternative testing method to obtain accurate values of the armature leakage reactance without any risk to the generator under test.

Subtransient and transient reactances and time constants. The direct-axis subtransient and transient reactances and their respective time constants can be obtained from the three-phase sudden short-circuit test.

In this test, with the synchronous generator rotating at synchronous speed and open-circuited, the three phases are suddenly short-circuited and the stator and field currents are recorded. Analysis of the envelope of the balanced alternating component of the short-circuit stator current leads to the determination of the subtransient and transient reactances and time constants for the direct axis. Nowadays, a computerized implementation of this test and the analysis of the short-circuit currents is used (25,26).

Recently, a test procedure for obtaining the direct-axis subtransient and transient reactances and time constants by frequency-response testing of synchronous generators at standstill has been proposed (7). Unlike the three-phase sudden short-circuit test, the standstill frequency-response test can also be applied to determine the quadrature-axis subtransient and transient reactances and time constants.

Analytical methods. With the advances in computer technology and the progress made in the area of numerical analysis, most of the synchronous-generator parameters can be calculated analytically with acceptable accuracy. At present, the most commonly used technique for obtaining the parameters numerically is the finite-element method (2728293031–32). In this method, a detailed magnetostatic field solution of Maxwell's equations, which can accurately reflect the effects of rotor saliency, slotting, saturation, winding layouts, and other effects, is used. The application of these methods is of great importance when the values of the synchronous generator parameters are to be determined in the design of synchronous generators.

METHODS FOR DETERMINING THE PARAMETERS REPRESENTING THE CROSS-MAGNETIZING PHENOMENON

If a synchronous machine has an auxiliary excitation winding in the quadrature axis and can thus be excited from both the direct and quadrature axes simultaneously, the parameters representing the cross-magnetizing effect in it can be determined experimentally as explained in details in Ref. 8. However, for industrial synchronous machines that have no auxiliary excitation winding along their quadrature axis, that cannot be done. For such machines, Ref. 9 has proposed an analytical approach to determine these parameters from their measurable direct- and quadrature-axis saturation curves. An indirect experimental method, which allows their determination from measurements of the output active and reactive powers, the excitation field current, the terminal voltage, and the load angle under various loading conditions, has also been proposed (33).

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