TURBOGENERATORS

The modern generator, which evolved from the discovery of magnetic induction by Michael Faraday in 1831, is a machine used to convert the mechanical energy of rotation into electric energy. As a high-speed rotating device, the generator is subject to various vibratory, fatigue, and tensile stresses. As an electromagnetic device, it is subject to the dielectric stresses associated with insulated high-voltage equipment and to the inherent heat transfer problems resulting from various electric and mechanical losses. In addition to these basic machinery problems, there are various other issues to consider, such as designing the generator to be suitable for the turbine which drives it, meeting special terminal voltage requirements specified by the purchaser, addressing stability problems of the machine connected to the power system, meeting environmental requirements, and transporting the generator to the station site.

Since the installation of the first alternating current (ac) central power station turbine generator in 1903 at the Hartford Electric Light Company, the most predominant single factor has been the tremendous increase in generator power ratings required by the demands of the industry. The highest power rating of single shaft generators has been increased seven hundred fold from the 2000 kW, 1200 rpm generator in 1903 to the 1500 MW generators available in 1998. Figure 1 shows a typical installation of a 400 MW hydrogen-cooled generator with a brushless excitation system.

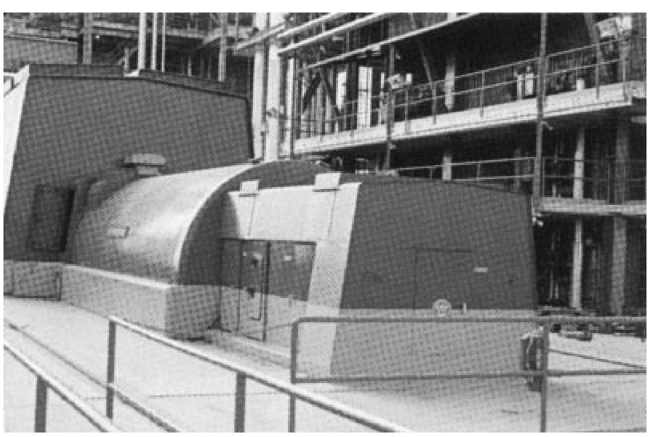

Figure 1. Hydrogen-cooled generator with brushless excitation system.

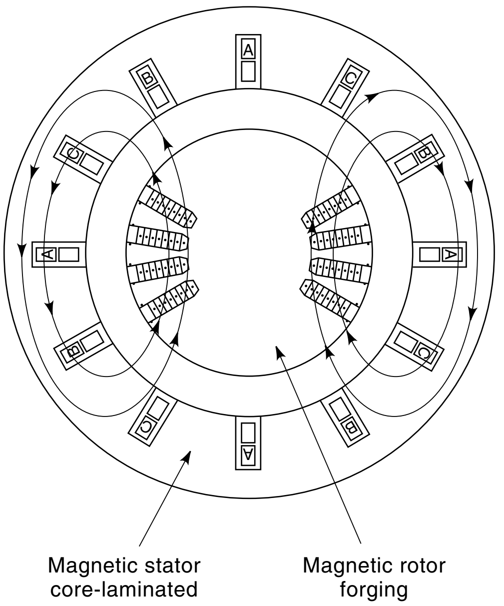

Figure 2. Simplified two-pole generator cross section.

FUNDAMENTALS

Modern turbogenerators usually operate at one of four rotational speeds:

- 3600 rpm (60 Hz) or 3000 rpm (50 Hz), 2 pole (usually with fossil-fueled steam or combustion turbines)
- 1800 rpm (60 Hz) or 1500 rpm (50 Hz), 4 pole (usually with steam turbines at nuclear stations)

These speeds are generally based on the most efficient turbine operating speeds, given the steam conditions, but because of the requirement to connect to a system of fixed frequency (50 or 60 Hz), the speed n_s is constrained to

$$n_s = \frac{120f}{P}$$

where f is the electric frequency (Hz), P is the number of generator field poles (even number), and n_s is the synchronous speed (rpm).

This means that the operating speed of a directly connected turbine must match the system frequency and the selection of the number of field poles. Some smaller applications (less than 70 MW) use a gear drive to allow separate optimization of generator and drive speeds.

With these rotational speeds, turbogenerators are designed with round-rotor field windings and support structures to support the windings with the centrifugal forces involved. A basic cross section of a two-pole generator is shown in Fig. 2. The rotor field winding is wound in machined slots in an alloy steel magnetic rotor forging that forms a rotating electromagnet when a dc current is applied to it. The resulting magnetic flux penetrates the rotor across the “air-gap” into a magnetic stator and closes back on itself as illustrated in Fig. 2. Faraday’s law states that a rotating flux field passing the stationary stator conductors generates a voltage in each conductor proportional to the rate of change of flux through the conduc-

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tor. As the rotor turns, the voltage in each conductor peaks, goes to zero and reverses, creating approximately a sine wave. For the two-pole generator shown, one complete rotor revolution generates one complete electric cycle.

All large alternating current generators have the stator conductors connected as three separate windings (or phases) spaced 120° apart around the periphery of the stator. Thus the voltages generated in each of these windings is 120° out of phase with the others. The cross section of Fig. 2 shows a typical configuration with two conductors per stator slot, each phase labeled A, B, or C. The top coil bars are connected to bottom coil bars of the same phase in the ends of the machine forming a coil-type winding. The ends of each winding are brought out to terminals, usually at one end of the generator. Although all six terminals are usually accessible from outside the generator housing, three are usually connected together, forming the neutral connection and creating a "Y"-connected generator as shown in Fig. 3(a). The neutral is often grounded through a large resistance to limit the current due to a phase-to-ground fault. There is little or no current through this ground connection during normal operation. A "delta" connection is also possible as shown in Fig. 3(b) but not common for generators.

When the stator windings are connected to a load, the currents that flow are also 120° out phase and thus create an additional rotating flux wave. The wave travels at the speed of the rotor (synchronously) and generally opposes that of the rotor flux at some angle depending on the operating phase angle of voltage and current at the terminals of the generator. Thus, to maintain a regulated voltage at the machine terminals, the dc field current in the rotor windings (also called excitation current) must be adjusted depending on the stator current and voltage magnitude and the phase angle difference. A common parameter describing this voltage and current phase angle is called power factor (PF), which is

$$\mathrm{PF} = \cos\theta$$

where θ is the phase difference between stator voltage and current.

The real power output of a three-phase electric generator in watts is given by

$$\text{Power Output} = 3I_\mathrm{P} \times V_\mathrm{P} \times \mathrm{PF} = 3I_\mathrm{P}V_\mathrm{P}\cos\theta$$

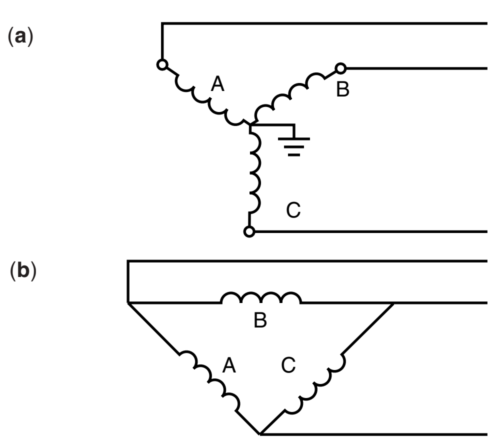

Figure 3. (a) "Y" connected generator. (b) "Delta" connected generator.

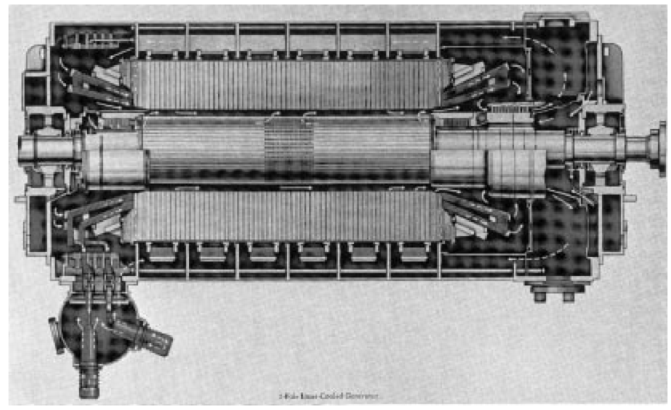

Figure 4. Two-pole hydrogen inner cooled generator axial cross section.

where I_P is the current in each phase (A) and V_P is the phase-to-neutral voltage in each phase (V).

A commonly used formula for a "Y"-connected generator, assuming balanced currents, is

$$\text{Power Output (kilowatts)} = \sqrt{3}I_\mathrm{p}V_\mathrm{T} \times \mathrm{PF}$$

where I_p is the current in one phase (A) and V_T is the phase-to-phase voltage (kV).

EXCITATION SOURCE

There are several common approaches for providing dc current to the generator rotor. One is to transfer dc current from a stationary source to the rotor via stationary carbon brushes riding on rotating "collector" or "slip rings." Another means is with a "brushless excitation system," which eliminates the need for brushes or slip rings. Excitation systems are discussed in a later section.

CONSTRUCTION FEATURES

A typical hydrogen-cooled generator axial cross section is illustrated in Fig. 4. The rotor is made of a solid high-strength magnetic forging with slots machined to contain the field winding. When the stator phase currents are balanced, a measurement on the rotor would observe no time-varying magnetic flux because the rotor and flux rotate together. The stator core is made of laminated "punchings" typically about 0.5 mm thick that are insulated from each other. The stator core carries a time-varying flux that creates the voltages and currents in the stator winding. The electric conduction path in the stator core is broken by laminating the core steel to minimize eddy currents in the stator core, which only generate heat and losses. The rotor and stator windings are usually made of copper, but aluminum is occasionally used. Bearings and bearing supports required at each end of the generator need bearing lubricating oil, usually from the same source as for the turbine bearings. For generators that use hydrogen cooling, a hydrogen-tight frame is required and hydrogen gland seals at each end of the generator where the rotor shaft must extend through the frame to minimize hydrogen leakage. The stator core must be mounted to the frame and in turn to a foundation. For large generators, the core is often spring-mounted to the frame to isolate core vibration induced by the rotating flux field from the frame and foundation. Rotor shaft lateral and torsional dynamics must be carefully calculated to avoid resonant modes at operating speed.

VENTILATION AND POWER DENSITY

The removal of heat from the generator is one of the most important design challenges as ratings are increased. Ventilation circuits must be designed to avoid any local overheating in any of the components that generate heat and in other nearby components. Smaller generators (i.e., under 200 MW) are air-cooled and simply take ambient air and discharge it back to the surroundings (open-air-cooled or "OAC") or use a closed, recirculating air circuit with air-to-water heat exchangers (cooler) in the path, called totally enclosed water-to-air cooling (TEWAC).

To design a generator with a significant increase in rating without a corresponding increase in size, better coolants must be used. Hydrogen is commonly used for larger generators because of its high heat capacity and heat transfer capabilities. A hydrogen-cooled generator must use a closed cooling path with a cooler and requires reasonable safety precautions. Hydrogen does not support combustion at purities above 80%, so hydrogen purity inside the generator must be kept well above this level. As generator ratings become even larger, direct water cooling is used for some of the active components, particularly the stator winding. The largest ratings usually utilize hydrogen-cooled generators with direct water cooling of the stator winding. A special water treatment and cooling system is needed for this water to keep the water deionized and therefore "nonconducting." Figure 5 illustrates the variation in megavoltamperes per active generator volume for different ventilation categories.

BASIC MECHANICAL DESIGN CONSIDERATIONS

There are two major mechanical components in a turbogenerator, the rotor that produces the magnetic field and the stator that produces the electric output of the machine.

Rotors are long cylindrical shafts supported on hydrodynamic bearings. The main body of the rotor has long longitudinal slots machined into its outer surface. The copper windings that produce the magnetic field are inserted into these

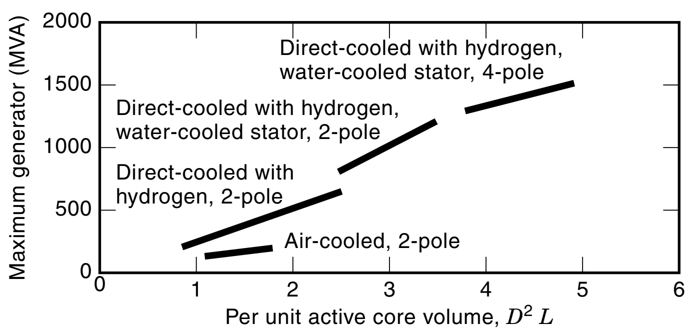

Figure 5. Generator maximum megavoltamperes versus active volume for different types of cooling.

slots. One of the most substantial loads imposed on the rotor is the force needed to retain the windings in the slots at operating speed. This is accomplished by placing a metal wedge at the top of the rotor winding in each slot. Loads from the windings and the wedge are transferred to the "tooth" of the unmachined portion of the rotor between the winding slots.

The copper conductors must exit the slots at the end of the rotor body, traverse the periphery of the shaft, and enter another slot in the rotor body to complete the circuit for the winding. These "end-windings" are not contained within slots as are the straight parts of the winding, but they still must be supported against the enormous rotational forces. End-windings are mechanically supported by high-strength cylindrical retaining rings. The retaining rings are mounted on the rotor body by shrink-fits and/or mechanical attachments. They extend over the end-windings and provide the required centripetal forces to keep the copper conductors and insulation in place during operation.

Power to drive the turbogenerator comes from combustion turbines, steam turbines, or a combination of combustion and steam turbines. The generator rotor must transmit the full torque of all of the turbines in the shaft system. In addition to the steady torque from the turbines, the shaft must be designed for the dynamic torque generated by a certain degree of start-stop cycles, out-of-phase synchronization, system faults, and other abnormal operating conditions that may occur over the generator's design life (often as long as 40 years).

The generator stator surrounds the rotor and provides the support for the stator windings (or bars) that produce the electrical output of the machine. The stator windings are placed into slots on the inside the stator core. As in the rotor, the windings are retained in the slots by wedges. The wedges must keep the windings tight within the slots and transfer the electromagnetic forces from the bars into the "teeth" of the core.

The stator core is the stationary part of the generator's magnetic circuit. It is composed of thousands of individual punchings (thin sheets of silicon steel) stacked to form a long hollow cylinder. The individual punchings are designed and stacked in a precise pattern so that the final core has slots for the windings, passages for the cooling gas, longitudinal holes for through-bolts to keep the core tight, and provisions for supporting the outside of the core to the frame. The stator core must support the windings against the magnetic and electrical forces and transfer these forces to the stator frame.

The stator frame is the main structural component of the stator. It must transfer the forces and torque from the core into the foundation of the building or supporting structure. The powerful magnetic field of the rotor attracts the core steel to the north and south poles of the rotor body. This causes the core to assume an oval shape. As the rotor turns, the oval shape of the core moves to align itself with the magnetic poles of the rotor body. This rotating oval induces vibrations in the frame at the attachment to the core.

If the vibrations are significant, they could damage the foundation supporting the generator and cause metal fatigue of the frame support. The noise from uncontrolled vibrations can also become excessive. Small generators directly connect the core to the frame because the magnitude of the core deformation is small. Large generators with high power densities must provide flexible mounting for the core so that vibration from the core is not transferred to the frame and the foundation.

Some frame designs include the bearings that support the rotor. Then the weight of the rotor must be carried by the frame and transferred to the foundation. Other generator designs have pedestal bearings mounted outside the generator frame. The pedestals support the rotor and transfer the loads to the foundation, allowing a smaller frame.

Hydrogen-cooled generators use pressurized hydrogen gas to remove the heat generated in the copper conductors and the core. The frame must be designed as a pressure vessel to retain the hydrogen within the generator and prevent its escape to the atmosphere. Because hydrogen and oxygen combine to form explosive mixtures, the frame must be designed to contain any explosion that might occur. The explosion pressure may be many times the hydrogen pressure, so large generator frames are typically made from steel plate several inches thick. The frame of hydrogen-cooled generators must also support coolers to remove the heat picked up by the hydrogen gas. The coolers are usually finned-tube heat exchangers. Hydrogen gas flows across the fins mounted on banks of tubes through which a liquid coolant passes. The generator frame must support the weight of the cooler, and it must also provide gas passages for the hydrogen to circulate. The hydrogen gas is circulated through the generator by either an external motor driven blower or a rotor-mounted fan or blower.

THERMAL DESIGN

Very large currents are carried by the copper conductors within the generator. The currents heat the copper to high temperatures, and this heat must be removed if the generator is to function reliably in continuous operation.

The rotor windings are normally cooled by forcing gas (air or hydrogen) through passages around or within the copper conductors. The gas picks up the heat from the conductors and then is expelled from the rotor. Then the circulating gas is exhausted from the generator (open air cooled designs), or it passes through a cooler (TEWAC or hydrogen-cooled designs) which removes the heat from the gas.

Several manufacturers have developed liquid (oil or water)-cooled rotor windings to improve the heat transfer from the copper conductors and improve the efficiency of the generators. Liquid-cooled rotors must have complex mechanisms to circulate the cooling liquid into and out of the rotor while it is turning at high speed. The connections within the rotor windings must also be leakproof to prevent the cooling liquid from contaminating the inside of the generator. The complications of liquid-cooled rotors have limited the number of units that utilize this cooling method.

Heat is also generated in the stator components during operation. Large alternating currents are generated within the stator windings. These currents heat the copper conductors to high temperatures. The rotating magnetic field also heats the core and the frame. All of this heat must be removed if the unit is to operate continuously.

Usually the core and frame are cooled by the cooling gas (air or hydrogen) which circulates through the generator. The core is constructed with axial and/or radial vents for the cooling gas. Heat generated in the windings and the core is conducted through the core steel to the vents where the heat is transferred to the gas. The frame is designed to direct the circulation of the cooling gas, and it is cooled by direct contact with the gas.

The windings may be cooled by one of three methods: conventional cooling, direct cooling, or liquid cooling.

In conventional cooling the heat generated in the copper is conducted through the insulation that surrounds the windings into the core where it is conducted through the steel to the vents. This is the simplest cooling method, and it has been used since the beginning of the electrical age. Heat conduction through insulating materials is not very efficient, so this method of cooling seriously limits the power density of the generator.

Direct cooling is achieved by providing cooling passages within the windings. This is normally accomplished by embedding nonmagnetic metal tubes within the winding. The circulating gas is forced through the cooling tubes. Conductors within the windings are electrically isolated from each other and the cooling tubes by a thin covering of insulation. The cooling tubes are in direct contact with the thin layer of insulation resulting in much improved heat transfer.

Liquid cooling is the most efficient method of removing heat from the copper conductors. The winding is designed so that approximately every third copper conductor is hollow. At each end of the winding, all of the hollow conductors within a half-coil (or bar) are joined together into a header. Liquid coolant is pumped into a manifold at one end of the generator. Insulated tubes connect the manifold to the header at one end of the winding, and coolant passes through each of the hollow conductors. Heat from the conductors is transferred to the liquid coolant. The header at the opposite end of the winding collects the liquid coolant from each hollow conductor and the coolant flows through another insulated tube into another manifold. The coolant from the manifold passes out of the generator, and the heat is rejected to the atmosphere through a cooler.

DYNAMICS AND VIBRATION

The shaft systems of large turbogenerators are subject to two types of vibration. Lateral vibration is characterized by the beam-bending of the shafts between the bearing supports. Torsional vibrations arise from the axial twisting of the rotor sections with respect to each other.

The lateral natural frequencies of shaft systems are called the critical speeds because the vibration of a rotating shaft system can become very large at certain rotational speeds when the natural frequency of the shaft system matches the rotating speed of the shaft. Small imbalances in the shaft system excite large vibratory motion at critical speeds. Clearly, it is essential that a turbogenerator shaft system be designed so that the operating speed does not match a critical speed.

It is also important to eliminate as much of the residual imbalance in the shaft system as possible. To accomplish this, turbine and generator shafts are designed and machined to precise tolerances to eliminate as much mass imbalance as is practical. Numerous balance planes are designed into the rotors and shafts so that residual imbalance can be reduced by adding balance weights to the shafts.

Torsional vibrations in shaft systems may arise due to unbalanced loads in the three-phase electric system. Phase imbalance results in an oscillating torque on the shaft system at twice the electric system frequency (120 Hz for 60 Hz systems and 100 Hz for 50 Hz systems). Short circuits, transmission line switching, and out-of-phase synchronization also briefly excite shaft system frequencies that lie near the electric system frequency (50 Hz or 60 Hz).

If one of the torsional natural frequencies of the shaft system is at or close to twice the electric system frequency, the magnitude of the torsional vibrations become very large, possibly large enough to produce fatigue cracking of shafts, turbine blade, or other rotating components.

Torsional vibrational problems are generally more serious than lateral vibrational problems for two reasons. First, there is no way to "balance" torsional vibrations. The magnitude of the lateral vibration is controlled by how close the critical speed is to the operating speed and by the magnitude of the residual imbalance. If the magnitude of a lateral vibration is too large, the system can be balanced to reduce the amplitude of vibration. Torsional vibrations can arise in turbogenerator shaft systems that have natural frequencies very near single or double line frequency. This is not something that can be easily corrected and often requires major design modifications to correct.

Another reason why torsional concerns are difficult to resolve is because there is very little damping present in torsional vibrations. The oil films in the bearings provide substantial damping for lateral vibrations, but not for torsional vibrations.

The best approach in avoiding torsional vibrational problems is in the initial (or upgraded) design of the turbine-generator, so that the rotor system is designed to avoid excitable torsional natural frequencies near single or double line frequency. Once operating, torsional vibration problems are resolved only by making substantial design changes to the generator rotor or the turbine shafts. The stiffness of the shaft system can be changed by reducing section diameters, or mass can be added at locations along the shaft.

APPLICABLE STANDARDS AND CODES—SUMMARY OF BASIC REQUIREMENTS

Turbogenerators are usually designed and built to certain national or international standards. Standards provide a base for objectively comparing machines of different designs. They also allow customers to specify and acquire products with consistent features without going deep into the details and intricacies of design and manufacture.

Standards are usually established by national, international or professional organizations. The most commonly used standards applied to turbogenerators are established by the American National Standards Institute (ANSI), the International Electrotechnical Commission (IEC), and the Institute of Electrical and Electronics Engineers (IEEE). ANSI and IEC are the two main governing sets of standards. ANSI is dominant in North America (predominantly 60 Hz), and the IEC standards are widely used elsewhere (predominantly 50 Hz, except in Brazil, South Korea, Japan, Taiwan, and a few other places that use 60 Hz power). IEEE standards deal more with specific technical aspects of testing, control, and applications of turbogenerators. They are routinely referenced worldwide.

Following are some of the specific standards that define the requirements and procedures for designing and testing turbine generators:

- ANSI C50.10 ANS for Rotating Electrical Machinery—Synchronous Machines
- ANSI C50.13 ANS for Rotating Electrical Machinery—Cylindrical-Rotor Synchronous Generators
- ANSI C50.14 ANS Requirements for Combustion Gas Turbine Driven Cylindrical Rotor Synchronous Generators
- ANSI C50.15 ANS for Rotating Electrical Machinery—Hydrogen-Cooled, Combustion-Gas-Turbine-Driven, Cylindrical-Rotor Synchronous Generators
- IEEE Std 115 IEEE Guide: Test Procedures for Synchronous Machines
- IEC 34-1 Rotating Electrical Machines Part 1: Rating and Performance
- IEC 34-2 Rotating Electrical Machines Part 2: Methods for determining losses and efficiency of rotating electrical machinery from tests
- IEC 34-3 Rotating Electrical Machines Part 3: Specific requirements for turbine-type synchronous machines
- IEC 34-4 Rotating Electrical Machines Part 4: Methods for determining synchronous machine quantities from tests.

The standards specify basic operating requirements, define rated and off-rated output, describe normal and emergency operating conditions. Definition of rating is principally related to temperatures reached by various generator components, primarily insulation. Insulating materials used in turbogenerators are categorized in classes according to the temperature they withstand without damage. For each class of insulation, temperature limits are specified for various components of the machine along with the method of measurement. The intent of these limits is to provide reliable operation of the machine throughout its design life. In addition to the base rating, peak and peak reserve capabilities are specified. Temperatures in the generator, at these special ratings, are allowed to be higher than at base rating at the cost of accelerated insulation life consumption, which is generally considered acceptable if it is of relatively short duration and infrequent (exceptionally hot summer or exceptionally cold winter day, unexpected outage of other generators, etc.).

The conditions in which a generator operates are determined by the temperature and pressure of the available cooling medium and the electrical parameters (voltage and frequency) at its terminals. Enclosed machines operating in pressurized hydrogen gas are typically operated with constant hydrogen pressure and cold gas temperature. The specified value of this temperature is such that it can be readily maintained in most typical situations. If this is not possible, agreements must be made for special design features. Air-cooled machines depend on their environment for pressure and, in some cases, for cold air temperature. The standards specify how the rated output of the generator must be adjusted so that the highest temperatures reached by its compo-

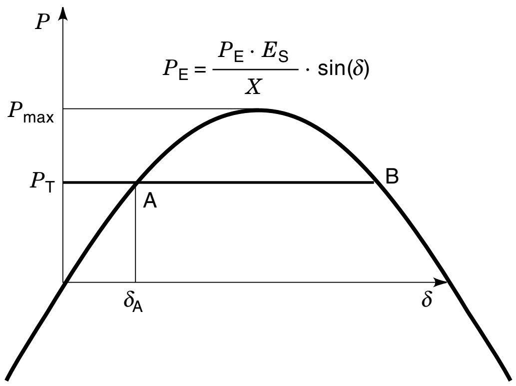

Figure 6. Steady-state stability.

nents stay within required limits for the insulation class, that is, at higher altitude and/or higher cold air temperature the rating of the generator may be reduced.

Even during perfectly normal operation, the voltage at the generator's terminals and the frequency at which it operates can normally be maintained only within a range around the nominal values rather than exactly at those values. The standards specify the voltage and frequency ranges in which the turbogenerators are required to operate reliably. The specified temperature limitations can be exceeded during off-nominal voltage and/or frequency operation within these ranges, as long as they do not pose a threat to the generator.

Emergency situations, such as lightning strikes, short circuits, erroneous switching, and short-time overloads, are inevitable in a power system. Standards define the types and severities of the disturbances that turbogenerators must withstand and the acceptable amount of damage they can suffer from extreme conditions.

Reactances and Machine Parameters

The primary purpose of a turbogenerator is to deliver electric power to a power system. This delivery, however, must satisfy certain conditions to make it acceptable by the system, particularly a modern, complicated system. The generator must reliably run in step (synchronously) with the system, it must properly support the voltage in its vicinity, and must not unnecessarily increase the short-circuit severity in its vicinity.

The concept of stability can be understood by considering Fig. 6. The power P_E delivered by the generator to the system is proportional to the voltage E_F induced in the generator, the voltage E_S of the power system and the sine of the angle of rotor rotation δ representing the time by which the peak of the generator internal voltage precedes the peak of the remote system voltage. This power has a maximum P_{max} taking place when the generator voltage precedes the system voltage by one-quarter cycle (90°). The power P_T supplied by the turbine is constant for a particular setting of the turbine's governor. In normal steady-state operation, delivered power P_E must be equal to the turbine power P_T (minus generator loss which is relatively small), and the angle δ adjusts itself accordingly (δ_A). The generator is said to be stable if this balance is established at the rising slope of the power curve, point A in Fig. 6. The equilibrium at point B is unstable because an increase in angle δ causes a reduction of delivered power. The generator's operation is more stable the smaller

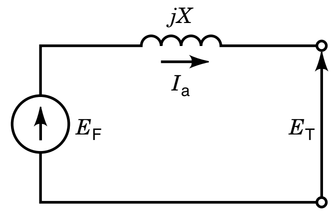

Figure 7. Equivalent circuit.

the angle δ_A is, that is, the larger P_{max} is with respect to P_T. This ratio can be improved by making the variable X smaller. This parameter is the total reactance between the internally generated voltage in the generator and a point in the power system that is considered sufficiently strong and remote from the generator not to be affected by the generator's performance. The internal reactance of the generator is a significant portion of this reactance. Transmission lines and transformers represent the balance. Similar considerations are in place during transient conditions.

Parameters that determine the generator's interaction with the power system are its reactances, time constants, and some other parameters. Reactances of a synchronous generator refer to its representation by a simple equivalent circuit shown in Fig. 7. A device as complex as a turbogenerator, consisting of a strongly nonlinear magnetic circuit and a number of mutually moving, coupled electric circuits, cannot be represented by constant parameters in a simple linear equivalent circuit. Therefore, several separate sets of parameters are, defined for the circuit in Fig. 7, that properly represent the machine's behavior in various situations.

The subtransient reactance and subtransient time constant X''_d and T''_d describe the machine in the first few cycles following a major disturbance (sudden short circuit, out-of-phase synchronization). These parameters control the generator's current and its rate of decay immediately after the short circuit and determine the demands on the circuit breakers and the electromagnetic forces experienced by all equipment between the generator and the short-circuit location.

After the initial period, transient reactance and time constant X'_d and T'_d better describe the machine and its ability to recover synchronous operation with the system after the fault has been cleared. The synchronous reactance X_d or its related representation, the short circuit ratio, determine how close to the stability limit the generator operates during normal steady-state operation. The rated power factor determines the

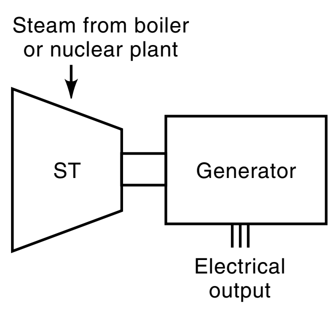

Figure 8. Simple cycle steam turbine drive.

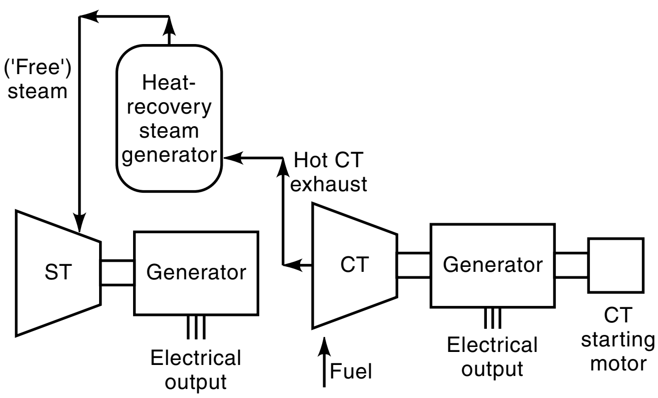

Figure 9. Dual-shaft (standard) combined-cycle arrangement.

generator's ability to supply reactive power to the system, and contribute to the local area voltage support.

Losses and Efficiency

Although the efficiency of synchronous turbogenerators is very high (98% and higher), considering and minimizing losses is of great importance. The losses in a turbogenerator are the main limitation on the output power, that is, the output is limited by the ability to remove the heat generated (resulting from losses) in the generator. From an investment perspective, every kilowatt of loss saved is an extra kilowatt available for sale. For both these reasons, it is important to predict a turbogenerator's losses precisely and to minimize them.

Various types of losses in a generator are related to design features, material properties, and output. The relationships are complex, nonlinear, and often partially uncertain (properties of actual materials that eventually become part of the generator are known only within some tolerances at the time of design).

According to their physical nature, the losses are categorized as follows:

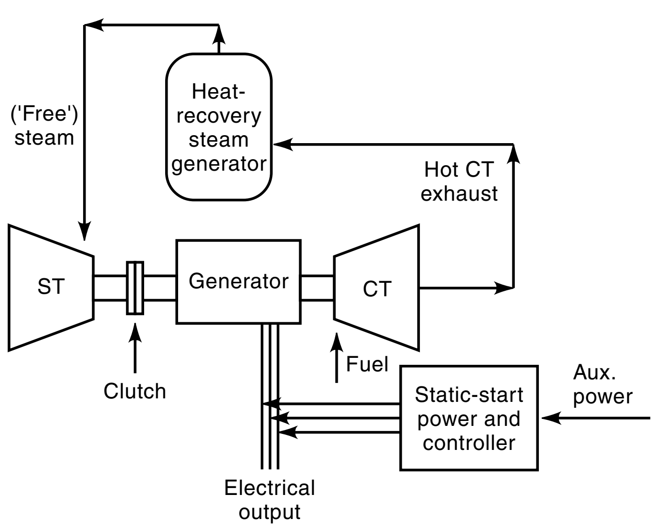

Figure 10. Single-shaft combined-cycle arrangement.

magnetic loss due to ac magnetic fields
electric loss due to current flow through windings
mechanical loss from friction in bearings and ambient gas
ventilation loss, that is, power to move the coolant needed for heat removal

According to their dependence on machine output, the losses are constant losses and load-dependent losses.

Because neither of the two classifications is very convenient for practical purposes, the standards define the schedule of losses with precise definitions. Such a schedule is given here with a very brief description. More detail can be found elsewhere, such as ANSI C50.10 or IEC 34-2.

- Armature I^2R loss: load-dependent electric loss due to load current flowing through the dc resistance of the armature winding
- Stray load loss: load-dependent electric and magnetic loss caused by load in various members of the machine (eddy loss in windings, additional loss in core, rotor surface loss, loss in various structural parts)
- Core loss: magnetic loss caused by the alternating magnetic flux in the stator core (constant for operation at constant terminal voltage)
- Field I^2R loss: load-dependent electric loss due to dc current flow through the rotor winding
- Exciter loss: sum of all losses in the equipment that provides exciting power for the generator
- Frictional and windage loss: generally constant mechanical loss caused by friction in the bearings and gland seals (friction) and friction of all rotating parts against the gas that surrounds them (windage)
- Ventilation loss: constant power needed to move the cooling media (air, hydrogen, water) through the machine's cooling passages

Testing

Numerous tests are performed during manufacturing and installing a turbogenerator. Components of a generator are tested during the manufacturing process to assure that they are of high quality and that the completed generator meets the final requirements. Particular attention is directed to nondestructive structural testing of the rotor forging, dielectric properties of armature coils, and proper performance of the stator core.

Once manufacturing is completed, running tests are often performed, of which there are two types. Commercial testing is performed to verify the performance of the generator and compliance with contractual agreements. These often apply only to the first of a design but depending on the contract, could be required for subsequent units. Most commercial tests are specified by standards. Development testing is much more detailed and is usually performed only on the prototype for a new design or if a substantially new design feature is introduced. The types of tests and measured variables depend on the type of development that is being investigated.

Large turbogenerators cannot be tested at their normal operating conditions in the manufacturing plant. No manufacturer in the world owns a facility that could test a turbogenerator at its full rating because it requires a tremendously large drive mechanism and electric load. Such tests are done only in the power plant after the generator is installed. Because a power plant environment poses substantial limitations on such testing, most manufacturers test generators in their own test facilities, using testing methods that validate the performance of the generator. These test facilities require a drive mechanism sufficient to bring the generator to the required speed and compensate for losses. These tests are the steady-state, open-circuit test; steady-state, short-circuit test; and sudden short-circuit test.

In a steady-state, open-circuit test the generator is driven at constant rated speed without load (terminals open-circuited). Several consecutive values of excitation are applied, and the resulting terminal voltage is measured. The shaft input power and excitation power are also measured. This test determines the open-circuit saturation curve (correlation between induced voltage and applied excitation current) that provides information for calculating the excitation required at load and, to a significant extent, validates the magnetic circuit design. The measured power supplies information for determining the losses that are independent of the load (core loss, friction and windage, ventilation).

The steady-state, short-circuit test is performed with the generator's terminals short-circuited (zero voltage) and the field excited until a desired armature current is established. The rotor is driven at rated speed. Excitation current, armature current, drive power, and excitation power are measured. This is repeated at several current values. This test supplies information about load-dependent losses, mainly the stray load loss.

Both open-circuit and short-circuit, steady-state tests are usually performed at a few selected voltage or current levels, respectively, for as long as it takes to reach thermal steady state. Then the temperatures reached by various machine parts are recorded. This supplies information about the adequacy of the thermal design.

The adequacy of the ventilation design, including pressures at various key points in the generator and gas flows through the machine's components, is determined in a separate ventilation test when the machine is run unexcited at constant speed while the measurements are taken.

Sudden short-circuit tests are performed to measure the machine's transient parameters (transient and subtransient reactances and time constants), and to verify its ability to withstand such events without structural or other damage, as specified by standards.

Before shipping, testing is concluded with a thorough inspection and final dielectric tests of the stator and rotor windings, as required by standards.

TURBOGENERATOR APPLICATIONS

Several different configurations of prime movers for generators are possible. The most common are the simple-cycle steam or combustion turbine and the combined-cycle configurations. A simple-cycle configuration consists of a steam turbine (ST) or a combustion turbine (CT) directly driving a generator at synchronous speed. For added efficiency, the hot exhaust of one or more combustion turbines is recycled through an air-to-water heat exchanger, called a heat-recovery steam generator (HRSG) to create steam. The steam produces power in a steam turbine. This configuration is referred to as a combined-cycle plant. Normally, the CT and the ST drive their own independent generators. If the CT and the ST of the combined-cycle plant are attached to opposite ends of the same generator, the configuration is called a single-shaft, combined-cycle arrangement.

A few fundamental issues must be addressed when selecting an electric generator to match a particular prime mover. First, the generator's real power output rating must meet or exceed that of the prime mover(s). Additionally, the generator must provide reactive power to the power system as needed, which is usually specified as a power factor. The power output of many combustion turbines varies according to their inlet air density, and thus is higher on cold days and lower on hot days. One way to assure that the generator capability meets or exceeds that of the CT is to map both CT output and generator capability against ambient air temperature and compare them.

A second important consideration is to determine the type of generator needed. Most synchronous generators rated over 50 MVA use water cooling, hydrogen cooling, or air cooling for the stator winding. The rotor cooling method can be specified independently, but because water-cooled rotors are relatively rare, most machines that use water cooling for the stator winding use hydrogen cooling for the rotor. Consequently, a "water-cooled" generator, as the term is often used, generally describes a generator with a water-cooled stator winding and hydrogen cooling for the rotor winding, core, and other active parts. Water- and hydrogen-cooled generators have the advantages of being more efficient and less susceptible to environmental contamination. They are also capable of higher power densities. Their disadvantages are cost, complexity, and maintenance. Because of advances in technology, today's air cooled generators obtain relatively high power densities, making them a very inexpensive and attractive alternative to water- and hydrogen-cooled generators for sizes under 150 MW to 200 MW.

Generator capability is defined by the output achieved while keeping temperatures inside the generator within limiting values listed in industry standards. Therefore the 'best' generator is defined as the least expensive generator that meets or exceeds its design requirements. With that in mind, the following concepts can be utilized to maximize a generator's capability:

1. Water provided to the generator for cooling should be as cool as possible. This allows the lowest generator temperatures and the highest generator capability.
2. Electric power factor requirements for the generator also contribute to the generator size. As the rated power factor decreases for a given real power output, the required reactive power increases, as do the stator current and rotor current. These increased currents cause more heat that restricts capability. Therefore, reducing the reactive power output requirement of a generator, often allows greater real power output capability.

In a simple steam arrangement, the boiler must produce steam before the steam turbine can produce power. After steam is available, the turbine generator unit can be brought up to full speed, and power produced.

In a combustion turbine unit, the CT must be brought to roughly 40% of synchronous speed before it can support combustion. Spinning the CT to start it is often accomplished by using a starting motor. Once the CT has started and accelerates itself, a clutch mechanism commonly disengages the starting motor from the turbine generator train. In some cases, the CT is started by a mechanism called 'static start.' A static start package is a power electronic circuit that converts auxiliary ac power into controlled, variable-frequency, three-phase ac. Then this is sent into the generator armature winding and temporarily utilizes the generator as a synchronous motor, accelerating the CT up to starting speed. Once starting speed is attained, the CT is used to bring the entire CT-generator train up to rated speed.

Combined-cycle units normally have their CT unit(s) started first. When the CT is operating at full speed, the exhaust is sent to the HRSG to make steam. After sufficient steam pressure is available, the steam turbine portion of the combined cycle can be started. If the combined-cycle unit has a single-shaft arrangement, a clutch mechanism keeps the steam turbine disconnected while it is being brought up to speed. This clutch can be engaged and disengaged at rated speed so that a single-shaft, combined-cycle plant can operate as simple cycle or combined cycle as desired.

Generator Efficiency—Optimization

Optimizing a generator for efficiency is very important. For example, an efficiency improvement of only 0.01% on a 250 MW generator results in an additional 25 kW available for sale. At 5 cents per kilowatt hour, this totals roughly $10,000 per year, assuming a 90% availability factor. Amortized at 10%, the resulting energy savings are roughly $100,000 in present worth. Additionally, each additional kilowatt represents capacity that normally costs in excess of $500/kW. The corresponding savings, considering both energy and capacity savings, are roughly $4500 per kW of efficiency enhancement.

Before an effective efficiency study can be done, a loss evaluation factor in $/kW saved must be established using appropriate parameters for the application. This evaluation factor is a guide in determining if changes to an existing generator design are warranted. The costs of the changes are compared to the dollar savings achieved by the efficiency enhancement.

Efficiency enhancements are occasionally obtained by utilizing excess generator capability if it is available. For example, consider a generator with excess capability (defined by its low operating temperatures). If the generator is hydrogen-cooled using 4 atm of hydrogen pressure, the generator could have its hydrogen pressure reduced to 3 or 3.5 atm, as the design allows. This would raise internal temperatures because of reduction in heat transfer capability of the hydrogen, but it would also reduce hydrogen density and decrease windage loss, thereby reducing generator loss. Other modifications can sometimes be effected to enhance efficiency. For example, a stator or rotor can sometimes be rewound with an optimized coil to enhance efficiency, but this most often results in reduced generator capability.

When selecting a new generator, efficiency may be enhanced by selecting a slightly oversized generator, particularly for hydrogen- and water-cooled generators, which have relatively low fixed loss. Because the point of maximum efficiency is where fixed loss equals variable loss, a reduction in variable loss, which occurs naturally in an oversized generator, often results in higher efficiency at the generator maximum output. This is shown in Fig. 11. As generator size increases, the generator efficiency curve shifts to the right. Although the curve maximum still peaks at approximately the same efficiency value, peak efficiency is closer to maximum output for the larger generator. In air-cooled generators, fixed loss often constitutes a larger percentage of the total, so maximum efficiency is generally obtained by using the smallest generator that satisfies the load requirements. Because of the relatively large amount of power necessary to provide ventilation to air-cooled machines, it is normally advantageous to operate these machines at elevated temperatures, if at all possible, by using insulation with high thermal capability (Class F or Class H insulation, for example).

Abnormal Operating Conditions

The following are among the anticipated abnormal operating conditions that affect the size and selection of a new generator:

1. Extended operation at other than nominal frequency
2. Extended operation beyond normal voltage limits
3. The existence of system-negative sequence sources
4. Low power factor operation, including synchronous condenser operation

Before discussing abnormal operating conditions, it is necessary to establish what normal operating conditions are. Normal operating conditions are generally recognized as those specified in industry standards.

The generator terminal voltage is directly proportional to the flux density inside the generator core. One of the concerns of operating with a continuous overvoltage is that the generator internal flux density exceeds design levels, possibly damaging core steel laminations. If the generator voltage is too low and this results in underexcited operation, core end-

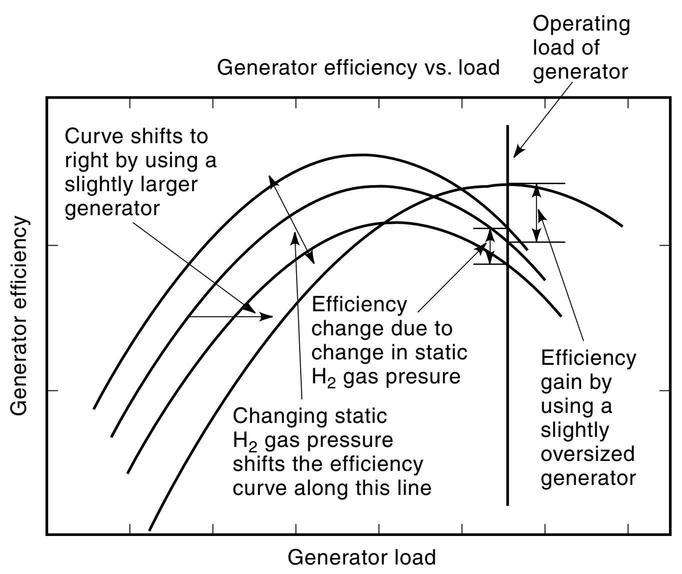

Figure 11. Variation in generator efficiency with size and gas pressure.

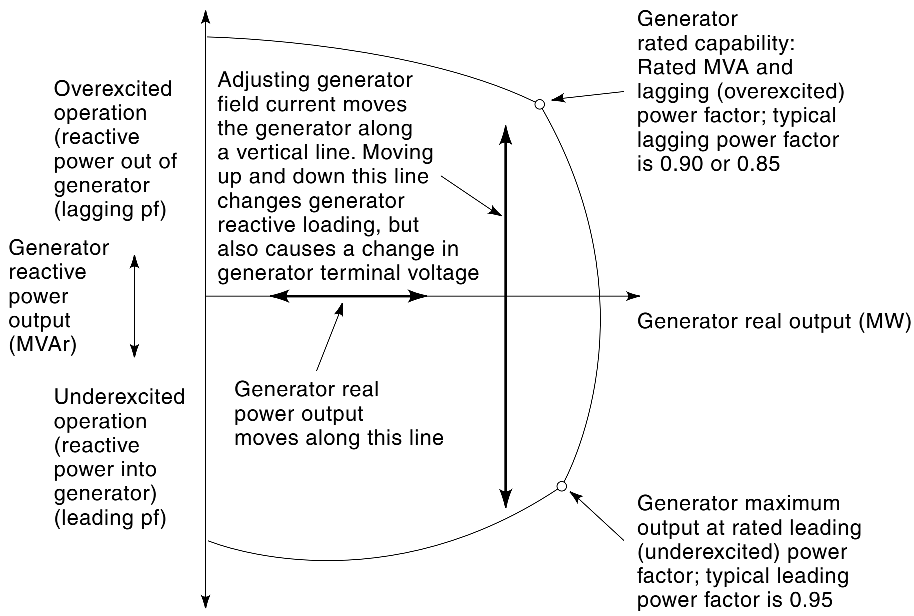

Figure 12. Generator reactive capability curve.

region heating concerns can arise. Also, to achieve rated power output, reduced voltage corresponds to higher current that may be excessive.

Operation at reduced frequency causes concerns of core heating similar to those from operation at excessive voltage. Voltage in a generator is defined by the following relationship:

$$\text{Volts} \propto \frac{d}{dt}\text{Flux}$$

or, equivalently,

$$\frac{\text{Volts}}{\text{Hertz}} \propto \text{Flux}$$

At normal operating frequency, the flux in the generator core is dictated by the terminal voltage. When the system frequency is reduced, more flux is required to maintain the same terminal voltage, which could result in a high flux condition in the generator core. Therefore, it is important to operate within the voltage-frequency band as shown in Fig. 13, which approximates the requirements of the IEC standards, or as dictated by the manufacturer.

During start-up conditions, the frequency changes rapidly as the unit is brought to operating speed. At low frequencies, the generator terminal voltage must be kept low (or zero) to prevent overfluxing the generator core. During a typical startup, field excitation is not applied until the generator achieves synchronous speed. Precautions must be observed to prevent overfluxing the generator core, particularly with the unit off-line during which flux increases cannot be constrained by armature reaction for corresponding increases in excitation level.

Balanced three-phase current in the generator stator is sometimes called 'positive sequence' current because it creates a flux wave that rotates in the same direction as the rotor. When stator currents become unbalanced, the magnitude of the current unbalance is called 'negative sequence' current because it results in flux components that rotate in a direction opposite to that of the rotor. The resulting flux variations due to negative sequence current cause rotor surface heating because of induced eddy currents.

Unbalanced operation of a three-phase generator is typically specified by limits of negative sequence current. Standards require generator manufacturers to allow up to 10% continuous negative sequence current, depending on the rating of the generator. Smaller continuous negative sequence limits are allowed for larger generators, which are assumed to be connected to high-voltage transmission systems with small amounts of unbalance. Voltage unbalances during operation are not specified by industry standards but they induce negative sequence currents and are taken into account in the limi-

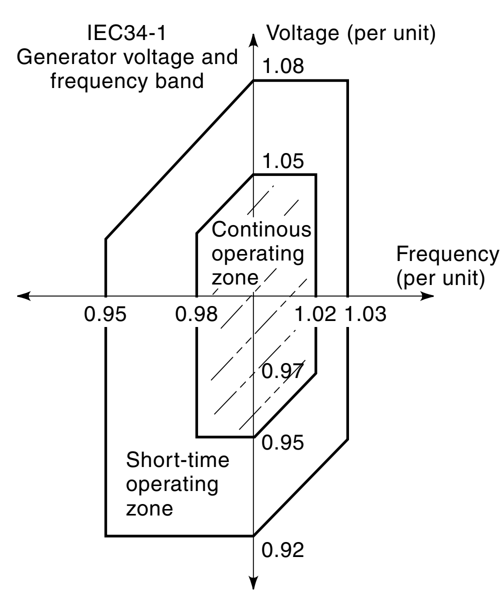

Figure 13. Normal voltage and frequency conditions for turbogenerators.

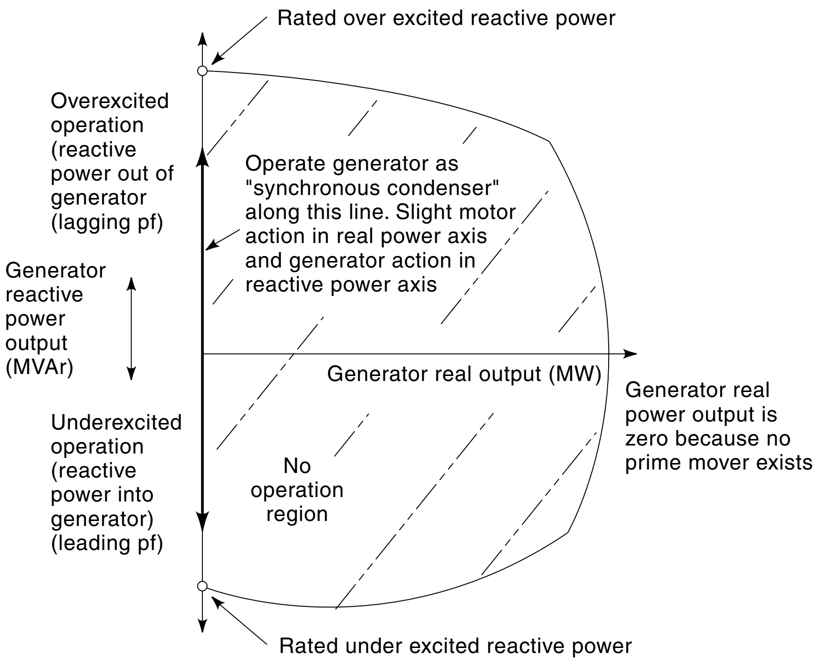

Figure 14. Operation as a synchronous compensator.

tations. Current unbalances normally result from system load, transmission line, transformer unbalance, or from unbalanced system disturbances, not from the generator.

For generators, a lagging power factor indicates overexcited operation and means that the line current out of the generator is lagging (or behind) the voltage in time. Likewise, a leading power factor indicates underexcited operation, or current leading the voltage in time. Typically, generators are specified with lagging power factors in the range of 0.9 to 0.85, whereas leading power factors are routinely specified as 0.95. Lagging power factor operation allows the generator to compensate for inductive power system loads and support low system voltage by producing reactive power (or vars). A leading power factor allows the generator to compensate for a capacitive power system and hold down high system voltage by absorbing vars. In general, power systems are more inductive than capacitive, requiring generator operation with a lagging power factor. Leading (underexcited) power factor operation is sometimes required in metropolitan areas with large underground cable systems, particularly during light load, when there is a surplus of capacitive reactive power in the system from cable charging. Operating a generator overexcited (lagging power factor), which is more typical, requires the generator to have more field current than when operating underexcited. Higher field current causes higher internal generator temperatures from rotor winding I^2R losses. Consequently, requirements for operation with lower lagging power factor typically require a larger generator.

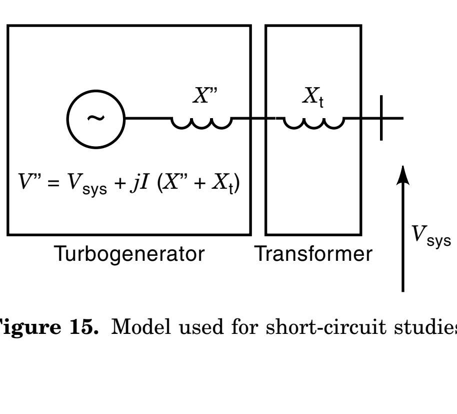

Figure 15. Model used for short-circuit studies.

Although operating with a leading power factor requires less field current than with a lagging power factor, other issues arise which limit the leading power factor to a value typically no less than 0.95. Magnetic flux in the end-region of a generator can travel axially, entering the end of the core normal to its surface. This axial flux causes many unwanted eddy currents and results in localized high temperatures. The axial magnetic flux component from the stator circuit opposes that of the rotor circuit, and together, the rotor and stator circuit produce very little axial flux. During underexcited operation (leading power factor), however, the stator circuit produces its normal amount of axial flux, which is counteracted by a weaker rotor component. This condition causes a net higher axial end-region flux and results in higher end-region localized temperatures. If it is essential that the generator be capable of leading power factors lower than 0.95, this may require increasing the generator size or capability.

Synchronous Compensator Operation

A generator without a prime mover is often called a “synchronous condenser” in the United States and a “synchronous compensator” elsewhere. Synchronous compensators are used for steady-state and dynamic voltage control. They supply or absorb reactive power to support and control local system voltage. Some synchronous compensators are synchronous generators at ‘retired’ power stations. The losses in the compensator are supplied by the power system itself through synchronous motor action in the generator. As reactive power is needed, excitation is adjusted to allow operation at zero real power output. Applying a generator for operation as a synchronous compensator generally necessitates carefully evaluating the generator terminal voltage and step-up transformer tap settings to optimize the performance of the compensator.

System Studies and Modeling

The precise modeling of turbogenerators requires very detailed representations to accurately reflect the internal operation of the machine, particularly if higher order characteristics, such as saturation, are considered. Because power system simulations may involve representing many machines, transmission lines, transformers, etc., to reflect the complexities of modern interconnected power systems, simplified models have been developed for power system equipment, including turbogenerators. These simplified generator models provide accurate simulations for specific types of power system studies. Consequently, the model used to represent a turbogenerator depends upon what is being studied in the power system.

For typical power system applications, studies are divided into three types: (1) steady-state, or "load flow," studies; (2) stability studies; and (3) short-circuit studies. Power system analysis software normally has standard modules to analyze these three areas.

1. **Steady-state:** Steady-state, or load-flow, studies analyze the system in the steady state and are concerned with common operating conditions, such as an outage of a local transmission line or of another local generator. These studies are generally performed to determine how the generator being studied can be best used to enhance steady-state operation of the system. They are sometimes used to determine local power transfer capabilities and operating reserve requirements for generation. For this type of study, the generator is modeled very simply using its reactive capability curve and its terminal voltage limits. Real power output of the generator is stipulated, and the reactive power is either stipulated directly or, more commonly, adjusted to maintain a desired voltage at a specific point in the power system. For example, the reactive output of the machine may be selected to maintain nominal voltage within ±1% at the midpoint of the generator step-up transformer leakage reactance. The point at which the voltage is controlled is a matter of local practice, but it is usually not on the transmission system because of the concern that other voltage control equipment (tap-changing transformers, switched capacitors, etc.) may have conflicting voltage control objectives.

2. **Stability:** Transient stability studies examine the integrated performance of the system during and following disturbances. Turbogenerators are generally the focus of these studies because of the relatively large amount of stored mechanical energy available from the spinning shaft of the turbine and generator. Unlike other power system components, such as transmission lines, transformers, and capacitors, generators normally have several seconds of stored energy that can be applied to stabilize the system during disturbances. Stability studies require knowledge of the generator's mechanical inertia, often described using the inertia constant (usually designated as the "H constant"). The H constant is the amount of spinning energy available from the generator, turbine, and exciter as a multiple of the rated output power. The H constant for a typical turbogenerator (including the connected turbine and exciter) is typically on the order of 2 to 4 MW-s/MVA of turbogenerator capacity. Although certain oscillatory stability incidents may last up to several minutes, most stability studies are concerned with the time domain between 0.1 s and 10 s. An understanding of the important considerations for stability analysis can be obtained from the "undamped-swing-equation," which roughly describes the operation of the generator rotor after a disturbance:

$$d^2\delta/dt^2 = (P_\mathrm{m} - P_\mathrm{e})/(2H)$$

where δ is a measure of the angular displacement of the generator rotor with respect to a continuously rotating reference frame; P_m is the accelerating mechanical power supplied by the turbine; and P_e is the restraining electric output power of the generator.

During steady-state operation, the electric output power equals the mechanical input power, and the rotor angular acceleration ($d^2\delta/dt^2$) is zero, so that the machine remains stable. When the electric output power is reduced to levels and durations that permit the rotor angle to advance beyond the point at which synchronism is maintained, "pole slipping" and system instability occurs. Before the widespread use of computers, the solution of the swing equation was sometimes performed graphically, using a diagram similar to Fig. 6, so the solution of the swing equation is sometimes described as application of the "equal area criterion." The criterion is that the accelerating area of the curve is less than the stabilizing area. The amount of time that the rotor can accelerate unrestrained without losing synchronism is sometimes called the "critical fault clearing time."

For typical studies that require simulations of less than 5 s to 10 s, the generator is modeled electrically as a voltage source connected to the step-up transformer by the generator's transient reactance X'. The transient reactance dominates the generator's behavior in this time domain, and the model that assumes this is said to use the "voltage behind the transient reactance." Longer simulations may require use of the voltage behind the synchronous reactance.

Excitation systems are often of considerable benefit during short duration transient situations, so stability studies normally often use a fairly detailed depiction of the generator excitation system. Stability studies are often used to determine power transfer levels between adjacent systems, for example, between New England and New York, and to determine spinning reserve requirements. Spinning reserve is the amount of generation kept on line beyond that required for satisfying load requirements to maintain safeguards against failure of a major unit or generating plant.

3. **Short circuit:** Short-circuit studies are performed to examine the capability of the power system to withstand major faults, such as three-phase short circuits, single-phase-to-ground short circuits, etc. These studies concern themselves with the capability of the system to isolate the faulted section by operation of relays and power circuit breakers. Modern protective relays and breakers sense and interrupt a short circuit in just a few electric cycles, so the time domain of interest for this type of study is 0.01 s to 0.1 s. Use of the proper model for turbogenerators is important for these studies because generators are the source of the short-circuit current in

the power system. No other component has such a large source of electromagnetic energy as the magnetic field of the generator. Indeed, often the only source of short-circuit current is assumed to be generators (both turbogenerators and hydrogenerators), although large motors and induction generators are sometimes also added. The model used for the generator in this type of simulation is that of a voltage source connected to its step-up transformer by the generator's subtransient reactance. The subtransient reactance dominates the performance of the generator in this time domain and limits the generator fault current during the critical first few cycles after initiation of the fault. Although modern excitation systems are employed to reduce generator short-circuit currents, excitation systems are normally not modeled for short-circuit studies, yielding conservative results.

SITING OF TURBOGENERATORS AND TRANSMISSION INTERCONNECTIONS

Important considerations for siting of new generating stations include:

1. The availability, cost, and security of the operating supplies (fuel, water, etc.).
2. The ability of the system to accommodate the generation, that is, adequacy of local transmission to transmit power and adequacy of the local distribution system to provide station service power.
3. The ability of the local transmission circuit breakers to accommodate increases in short-circuit current that occurs after introducing new generation.
4. The need of the local system for enhanced voltage regulation and stability that accompanies the introduction of new generation.

Sometimes these objectives conflict. For example, an area with poor voltage regulation often has low-capacity circuit breakers. The introduction of new turbogenerators improve the voltage regulation capability, but the resulting short circuit currents may exceed the interrupting and/or continuous capabilities of the existing breakers, necessitating upgrade.

The responsibility for establishing rules for interconnection of turbogenerators is the responsibility of the local utility, but a few generalizations can be made:

1. Generators with a capability in excess of 50 MW are generally connected to the local transmission system by using a step-up transformer. A simple "rule of thumb" is that the MVA rating of the plant should not exceed roughly twice the kilovolt rating of the interconnected transmission system. For example, a 132 kV transmission system normally accommodates a generating plant of up to about 265 MVA without extensive reinforcements because the output of the plant can be transmitted by a single transmission line. Higher outputs typically require multiple lines or lines consisting of bundled conductors.
2. Generators with rated outputs much above 150 MVA generally must be unit-connected (i.e., they must be connected to the transmission system directly via the step-up transformer, with no generator circuit breaker) because of limitations on continuous loading (ampacity) of generator circuit breakers.
3. Interconnections of unit-connected generators are generally via multiple transmission circuit breakers, typically in a "ring-bus" or "breaker-and-a-half" scheme, as shown in Fig. 16, so that maintenance or problems with a single circuit breaker or bus do not force the generator out of service.
4. The interconnection of a generator to a transmission system generally adds three to five times the generator rating (MVA) to transmission system short-circuit interrupting requirements in the local area. For example, addition of a 250 MVA plant to a 132 kV transmission system increases short-circuit interrupting duties of circuit breakers at the point of interconnection by roughly 1000 MVA (4.4 kA) and increases interrupting duties by a smaller amount for a considerable distance. Area breakers must be examined to determine whether they can accommodate this increase in interrupting duties.

OPERATION OF TURBOGENERATORS

An excellent guide for operating turbogenerators is provided by The *IEEE Guide for Operation and Maintenance of Turbine Generators* (IEEE publication 67). This document addresses day-to-day operating and maintenance considerations, such as start-up and synchronization, changing load, adjusting load to recognize constraints of the reactive capability curve, shutdown, operation with unbalanced system voltages, and other routine operating measures that apply to individual machines. The information in IEEE 67 should be considered a supplement to manufacturer's literature, which addresses operation of specific turbogenerators. The reader is referred to IEEE 67 for specific operating information.

From a system perspective, operation of turbogenerators is normally dictated by economic considerations. Power stations use different fuels, have different operating characteristics and efficiencies, different start-up and shut-down times, etc. All of these factors must be considered to determine when to shut a unit down or start it up and how to load it during operation. This is often called the "unit dispatch" problem, the term "dispatch" describing the output (MW) loading level for each unit. It has been demonstrated that a power system,

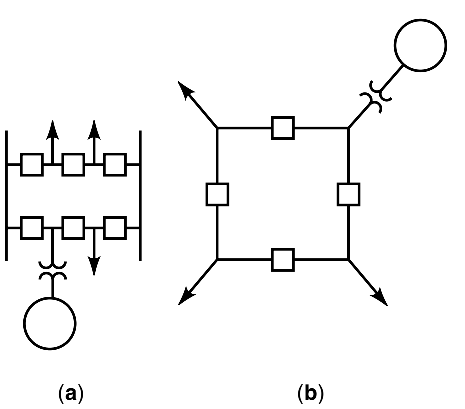

Figure 16. Generator installed in (a) a "breaker-and-a-half" and (b) "ring-bus" configuration.

consisting of multiple operating units, is optimally dispatched when all of the units have the same incremental operating cost. The plant incremental operating cost is often referred to as the plant "lambda" (λ), which has the units of dollars (or other appropriate unit of currency) per incremental (MWH megawatt-hour) of output. A related problem is the "unit commitment" problem, which determines when a given unit should be started up or shut down, considering economic and technical criteria. Solution of the unit commitment problem entails considering fuel costs, power supply contracts, projections of system lambdas, estimates of costs associated with start-up and shut-down of individual units, and turbine loading ramp rates and other operating restrictions. Normally, because of its complexity, the unit commitment problem is solved by a computer simulation that employs linear programming techniques to evaluate possible alternative courses of action and to select the alternative with the highest likelihood of financial gain.

To illustrate the considerations used in solving the unit commitment and unit dispatch problems, consider this example.

A plant consists of *three* units, each with a rated capability of 100 MW. Two of the units, units 1 and 2, are identical. The fuel cost of each of these units is described by the equation $L = 250 + 2P + 0.1P^2$, where L is the unit fuel cost (\$/h) and P is the unit output (MW). The third unit has a fuel cost described by $L = 300 + 1.5P + 0.15P^2$. It is estimated that a unit start-up costs roughly \$1500 for any of the three units, based on fuel costs and increased maintenance costs. The plant has a contractual obligation to supply a daily output of 235 MW from 9:00 A.M. to 9:00 P.M. and 135 MW from 9:00 P.M. to 9:00 A.M. How many units should be committed during each 12 h period and how should the units be loaded during those periods?

The incremental operating costs of units 1 and 2 are given by $\lambda_n = dL_n/dP_n = 2 + 0.2P_n$, and that for unit 3 is given by $\lambda_3 = dL_3/dP_3 = 1.5 + 0.3P_3$. Between 9:00 A.M. and 9:00 P.M., it is required that all three units be committed to satisfy the output requirement of 235 MW. Solving the "unit dispatch problem" for equal incremental costs, $\lambda_1 = \lambda_2 = \lambda_3 =$ \$19.5/MWH when $P_1 = P_2 = 87.5$ MW and $P_3 = 60$ MW, so that $P_1 + P_2 + P_3 = 235$ MW. Between 9:00 P.M. and 9:00 A.M., only two units must be committed, but it may prove more economic to commit all three units to avoid the start-up cost. Explicit evaluation of the possible alternatives (i.e., solving the "unit commitment problem"), shows that the most economic alternative is to commit all three units rather than keep two units on line for 12 h, followed by a daily unit startup for the third unit. Then, between 9:00 P.M. and 9:00 A.M., with all three units committed, the units should be assigned loadings of $P_1 = P_2 = 50$ MW and $P_3 = 35$ MW, on the basis of equal incremental costs.

Obviously, a more realistic example, with unequally sized units, ramp rate and other operating restrictions, and provisions for complex fuel contracts, hourly power transactions, and so on, would considerably complicate the problem. Computer analysis is normally required for optimal economic operation of all but the smallest power systems.

Excitation Systems

An excitation system provides controlled dc current to the generator field (rotor) winding. It must have a continuous output capability sufficient to satisfy all generator operating conditions. In addition, a modern excitation system has the following additional characteristics:

- Transient forcing capability, in which the excitation system output is temporarily increased above rated conditions to aid in recovery during and following power system disturbances, such as faults.
- Feedback control to adjust the excitation system output automatically to maintain stable steady-state terminal voltage during changes in load and system conditions.
- Limiting and protective features to prevent operation beyond the capability of the generator.

An excitation system can be generally divided into two major parts: the *voltage regulator,* which includes the signal-level control, limiting, and protective functions, and the *exciter,* which includes the power conversion apparatus to supply the required dc output to the generator field. Over the years, the following types of exciter designs have been utilized.

Dc Generator-Commutator Exciter. Prior to the widespread availability of solid-state semiconductor power rectifier devices, the only practical means of supplying the dc current required for the field winding of a large ac generator was with a dc machine. The dc machine output is rectified by a multisegmented commutator ring and brushes. These exciters are driven by the generator shaft, either directly or through a speed reduction gear, or are driven separately by an induction motor. The exciter dc output supplies the main generator field by a collector assembly composed of slip rings and brushes.

Although many dc generator-commutator exciters are still in service, maintenance problems and unavailability of replacement parts make them increasingly popular candidates for retrofitting with static exciters.

Rotating Ac Exciter. Rotating ac exciters employ an ac generator whose output is rectified and sent to the main generator field. Some rotating ac exciters employ a rotor-mounted field winding and stationary armature. The three-phase ac exciter output is rectified by one or more stationary rectifier bridges, and the dc bridge output is sent to the generator field through brushes and slip rings. However, most rotating ac exciters built today are brushless, so that they use rotating rectifiers and do not require slip rings to provide generator field current.

Brushless Exciter. Figure 17 shows the arrangement of a typical brushless excitation system. The shaft-driven rotating ac exciter utilizes a stationary field winding and rotating armature. The three-phase armature ac output is sent to a rotating rectifier wheel whose dc output is sent directly to the main generator field, typically through a bore in the generator shaft. The brushless exciter accomplishes this without brushes, slip rings, or commutators and thus eliminates the maintenance and carbon dust associated with them. The rectifier wheel typically includes diodes and fuses connected in a bridge rectifier configuration.

Most brushless exciters also employ a shaft-driven permanent magnet generator (PMG) as a pilot exciter for the voltage regulator. The voltage regulator includes a controlled rectifier bridge composed of silicon controlled rectifiers (SCRs)

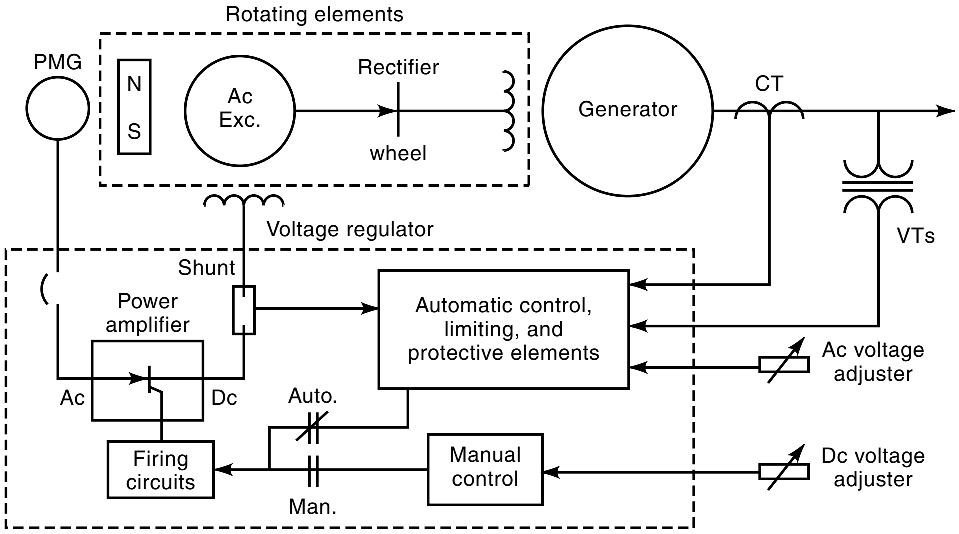

Figure 17. Simplified block diagram of a typical brushless excitation system.

which rectify the PMG output and control the level of dc voltage to the brushless exciter field winding. The firing angle of the SCRs relative to the PMG voltage, and thus the dc output voltage, is determined by the voltage regulator control circuits. All excitation power in a brushless excitation system is derived from shaft rotation.

Potential Source Static Exciter. A potential source static exciter, as shown in Fig. 18, is so named because it derives its power from a potential source (either the main generator terminals or station service supply), and all power conversion devices are stationary. The excitation power potential transformer (PPT) isolates and steps down the ac source voltage to a level that, when rectified, supplies the required excitation voltage to the generator field. The PPT output is rectified and controlled by a solid-state power amplifier, which uses one or more SCR rectifier bridges whose dc output is sent to the generator field via brushes and slip rings. The voltage regulator adjusts the SCR firing pulses to control the dc output. In a static excitation system that derives excitation power from the generator terminals, a means of momentarily flashing the generator field is typically provided to initiate a buildup of generator voltage each time the unit is started.

Compound Source Static Exciter. A compound source static exciter derives its power from both the voltage and current output of the generator. The current source provides short-circuit support by supplementing the power to the exciter during periods of low terminal voltage, such as during system fault conditions. This type of exciter is not often used because of the added cost, size, complexity, and losses of utilizing both potential and current power transformers along with the additional rectifying and control equipment.

Voltage Regulators

The voltage regulator is the portion of the excitation system that provides the means of automatically controlling the output of the exciter. In an excitation system with a rotating exciter, the voltage regulator controls the voltage to the ex-

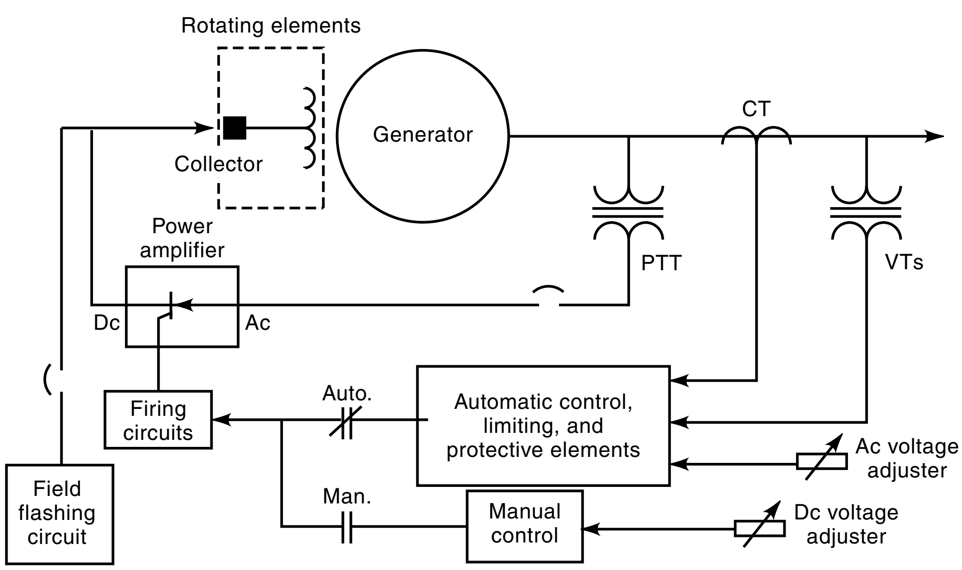

Figure 18. Simplified block diagram of a typical potential source static excitation system.

citer field. In a static excitation system, the voltage regulator directly controls the generator field voltage by determining the firing angle to the power amplifier SCRs.

Modern analog voltage regulators utilize integrated circuits containing operational amplifiers and other electronic devices. Digital microprocessor-based voltage regulators are becoming more prevalent as such hardware becomes faster and more inexpensive.

Excitation Performance Characteristics

In addition to supplying the generator with the appropriate excitation level for steady-state conditions, an exciter usually has additional transient forcing capability to help the generator recover from severe faults and other disturbances. Excitation systems that are faster responding and have higher maximum (ceiling) voltages have a greater potential to contribute to generator transient stability. Excitation systems that have higher ceiling voltages are typically larger and costlier than their lower ceiling counterparts. Therefore, high ceiling voltage excitation systems are typically used only when there is an apparent need for transient stability improvement.

An excitation system has *high initial response* (HIR) characteristics if it can force its output voltage from rated conditions to ceiling in 0.1 s or less. A typical brushless exciter is not HIR, although it is usually faster than other types of rotating exciters. A static excitation system is inherently HIR.

Generator Synchronizing

Synchronization is the process of connecting a generator to the power grid. Successful synchronization for large generators is accomplished by closing the generator output circuit breaker only while meeting certain conditions. The conditions are that the magnitude, frequency, phase rotation, and phase angle of the voltage on the generator side of the synchronizing breaker match those on the system side of the breaker. Faulty synchronization can cause severe equipment damage and system transients.

Prior to synchronization, voltage magnitude matching requires adjusting the generator excitation level so that the generator terminal voltage matches the system voltage. Matching the frequency requires that the turbine speed be precisely adjusted such that the generator output frequency is the same as or slightly higher than the system frequency. Phase rotation matching means that the order in which the three-phase voltages reach their peaks are the same. This requires proper connections and verification of phase order prior to initial start-up. Matching phase angle means that the voltages in each phase on the generator and system side of the breaker are in phase or reach their peaks at precisely the same time. Synchronization is performed manually by an operator or automatically by an automatic synchronizer.

Generator Control

Once a large turbine-generator is connected to a power grid, there are two basic means utilized to control its output. One is through controlling the turbine mechanical output via valve control on a steam turbine, or fuel control on a combustion turbine, or gate control on a hydro turbine. When the generator is off-line, the turbine control adjusts generator speed and electrical frequency. When the generator is on-line (connected to the power grid, so that the grid frequency determines the generator output frequency and speed), adjustments in the turbine mechanical output result in corresponding changes in generator real power (or kilowatt) output.

The other means of controlling generator output is by adjusting the excitation system output. Although turbine output controls the real power output of an on-line generator, the excitation level determines the generator reactive power (or kilovar) output. Therefore adjustments in generator kilovar output are made through the voltage regulator.

Generator Protection

Because the consequences of generator damage resulting from abnormal external conditions, internal faults, and misoperation might be extensive, it is important to protect against such damage with an adequate protection system. Similarly, if protection systems act to trip generators or other critical equipment unnecessarily during system disturbances, the security of the entire power system can be jeopardized. Thus, a suitable generator protection system allows a generator to continue operation during certain types and degrees of abnormal conditions but reliably trips the generator when necessary.

Most protective relays are available now in both electromechanical and solid-state designs. The solid-state models are finding increasing acceptance, mainly because of their accuracy, flexibility, and reduced maintenance. In addition, microprocessor-based protective relaying systems, in which many standard relaying functions are combined into one package, are becoming more prevalent.

Because both the voltage and current levels on modern large generators are too high to be used directly by protective relays and other such devices, special instrument transformers are required. Voltage transformers (VTs) are connected across the generator ac terminals and have an appropriate turns ratio to step down the sensed generator voltage to a reduced level (typically 120 V rms) at the secondary. Current transformers (CTs) are usually of the window type, in which the single-turn primary winding is the generator conductor or bushing that passes through the opening of the CT and the secondary winding has the appropriate number of turns so that secondary current is nominally 5 A rms at full load.

The following are some of the protective functions utilized on a large generator:

- *Generator differential current protection,* in which CTs in each phase on both ends of the stator winding are used to quickly detect the presence of internal multi-phase faults.
- *Stator ground fault protection,* in which a high-impedance grounded generator is protected against the potentially damaging effects of a low-current, single-phase-to-ground fault before it spreads to a much more severe multi-phase fault.
- *Negative sequence current protection,* which protects the generator from excessive heating resulting from induced eddy currents on the rotor surface due to the effects of unbalanced (or negative sequence) currents in the stator.
- *Field ground protection,* which protects the field winding on the rotor from the potentially damaging effects of grounds.

- *Overexcitation protection,* which protects the generator field winding from overheating due to excessive excitation current.
- *Volts-per-hertz protection,* which protects the core of the generator (and connected transformers) from the heating effects due to excessive magnetic flux.
- *Loss of excitation protection,* which senses the condition in which generator synchronism is jeopardized because of a loss or severe reduction in excitation level.
- *Loss of synchronism protection,* in which a generator that loses synchronism with the system is tripped off-line before damaging pole-slipping takes place.
- Motoring protection, in which negative real power is sensed which would indicate the loss of turbine output power.

For any particular application, the costs associated with particular protection systems and the degree of protection they afford must be carefully weighed against the risks encountered for lesser degree of protection. The amount and complexity of protection that is usually applied varies according to the size and importance of the generator.

BIBLIOGRAPHY

P. M. Anderson and A. A. Fouad, *Power System Control and Stability,* Iowa State University Press, 1977.

Applied Protective Relaying, Newark: Westinghouse, 1976.

T. Baumeister and L. S. Marks, *Standard Handbook for Mechanical Engineers,* New York: McGraw-Hill, 1967.

A. F. D'Souza and V. K. Garg, *Advanced Dynamics,* Englewood Cliffs, NJ: Prentice-Hall, 1984.

A. E. Fitzgerald, C. Kingsley, and A. Kusko, *Electric Machinery,* New York: McGraw-Hill, 1971.

C. M. Harris and C. E. Crede, *Shock & Vibration Handbook,* New York: McGraw-Hill, 1976.

E. W. Kimbark, *Power System Stability: Synchronous Machines,* New York: Wiley, 1956.

L. K. Kirchmayer, *Economic Operation of Power Systems,* New York: Wiley, 1958.

G. Kron, *Equivalent Circuits of Electric Machinery,* New York: Wiley, 1951.

M. Liwschitz-Garik and C. Whipple, *Alternating Current Machines,* New York: Van Nostrand, 1961.

L. Matsch, *Electromagnetic and Electromechanical Machines,* Intext, Scranton, 1972.

G. R. Slemon, *Magnetoelectric Devices: Transducers, Transformers, and Machines,* New York: Wiley, 1966.

W. D. Stevenson, *Elements of Power System Analysis,* New York: McGraw-Hill, 1982.

F. S. Tse, I. E. Morse, and R. T. Hinkle, *Mechanical Vibrations,* Boston: Allyn and Bacon, 1968.

D. C. White and H. H. Woodson, *Electromechanical Energy Conversion,* New York: Wiley, 1957.

A. J. Wood and B. Wollenberg, *Power Generation, Operation, and Control,* New York: Wiley, 1984.

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TURBULENCE, PLASMA. See Plasma turbulence.
TURING MACHINE. See Computational complexity theory.
TV, INTERACTIVE. See Interactive video.
TWIN LEAD. See Antenna accessories.
TWO-DIMENSIONAL CODES. See Mark scanning equipment.
TWO-DIMENSIONAL GRAPHICS TRANSFORMATIONS. See Graphics transformations in 2-D.
TWO-PORT PARAMETERS. See Network parameters.
TWO-PORTS. See Multipole and multiport analysis.
TWT. See Traveling wave tubes.