

Generator Principles

Introduction

Electrical generating systems may be of great complexity and spread over large geographical areas. There are several components that make up the generating system with the main components being the following:

Energy Source

The energy source may be coal, gas, or oil burned in a furnace to heat water and to generate steam in a boiler; it may be fissionable material, which in a nuclear reactor, will heat water to produce steam; it may be water in a lake or river; or it may be oil or gas burned in an internal combustion engine.

Prime Mover

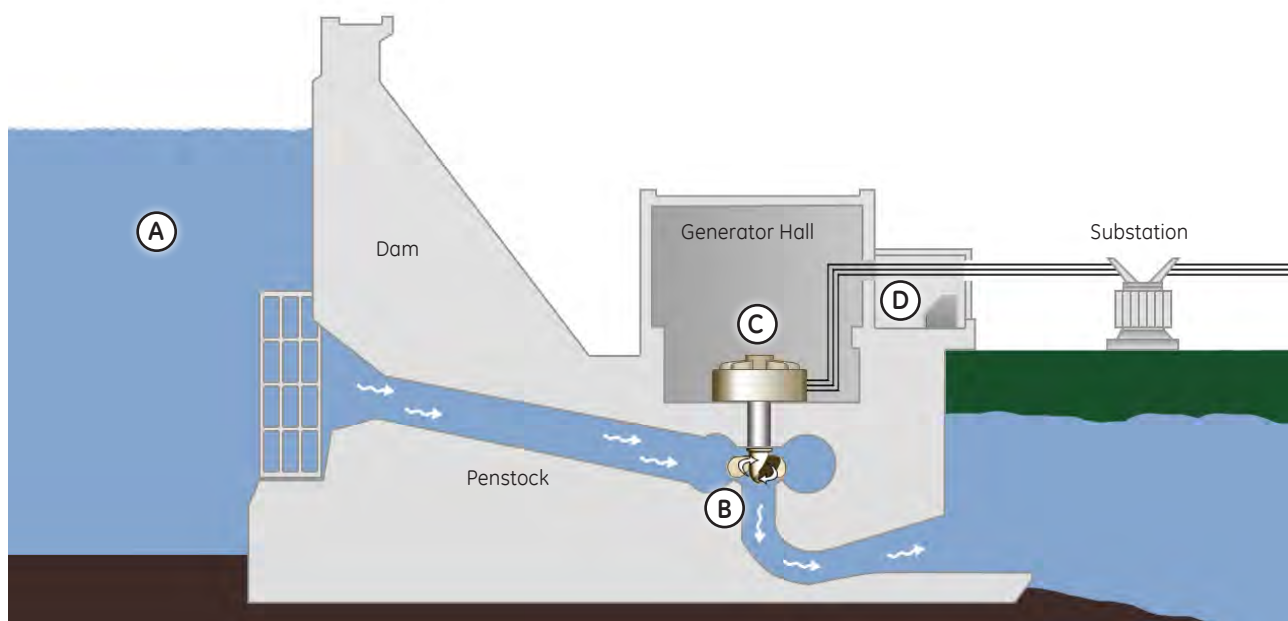
The prime mover may be a steam driven turbine, a hydraulic turbine or an internal combustion engine. Each one of these prime movers has the ability to convert energy in the form of heat, falling water or fuel into rotation of a shaft, which in turn will drive the generator.

Generator

Generators are used to convert the supplied mechanical energy to electrical energy. They have a wide variety of power ranges up to and including 1500MW and are typically an AC machine. In some applications a DC generator may be used depending on the application.

Control System

The control system is used to keep the speed of the machine substantially constant and the voltage and frequency within prescribed limits even though the load may change. To meet the need of changing load conditions, it is necessary for the fuel input to change, which in turn varies the torque requirements to the prime mover and the generator in order to keep the generator at the speed requirements of the load requirements. This control system constantly monitors the load requirements and generating needs and adjusts the system accordingly.



(A) Energy Source

A built-up water reservoir provides the primary energy source required for generation

(B) Prime Mover

Water flowing through the penstock spins the turbine

(C) Generator

The spinning turbine causes the generator to convert the mechanical energy into electrical energy

(D) Control System

Control system ensures the power generated is matched to the power demanded

Figure 1.
Cross section of a hydroelectric generating station

Synchronous Generators

Stationary Field Synchronous Generator

Synchronous generators are made with either a stationary or rotating dc magnetic field. The stationary field synchronous generator has the same appearance as a dc generator. The salient poles create the dc field, which is cut by a revolving armature. The armature possesses a three phase winding whose terminals are connected to three slip rings mounted on the shaft. A set of brushes, sliding on the slip rings, enables the connection of the armature to an external three-phase load.

Rotating Field Synchronous Generator

In typical generator applications a rotating dc field is usually used. The rotating field synchronous generator has a stationary armature called a stator. The three-phase stator winding is directly connected to the load without going through large, unreliable slip rings and brushes. The stationary stator also makes it easier to insulate the winding because they are not subjected to centrifugal forces.

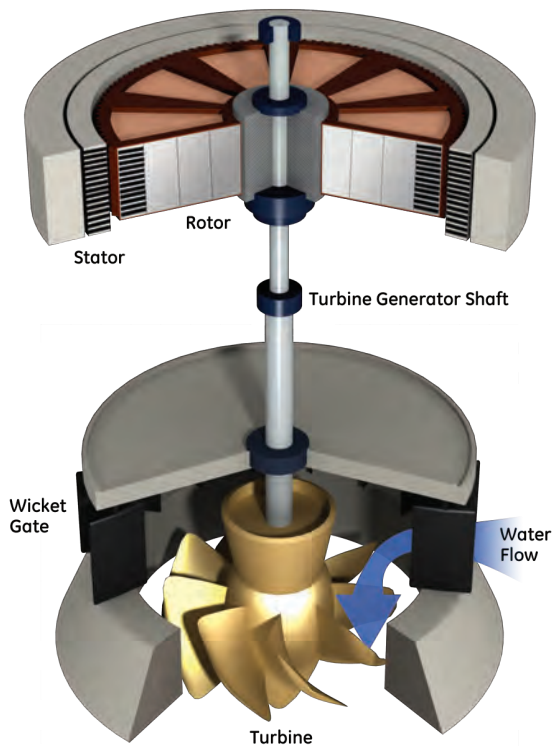


Figure 2.
Typical operation of a hydraulic generator

The nominal line voltage of a synchronous generator depends on its kVA rating. In general, the greater the power rating, the higher the voltage. However, the nominal voltage rarely exceeds 25kV because the increased slot insulation take up valuable space at the expense of the copper conductors.

Synchronous generators are built with two types of rotors: salient-pole rotors and smooth, cylindrical rotors. Salient-pole rotors are usually coupled to low-speed hydraulic turbines where cylindrical rotors are driven by high-speed steam turbines.

Salient Pole Rotors

Salient-pole rotors are typically used in most hydraulic application, because they run at low speeds, typically in the range of 50 to 300 rpm in order to extract the maximum power from the waterfall. Because the rotor is directly connected to the water-wheel and must maintain a frequency of 60 Hz, a large number of poles are required.

Cylindrical Rotors

Cylindrical rotors are used in applications where they are connected to high-speed steam turbines. These units are smaller and more efficient than low speed turbines. Since these units are connected to high-speed steam turbines they are typically 2 or 4 pole machines that operate at either 3600 or 1800 rpm for 60 Hz systems.

Generator Cooling

As the generators increase in size and power output, additional consideration must be taken into account for the cooling of the machine. Traditionally there have been three methods that have been used for cooling generators; cold air cooling, hydrogen cooling and water cooled conductors. The cooling method will be dictated depending on the size of the generator.

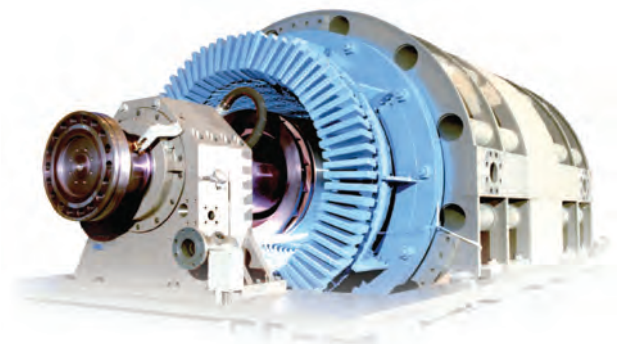


Figure 3.
Stator of an air-cooled generator

Generating Stations

Since electrical power demands vary throughout the day, week, year different types of power generating stations are better suited to react to required electrical demand.

In power generating applications there are three areas of usage that must be taken into account: Base demand, Intermediate demand and Peak demand. Each demand type will have a different type of generating station associated with it because of the method of system startup.

Base Demand Power Stations

Base demand power stations deliver full power all the time. The types of generating that are best suited for these applications are Nuclear generating stations and coal-fired stations. Nuclear generating stations can take up to several days to start and coal-fired stations can take up to several hours to start making them both ineffective to changing power demand, therefore limiting their applications to base demand power stations.

Intermediate Demand Power Stations

Intermediate power stations are designed to react to slight changes in the power requirement and can respond relatively quickly to this need by adding or removing generating units as required. Hydraulic generating stations are best suited for intermediate generations applications.

Peak Demand Power Stations

Peak demand generating stations are required to deliver power for brief intervals during the day. These stations must be put into service very quickly; therefore they are equipped with prime movers, such as diesel engines, gas turbines, compressed-air motors or pumped-storage turbines that can be started in a few minutes.



Figure 4. Nuclear generation

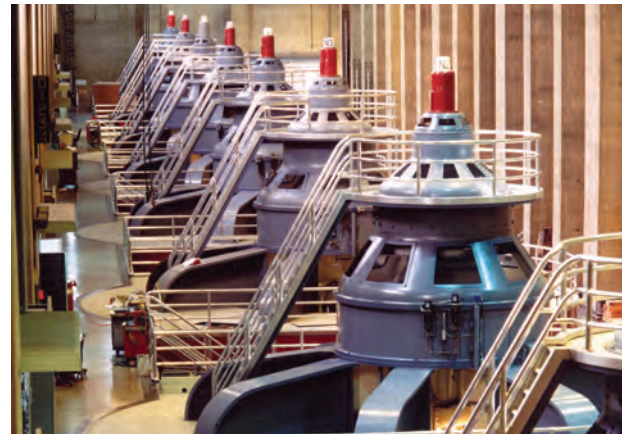


Figure 5. Hydraulic generation

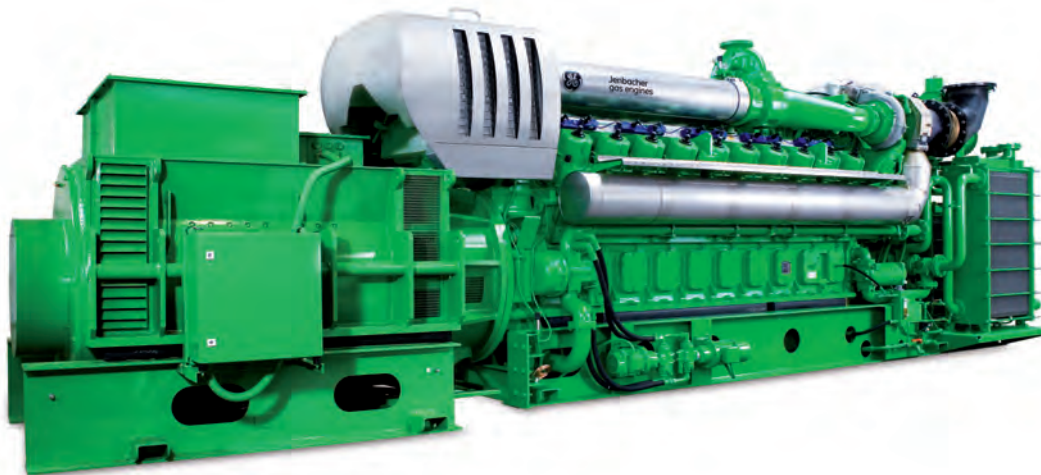


Figure 6. GE Jenbacher gas generator

Generator Protection



Figure 7.
integrated coal gasification combined cycle (IGCC) power plant

Generators provide the energy used by all of the loads in the power system and much of the reactive power needed to supply the inductive elements thereby maintaining the system voltage at nominal values. Power systems have little capacity for energy storage. As such, lost generation must be immediately replaced or an equivalent amount of load must be shed. It is of primary importance that the protection system for the generator is highly secure during external disturbances.

The generator is one component of a complex system that includes a prime mover, an exciter, and various auxiliary systems. In addition to the detection of short circuits, the generator protection IED is therefore required to detect an array of abnormal conditions that could damage the generator or one of its subsystems.

Generators can be classified into two major types: induction and synchronous. Induction machines are typically smaller in size, ranging down to as little as one hundred kVA, and are normally driven from a reciprocating engine. Synchronous machines range in size from several hundred kVA to 1200 MVA. Synchronous generators may be driven by a variety of prime movers, including reciprocating engines, hydro turbines, combustion turbines, and large steam turbines. The type of turbine affects the design of the generator and can therefore impact protection requirements.

The generator size and its method of grounding also affect its protection requirements. Small and medium sized machines are often directly connected to a distribution network (direct connected). In this configuration several machines can be connected to the same bus. Large machines are usually connected via a dedicated power transformer to the transmission network (unit connected). A second power transformer at the generator terminals provides auxiliary power for the unit. Generators are grounded in order to control from damaging voltage transients and to facilitate the operation of protection functions. Direct-connected generators are often grounded through a low impedance that limits the ground fault current to 200-400 amps. Unit connected machines are typically grounded through a high impedance that limits the current to less than 20 amps.

Generator Protection Overview

There are many abnormal conditions that can result in damage to the generator. Some of these conditions are a result of a failure within the generator or one of its subsystems and others originate in the power system itself. The following table summarizes the types of failures that can occur and the associated methods of protection.

Stator Ground Faults

The most commonly occurring failure of the stator winding is a break down of the insulation between a single phase and ground. Undetected, this fault can quickly damage the generator core. Fires are also possible on air-cooled machines. The ability of the stator differential element to detect a ground fault is a function of the available ground fault current. As such, dedicated ground fault protection is generally required for the stator.

Type of Fault	Protection Philosophy
Internal Fault	
Stator ground faults	Voltage displacement (59x), 100% stator ground (27TN/59N), 3rd harmonic neutral undervoltage (27TN), ground overcurrent (51G), restricted ground fault (87RGF), neutral directional (67N)
Stator phase faults	Generator Stator differential (87G), phase distance (21P)
Inter-turn faults	Split phase (60SP)
Loss of excitation	Impedance (40), power factor (55)
Loss of prime mover	Reverse power (32R), low forward power (32L)
Overfluxing	Volts per hertz (24)
Overvoltage	Overvoltage (59P)
Abnormal operating speed	Underfrequency, overfrequency (81U/O)
External Fault	
Unbalanced loading	Generator unbalance (50_2/51_2)
System backup	Phase distance (21P), voltage restrained overcurrent (51V), ground overcurrent (51G)
Overloading	Overcurrent, thermal overload (49)
Mechanical	Vibration sensor (39)
Loss of synchronism	Power swing blocking (68), Out-of-step tripping (78)
Accidental energization	Accidental energization (27/50)

Table 1.
Generator faults

For direct connected, low impedance grounded machines, a current-based detection method is used. This protection needs to be fast and sensitive for internal ground faults while at the same time secure during external disturbances. This can be achieved using a restricted ground fault element or a neutral directional element. The restricted ground fault element implemented in the G30 and G60 employs a symmetrical component restraint mechanism that provides a high degree of security during external faults with significant CT saturation. For unit connected, high impedance grounded machines, voltage-based methods are often used to provide ground fault detection. Using a combination of fundamental and third harmonic voltage elements, ground fault coverage for 100% of the stator winding can be achieved. GE relays employ a third harmonic voltage element that responds to the ratio of the neutral and terminal values of the third harmonic. This element is simple to set and insensitive to variations in third harmonic levels under normal operation.

Stator Phase Faults

Phase faults not involving ground can occur at the winding end or within a slot on in machines having coils of the same phase in the same slot. Although a phase fault is less likely than a ground fault, the current resulting from this fault is not limited by the grounding impedance. As such it is critical that these faults be detected quickly so as to limit the damage to the machine. Since the system XOR ratio is particularly high at the generator, the stator differential element is particularly susceptible to CT saturation due to the DC component of the current during an external disturbance. The G60 stator differential algorithm adds additional security in the format of a directional check when CT saturation is suspected due to either the AC or DC components of the current.

Inter-turn faults

The stator of some generators (hydroelectric in particular) are formed as a double-layer, multi-turn winding. In such machines a significant percentage of stator faults begin as turn-to-turn faults. Furthermore, these faults are not detectable by the phase or ground fault protections. If these faults can be detected before they evolve into phase or ground faults then the damage to the machine and associated downtime can be greatly reduced. The split phase element in the G60 and G30 has a unique operating characteristic that allows it to compensate for steady state errors in the split phase current (due to a winding repair, for instance) while allowing it to remain sensitive to an inter-turn. (available in the G60 and G30).

Overload/Thermal

Figure 8 shows the permissible short-time loading limits of a generator according to C50.13-2004. Loading beyond these limits will quickly damage the machine. An overcurrent element with a very-inverse characteristic can be used to ensure that the generator is operated within permissible limits. GE IED's are also equipped with RTD inputs. In addition to detection of overloading, RTDs can detect overheating due to a cooling system failure or localized overheating due to a failure of the insulation between the stator core laminations.

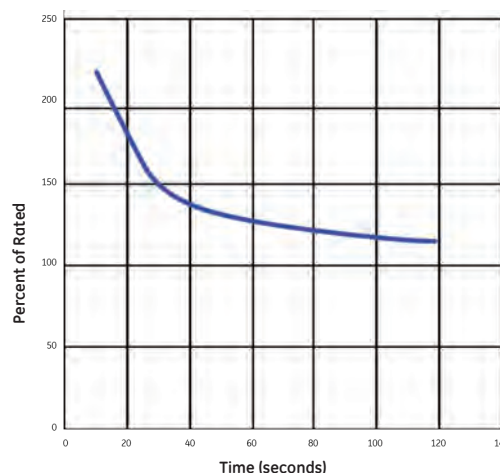


Figure 8. Permissible short-time loading limits

Tripping Faults

There are a variety of faults or disturbances for which the generator protection IED must operate. For each fault type there are generally a set of actions that are carried out. These include tripping the generator breaker, tripping the field breaker, transfer of the auxiliaries, and tripping the prime mover. For example, an overfluxing condition requires a trip of the generator and field breaker, a transfer initiation, but no trip to the prime mover. This allows the machine to be resynchronized if the problem is resolved quickly. Internal programmable logic allows the tripping logic to be easily implemented.

Additionally there are instances where the generator powerhouse is at a substantial distance from the switchyard. Using peer-peer messaging, tripping and status signals can be sent directly from the relay over fiber to a controller such as a C30 located adjacent to the generator breaker.

System Diagnostics

Modern microprocessor generator relays have superior operational recording capability that can be invaluable to both generator owners and generator system consultants. With this recording ability, generator operators can perform forensic engineering to get equipment back up and running, while at the same time, have all of the historical system operating information available to comply with statutory reporting requirements imposed by NERC and other regulatory bodies. Recording functions found in sophisticated generator relays include:

- Event Recording with the ability to apply customized naming to inputs and elements shown in records
- Waveform recording with both digital and analog information that includes naming of all inputs
- Fault Reports with a summary of all critical info at the time of the fault
- Trending reports for recording customize parameters to assist with specifying specific characteristics of the generator
- Metering of voltage, current, power, frequency, power factor etc.

Generator owners find recording capabilities invaluable for performing forensic engineering to get equipment back up and running and to comply with statutory reporting requirements imposed by NERC and other regulatory bodies.

Integration

The integration of information collected from intelligent devices located throughout power plants into DCS and SCADA systems have provided a means for operational staff to get real time access to the status of their generators and have immediate control to the generators and their sub-systems. Through the use of robust, high-speed communications and industry standard protocols, modern generator relays can send data measured by the relays into dedicated power monitoring systems or balance of plant monitoring and control systems to allow for easy analysis of plant efficiencies.

PMU

Power Authorities wishing to have synchronous measurement and reporting of power system Phasor information can use a generator relay (G60) to provide this synchrophasor measurement of power being produced for integration into operation recording and monitoring systems. With this data available, power providers can accurately identify impending system problems and allow operators to react to these conditions that if left unresolved, could cause the generator to needlessly be brought offline, or worse, lead to an overall system collapse.

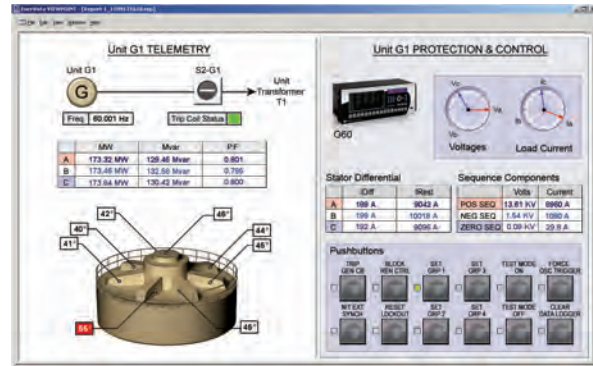


Figure 9. Advanced diagnostics using EnerVista™ Viewpoint Monitoring

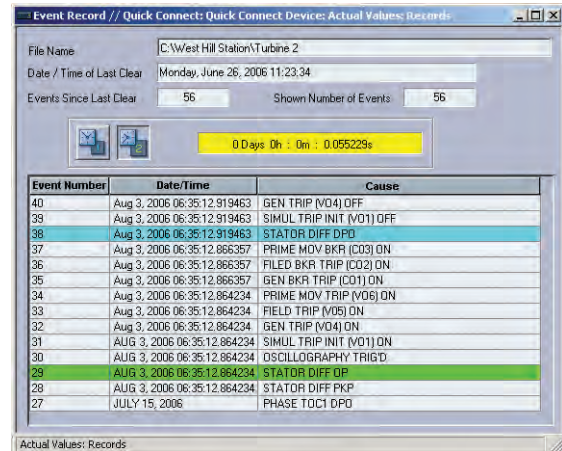


Figure 10. Generator event record data acquired using the Multilin G60 generator protection system