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Synchronous Generator Protection and Generator Synchronization in a Power System

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Dedication

This work is dedicated to the Almighty God who provided me with the inner strength to persevere from the beginning to the end of this work. Lord, your grace truly is sufficient for me.

Acknowledgement

My special thanks to my family for their invaluable contribution and guidance throughout the course of this work.

Abstract

The paper explained the electrical workings and dynamics of synchronous generators and their connections to the power system. Generator performance under short-circuit conditions is also described, along with generator grounding practices. In addition, some of the most misunderstood aspects of generator protection were discussed. The paper also discussed about Stator Phase Fault Protection and Stator Ground Fault Protection. Both the generator and turbine are limited in the degree of abnormal frequency operation that can be tolerated. At reduced frequencies, there will be a reduction in the output capability of a generator. Turbines, especially steam and gas turbines, are considered to be more restrictive to operation at reduced frequencies than the generator because of resonances in the turbine blades. The paper also presents a detailed meaning of generator synchronization.

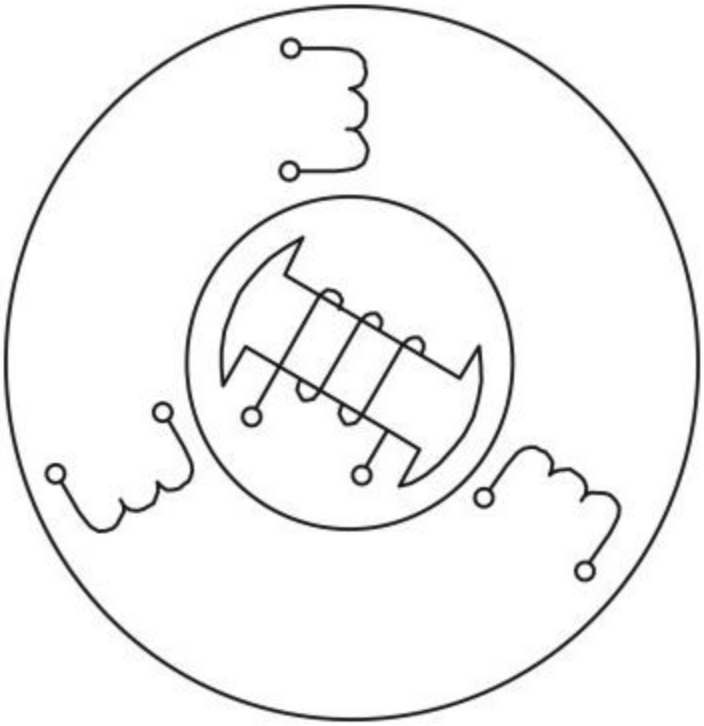
Introduction

Synchronous machine is an AC machine; its rotor rotates with the same speed of rotating field (synchronous speed). Synchronous machines are predominantly used in power generation. They are called *synchronous generators* (or alternators). Synchronous generators are the primary energy conversion devices and their power ratings can reach from fractional horsepower to several hundred megavolt-amperes (MVAs). They are generally used in pumps, servomotors, and electric clocks, where constant speed is desired [6].

In the synchronous machines the rotor has DC excited winding or PMs for establishing excitation field, slip rings, and brushes for external connection. The stator carries the armature winding. The field winding is excited by DC to produce flux in the air gap. When the rotor rotates, voltage is induced in the armature winding placed on the stator. The armature current produces a revolving flux in the air gap, whose speed is the same as the speed of the rotor, hence the name synchronous machine.

Synchronous machines are often classified into two groups according to the rotor configuration: cylindrical rotor and salient pole. Cylindrical or round rotor synchronous machines have uniform air gap, 2–4 rotor poles with high speed, a rotor that usually has a small diameter but is axially long, and are usually driven by steam turbines. Salient pole synchronous machines have non-uniform air gap, high number of rotor poles with low speed, a rotor that usually has large diameter but is axially short, and are usually driven by water turbines.

The operation principle of synchronous generators relies on the poles, which are magnetized either by PMs or by a DC current. The armature, normally containing a three-phase winding, is mounted on the shaft. The armature winding is fed through three slip rings and a set of brushes sliding on them. The rotor is rotated by a prime mover. Schematic cross-sectional view for a two-pole synchronous machine is shown

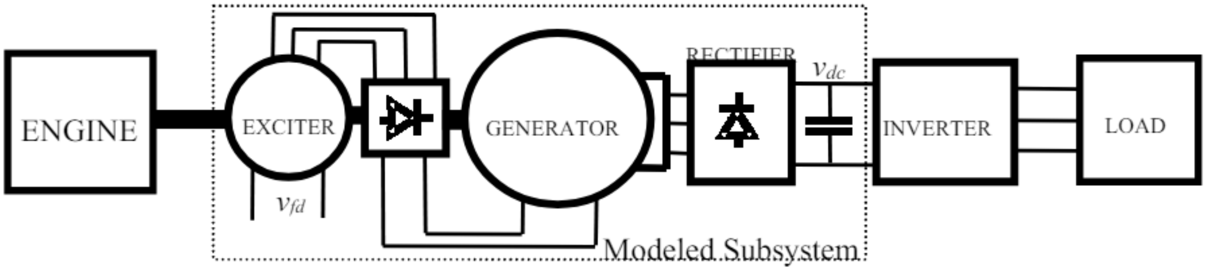


Two-pole Synchronous Machine [5]

The synchronous machine has the field-winding wound on the rotor and the armature wound on the stator. A DC current, creating a magnetic field that must be rotated at synchronous speed, energizes the rotating field winding. The rotating field winding can be energized through a set of slip rings and brushes. In externally fed fields, the source can be a shaft-driven DC generator; several variations to these arrangements exist. The stator core is made of insulated steel laminations to minimize eddy current and hysteresis losses [5].

The number of poles in an electric machine is always an even number. While increasing the number of poles, the rotating speed decreases. Synchronous speed is the rotating speed of the excitation field. The rotor speed is decided by the excitation frequency and the number of poles.

In [5], the author was motivated by the need to study dynamics and control design of the system whose block diagram is shown. It was a 150 kW generator set with inverter output, in which a natural gas engine drives a synchronous generator (which, throughout this text, was referred to as main generator). Field voltage was provided to the main generator by means of a separate, smaller synchronous machine, an exciter. The exciter was constructed with field winding on the stator and armature winding on the rotor; that made it possible to rectify the exciter's armature ac voltages by a rotating diode bridge, and connect the rectifier's output directly to the field winding of the main generator.



Block diagram of the synchronous generation system [5]

The author in [5] determined that main generator’s output was rectified by another diode bridge, in order to form a dc-link that feeds an inverter. Balanced three-phase voltages was supplied to the load by the inverter. Since the inverter also determines load frequency, it was not necessary to operate the generator at constant speed corresponding to 60 Hz.

In order to make engine operation as efficient as possible, speed was varied from 1800 rpm to 4000 rpm. Such variable speed operation affects generator design in several ways, of which the most important for the study was the effect it has on the value of main generator’s synchronous inductance. With standard generator design, at minimum speed a relatively large main generator’s field current would be required in order to achieve the rated generator output voltage. That would result in large exciter’s armature currents, and overheating of the exciter. The minimum amount of cooling (due to minimum speed) would make this problem even more serious. In order to avoid the problem, generator designers increased the number of turns of the main generator’s armature windings. That resulted in a smaller field current required to obtain the rated output voltage but, at the same time, it significantly increased main generator’s synchronous inductance.

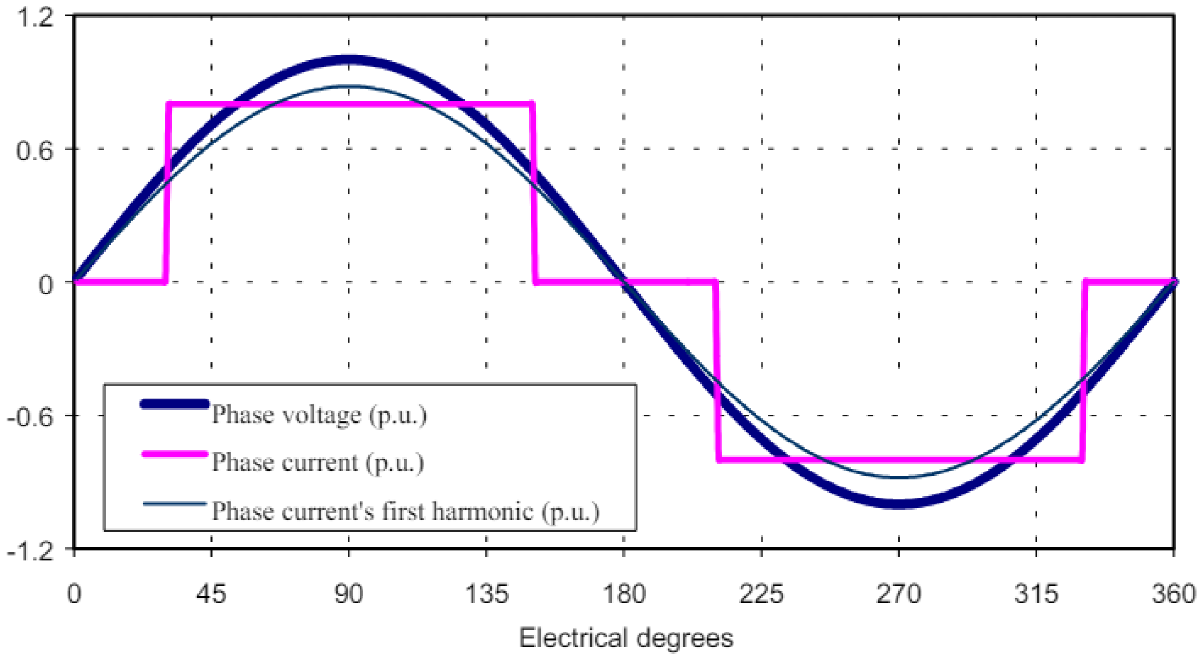
A peculiarity of the system shown below was the fact that both synchronous machines, the exciter and main generator, have electronic load: they feed reactive dc loads through diode rectifiers. If a synchronous machine were an ideal voltage source. It was a textbook example of how non-linear, switching elements (diodes) cause non-sinusoidal ac waveforms. v_a, v_b and v_c were sinusoidal voltages with amplitude V_p and a phase shift of 120° one with respect to another. I_{dc} was a constant dc current representing dc load. Average value of the dc voltage v_{dc} at the rectifier’s output was calculated as;

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_p \tag{2.1}$$

Where V_{dc} and V_p represents the DC voltage and the amplitude voltage respectively

Three phase voltage source feeding a dc current source through a diode rectifier

The phase waveforms from the outcome



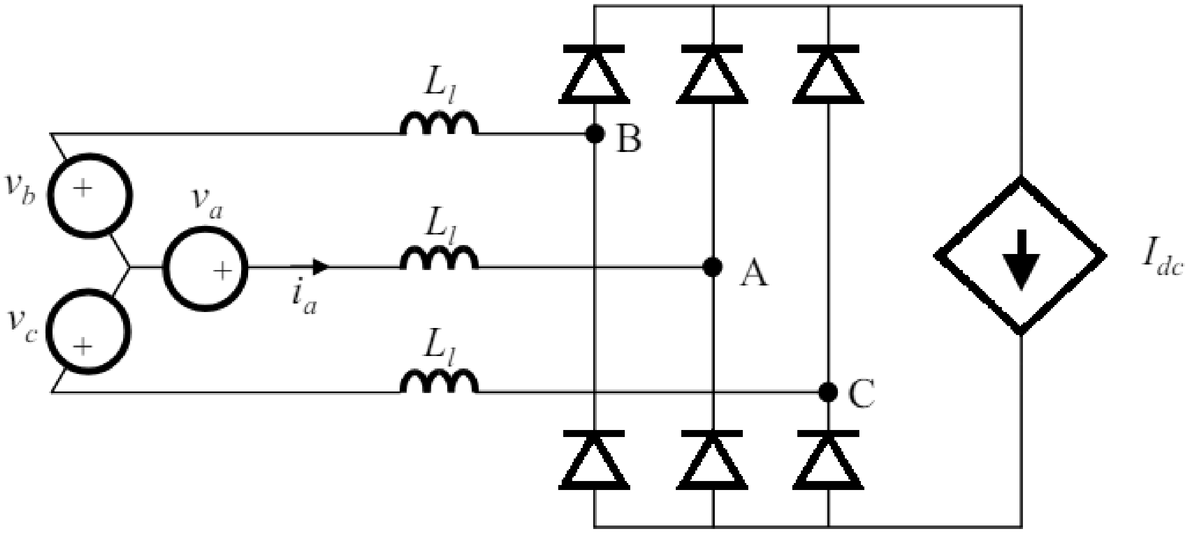
Wwaveforms of the outcome

Figure above shows qualitative waveforms of phase voltage v_a and phase current I_a. It can be seen that, due to diode rectification and current-source dc load, the phase current had a quasi-square waveform. First harmonic of i_a, i_{a1}, was also shown. Its amplitude can be calculated as shown in equation 2.2.

$$I_{ai} = \frac{2\sqrt{3}}{\pi} I_{dc} \tag{2.2}$$

Where I_{dc} represents the DC current of the machine and I_{ai} represents the amplitude current of the machine.

It was important to notice that the voltage was in phase with current's first harmonic. Therefore, from the point of view of the ac input's fundamental voltage and current harmonics, an ideal diode rectifier with a current source dc load behaves like a nonlinear resistor. The real time voltage source feeding on current source dc load through a diode rectifier was shown.



The real time voltage source feeding on current source dc load through a diode rectifier

The situation was somewhat more complicated if ac side's parasitic inductances L_l were considered. These inductances normally represent transformer or power line leakage inductance, and need to be placed in series with ideal voltage sources v_a, v_b and v_c, as shown in Figure 2.8. They cause non-ideal operation of the diode bridge, which implies, they cause diode commutations to be non-instantaneous; the time required for commutation was usually expressed in terms of commutation angle u, which was a function of parasitic input inductance L_l, line frequency ω and output current I_{dc}:

Summary

A synchronous generator converts mechanical/thermal energy into electrical energy. The mechanical power of the prime mover rotates the shaft of the generator on which the dc field is installed. The energy that is produced turns the generator shaft (rotor) at typical speeds of 1,800 or 3,600 rpm on a 60 Hz system. Energy is converted to mechanical rotation in a turbine. At nuclear plants, uranium fuel is converted to heat through the fission process that produces steam. Steam is forced through a steam turbine to rotate the generator shaft. Prime mover energy can also be obtained from falling or moving water. Hydroelectric generators rotate much slower (around 100 to 300 rpm) than steam turbines.

The protection of synchronous generators involves the considerations of more harmful abnormal operating conditions than the protection of any other power system element. In a properly protected generator, automatic protection against harmful abnormal conditions is required. The bulk of this paper deals with the need to provide such protection. The objections of some to the addition of such protection is not so much that it will fail to operate when it should, but that it might operate improperly to remove a generator from service unnecessarily. Unnecessary generator tripping is undesirable, but the consequences of not tripping and damaging the machine are far worse. The cost to the utility for such an occurrence is not only the cost of repair or replacement of the damaged machine, but also the substantial cost of purchasing replacement power while the unit is out of service. At manned locations, an alert and skillful operator can sometimes avoid removing a generator from service by correcting the abnormal condition. In the vast majority of cases, however, the event will occur too rapidly for the operator to react; thus, automatic detection and isolation are required.

Synchronous machines are classified into two principal designs: round rotor and salient. Generators driven by fossil fuel turbines have cylindrical (round) rotors with slots into which distributed field windings are placed. Most cylindrical rotors are made of solid steel forgings. The number of poles is typically two or four. Generators driven by water wheels (hydraulic turbines) have laminated salient-pole rotors with concentrated field windings and a large number of poles. Whatever type of prime mover or machine design, the energy source used to turn the shaft is maintained at a constant level through a speed regulator known as a governor. The dc flux rotation in the generator field reacts with the stator windings, and because of the induction principle, a three-phase voltage is generated.

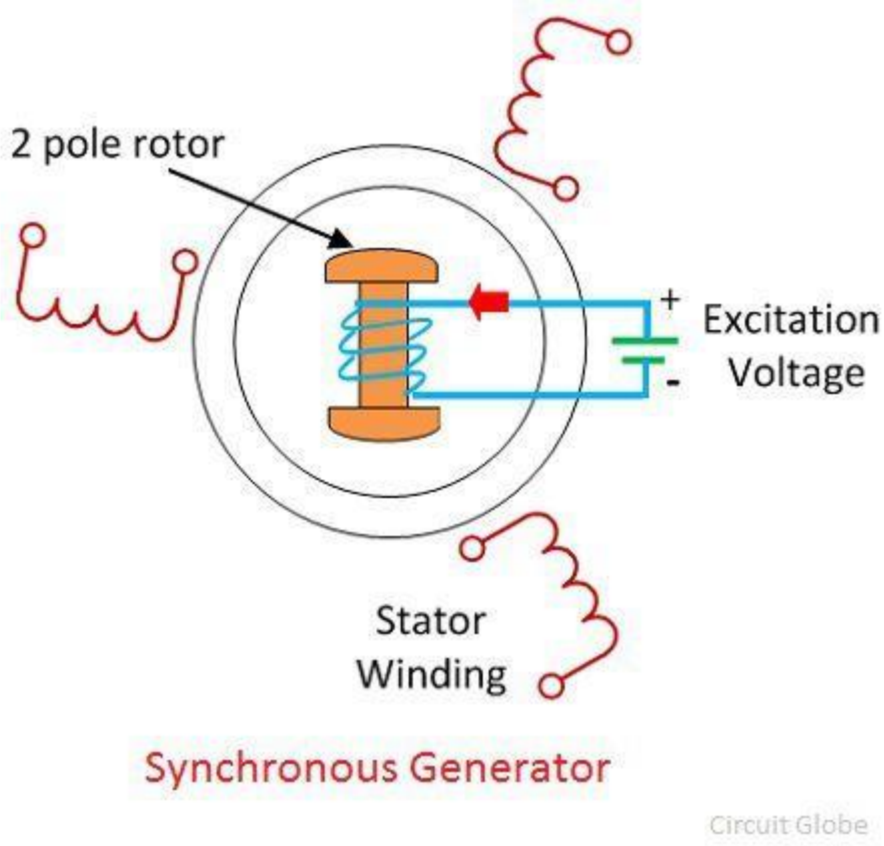
Working principle of a synchronous generator

The synchronous generator works on a principle of faraday law of electromagnetic induction. Electromagnetic induction state that electromotive force induced in the armature coil if it is rotating in the uniform magnetic field. The EMF will also be generated if the field rotates and the conductor becomes stationery. The relative motion and the field induces the EMF in the conductor. The wave shape of the induced voltage is always a sinusoidal curve.

Construction of synchronous generator

Synchronous generator construction consists of two main parts, namely: the stator and the rotor. The stator is the stationary part that emits alternating voltage and the rotor is a moving part that produces a magnetic field that induces it to the stator

The stator are the rotating part of the synchronous generator. They are the power generating components of the synchronous generator. The rotor has the field pole and the armature conductor. The relative motion between the rotor and the stator induces the voltage between the conductor.



Application of synchronous generator

The three phase synchronous generators have many advantages in generation, transmission and distribution. The large synchronous generator use in the nuclear thermal and hydropower system for generating the voltages.

The synchronous generator with 100MVA power rating uses in the generating station. The 500MVA power rating transformer use in the super thermal power stations. The synchronous generator design for the voltage ratings between 6.6KV and 33KV.

Generator Stability

Generators that are subjected to abnormal conditions can become unstable and lose synchronism. Generator instability can be classified into three types: steady-state, transient, and dynamic.

A. Steady-State Instability Steady-state instability occurs when too few transmission lines are available to transport power from the generating source to the load center.

B. Transient Instability Voltage phase angle instability can also occur because of slow-clearing transmission system faults. Called transient instability, it occurs when a fault on the transmission system near the generating plant is not cleared rapidly enough to avoid a prolonged unbalance between the mechanical and electrical generator outputs. A fault-induced transient instability has not caused any major system blackouts in recent years; however, generators need to be protected from damage that can result when transmission system protection is slow to operate. Relay engineers design transmission system protection to operate faster than a generator can be driven out of synchronism, but protection system failures have occurred that resulted in slow-clearing transmission system faults. It is generally accepted that loss-of-synchronism protection at the generator is necessary to avoid machine damage. The larger the generator, the less time it takes to drive the machine unstable for a system fault.

C. Dynamic Instability Often associated with the western United States, dynamic instability occurs when a fast-acting AVR control amplifies rather than damps some small, low-frequency megawatt oscillations that can occur in a power system. It can, however, occur anywhere the load is remote from the generation, particularly if the system is weak. While fast-responding excitation systems are important for improving transient stability, as discussed previously, they can also contribute a significant amount of negative damping. This reduces the natural damping torque of the system, causing undamped megawatt oscillations after a disturbance, such as a system fault. Small signal stability is defined as the ability of the power system to remain stable in the presence of small disturbances, most often caused by remote faults. Insufficient damping torque can cause generator rotor angle oscillations of increasing amplitude. When these megawatt oscillations grow, the generator can eventually be driven unstable, lose synchronism, and slip a pole. A power system stabilizer (PSS) working with the generator AVR provides positive damping when megawatt oscillations occur.

Faults Detection and Protection

A generator fault detected by protective relays is separated from the power system by tripping the generator breaker, field breaker, and prime mover. The system contribution to the fault will immediately be removed when the generator breaker trips. However, the generator current will continue to flow after tripping. The generator short-circuit current cannot be “turned off” instantaneously because of the stored energy in the rotating machine. Fault current will continue to flow for several seconds after the generator has been tripped, making generator faults extremely damaging. Generator terminal leads are usually isolated through bus construction to minimize multiphase terminal faults (isolated phase bus). To substantially reduce ground fault currents, the generator is also grounded by increasing the zero-sequence impedance through inserting neutral-ground impedance.

Transformers Used for Protective Relaying Purposes recommends that “the differential CTs on both sides of a generator should be of the same ratio, rating, connected burden, and preferably have the same manufacturer, so that the excitation characteristics are well matched" [1]. This recommendation ensures that the CTs saturate similarly. Small differences in the CT characteristic or in the secondary burden can produce significant differences in the CT saturation time. Spurious differential currents are at their worst when one CT begins to saturate while the other is still healthy. When the differential zone spans the generator breaker, the CTs are more likely to be dissimilar because they may have been supplied by different manufacturers. It should be stressed that using the same standard accuracy CTs does not guarantee the same characteristics. Furthermore, because the relay is often installed adjacent to the generator breaker, the secondary leads may be much shorter than those of other CTs installed in the neutral side of the generator CT.

Generator Grounding Practices

High- and low-impedance grounding represent the two major methods used within the industry to ground generator stator windings. Recently, hybrid grounding has become popular in industrial generators to reduce stator ground fault damage.

A. Low-Impedance Grounding:

The grounding resistor or reactor is selected to limit the generator ground fault contribution to current between 200 amperes to 150 percent of generator-rated current. LRG is generally used when multiple generating units operate on a common bus or directly connect to load buses without a voltage transformation providing the ground source for the system.

B. High-Impedance Grounding:

This grounding method allows the ground fault current to be reduced to low levels, typically 5 to 25 amperes. It is used on unit-connected generators.

C. Hybrid Grounding:

Combining HRG and LRG, this grounding method is used primarily at industrial facilities to reduce damage during stator ground faults. The generator normally operates with both ground sources in parallel. When a generator ground fault is sensed, the high-speed switch in series with the LRG is tripped during generator shutdown to reduce damaging ground fault current during generator "coast down."

Types of Differential Schemes

Three high-speed differential schemes are used for stator phase fault detection: percentage differential, high-impedance differential, and self-balancing differential schemes.

A. Percentage Differential Scheme

   The percentage differential scheme achieves security during external faults by employing a restraining signal to bias the operating signal. The operating signal is usually the vector sum of the two CT currents, and the restraining current is usually the average magnitude of the two CT currents. The ratio of the operating signal and restraint signal (slope) may be variable, fixed, or dual slope.

B. High-Impedance Differential Scheme

The high-impedance differential scheme employs a stabilizing resistor to provide security for CT saturation during an external fault. The relay is actually a voltage relay and responds to high voltage impressed across its coil, caused by the CTs all trying to force current through the operate winding during an internal fault. These relays should be supplied from identical CTs with fully distributed secondary windings with negligible leakage reactance. The setting of the highimpedance relay is based on the perfect performance of one input CT and the complete saturation of the others.

C. Self-Balancing Differential Scheme

The self-balancing differential scheme is used on small generators. This scheme detects phase and ground faults on the generator stator using a single low-ratio CT per phase with the leads of both ends of each winding passing through it, so the net flux is zero for normal conditions. A simple instantaneous overcurrent relay connected to the CT secondary provides fast, reliable protection by detecting any difference between current entering or leaving the winding. The limited size of the CT window limits conductor size and consequently the size of the unit that can be protected. Saturation for external faults is not a concern, but saturation during internal faults is possible. The relay should have as low a burden as possible, typically solid state, to maintain high sensitivity and lessen the likelihood of CT saturation. Very high fault currents can saturate this type of CT if a sensitive electromechanical relay with high burden is used.

Stator Ground Fault Protection

The stator grounding method used in a generator installation determines the generator performance during ground fault conditions. If the generator is solidly grounded, it will deliver a very high-magnitude current to a single-line-toground (SLG) fault at its terminals, accompanied by a 58 percent reduction in the phase-to-phase voltages involving the faulted phase and a modest neutral voltage shift. If the generator is ungrounded, it will deliver a negligible amount of current to a bolted SLG fault at its terminals, accompanied by no reduction in the phase-to-phase terminal voltages and a full neutral voltage shift. These conditions represent the extremes in generator grounding, with normal practice falling predictably in between. In practice, generators are rarely operated solidly grounded or ungrounded, with the possible exception of low-voltage systems. A high magnitude of fault current is available when a generator is solidly grounded. This is not acceptable because equipment damage will be severe. Furthermore, shutting down the generator by tripping the generator breaker, excitation (field) breaker, and prime mover does not cause the fault current to immediately go to zero. The flux trapped in the field will result in the fault current slowly decaying over a number of seconds after the generator is tripped, which can cause substantial damage. At the other extreme, operating an ungrounded generator provides negligible fault current, but the line-to-ground voltages on the unfaulted phases can rise considerably during ground faults, which could cause the failure of generation equipment insulation. As a result, stator windings on major generators are grounded in a manner that will reduce fault current and over voltages and yet provide a means of detecting the ground fault condition quickly enough to prevent burning of core iron. Two types of grounding are widely used within the industry. They are categorized as high- and low impedance grounding. An emerging method known as hybrid grounding is also used as an alternative solution.

System Backup Protection

System backup protection for generators consists of time delayed protection for phase-to-ground and multiphase fault conditions. Backup generator protection schemes protect against failure of the system protection relaying and subsequent long clearing system faults. Relay settings for backup relaying must be sensitive enough to detect low fault current conditions. The settings must balance the opposing requirements for sensitivity to detect distant faults and the security to prevent unnecessary generator tripping. There are tradeoffs in the application of system backup protection [2]. NERC is examining requirements for ensuring coordination of system backup protection with the transmission system and has created a technical reference document that explores generating plant protection schemes and their settings to provide guidance for coordination with transmission protection, control systems, and system conditions to minimize unnecessary trips of generation during system disturbances [3].

Phase Fault Protection

Two types of relays are commonly used for system phase fault backup protection, distance type relays or voltage controlled (or voltage-restrained) overcurrent relays. System backup protection is time-delayed and coordinated with transmission line protection. The relay type selected for any application is usually a function of the type of relaying used on the lines that are connected to the generator (i.e., overcurrent protection for lines that are protected by overcurrent relays and distance protection for lines that are protected by phase distance relays). Overcurrent backup relays are difficult to coordinate with line distance relays because of the variability in trip time for overcurrent relays for different system conditions. These system configurations generally require settings criteria that include compromises in the desired protection to maintain generator security.

Abnormal Frequency Protection

When a power system is in stable operation at normal frequency, the total mechanical power input from the prime mover to the generators is equal to the sum of the connected loads and all real power losses in the system. A significant upset of this balance causes an abnormal system frequency condition [4]. Abnormal frequency conditions can cause generators to trip, tie lines to open from overload, or parts of the system to separate because of power swings and resulting instability. This could result in the power system separating into one or more electrically isolated islands. Most utilities have implemented an automated load shedding program to prevent total system collapse as well as minimize the possibility of equipment damage during an abnormal frequency operating condition. These load-shedding programs are designed to:

- Shed just enough load to relieve the overloading on connected generation.
- Minimize the risk of damage to the generating plant.
- Mitigate the possibility of cascading the event as a result of a unit under frequency tripping.
- Quickly restore system frequency to near normal.

Conclusion

Protection and prevention are needed in a synchronous generator. Both Relays, Circuit breakers and others, also serve as protection. The application of system backup protection at generating plants involves the careful consideration of tradeoffs between sensitivity and security. The risks in applying backup protection can be minimized by careful consideration of the points discussed in this paper. These risks are far outweighed by the consequences of not having proper backup protection.

Generator Synchronization

Generator synchronization is the process of matching parameters such as voltage, frequency, phase angle, phase sequence, and waveform of alternator (generator) or other source with a healthy or running power system. This is done before the generator is reconnected to the power system. Once a generator is synchronized with the parameters of another generator, alternator, or bus bar, the system can run smoothly again.

Generator synchronization to a power system must be conducted carefully to prevent damage to the unit, as well as the power system itself. When synchronizing a generator to a power system, the frequency and voltage of the generator must match closely. The rotor angle and the instantaneous power system phase angle must be close prior to closing the generator breaker and connecting the isolated generator to a power system.

In the majority of cases for generator synchronization, the synchronization process is automated via an automatic synchronizer with manual control capabilities that can be used in backup situations. Synchronizing panels generally indicate any adjustments that the operator should make in regards to the governor and excited and when it’s deemed acceptable to close the breaker.

Need For Generator Synchronization

A generator cannot deliver power to an electrical power system unless all the aforementioned parameters exactly match those of the network. The need for synchronization arises when two or more alternators work together to supply the power to the load. Since electrical loads do not remain constant, the two or more generators supplying the power need to be interconnected and operate in parallel to handle larger loads.

Using a series of small units instead of a single generator is known as parallel operation. Synchronization is critical for parallelization, and many commercial plants prefer this for its:

Reliability: With multiple alternators, parallel operation is much more reliable than single-unit generators. In a single-unit system, the whole setup will shut down if the alternator fails. In parallel systems, one alternator can fail and the other units will keep the system active.

Continuity: If a unit needs maintenance, the other systems can stay up and running to prevent your entire operation from stopping.

Load: Your load requirements may vary throughout the day. Adjust your parallel system to accommodate higher and lower loads with more or fewer active systems.

Efficiency: Generators run at the highest efficiency when they operate at their load rating. By adapting to load changes, your system can remain efficient at all times.

Capacity: Bigger operations require more power. With more generators, systems have more alternators for increased capacity.

Requirements for Synchronization of Generators

During your generator synchronization procedure, you will need to make sure four parameters align between your generators. These parameters are:

Phase sequence: The three phases of the alternators in your system must have the same phase sequence as the phases of your electric grid or bus bar.

Voltage magnitude: Voltage magnitude can cause significant disruptions if the alternators and bus bar are not parallel. When alternator voltage is higher than the bus bar, you’ll create a high reactive power in your grid that could pose safety concerns. If the alternator voltage is lower, the generator will absorb high reactive power from the bus bar and potentially fail.

Frequency: When frequencies are unequal, they create an unstable flow of energy. This instability may lead to damaged equipment.

Phase angle: The phase angle of the bus bar and generator alternator must be zero.

Your generator synchronization procedure will help you determine if these parameters are equal between your bus bar and generator alternators.

Techniques for Synchronization

Generator synchronization can be a complex idea to understand, but here are the basics of three techniques for generator synchronization:

Three Dark Lamps Method – uses bus bar to synchronize second generator; cannot provide information on generator and bus bar frequency.

Two Bright, One Dark Method – measures frequency but cannot check the correctness of the phase sequence.

Synchroscope Method – indicates whether the alternator frequency is higher or lower than the bus bar frequency

Modern synchronization equipment automates the entire synchronization process in order to avoid manual lamps and synchroscope observations. These methods are far more reliable.

Faulty Generator Synchronization

If generator synchronization with a power system is done incorrectly or poorly executed, there is the potential for:

Generator & prime mover damage due to mechanical stress caused by rapid accelerator/deceleration need to bring the rotating masses in synch.

Damage to the generator and step-up transformer windows due to the high currents

Disturbance to the power system, such as oscillations and deviating voltages that are not nominal

Keeps the generator from staying online and pick up loads when the protective relay determines the generator is running in abnormal operating conditions, which can cause the generator to shutoff

With all the possible risks of faulty synchronization, it’s critical for all operations to take the appropriate measures during the process. Consult a professional if you’re unsure about the steps to take, and they’ll help you keep your system up and running.

Conclusion

Generator synchronization is very important and needed because, a generator cannot deliver power to an electrical power system unless all the aforementioned parameters exactly match those of the network. The need for synchronization arises when two or more alternators work together to supply the power to the load. Since electrical loads do not remain constant, the two or more generators supplying the power need to be interconnected and operate in parallel to handle larger loads.

References

[1] IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes, IEEE Standard C37.110-2007.

[2] G. D. Rockefeller, A. N. Darlington, W. A. Elmore, R. J. Fernandez, J. R. Gil-Berlinches, R. W. Haas, L. E. Landoll, W. J. Marsh, G. R. Nail, A. C. Pierce, C. L. Wagner, and L. S. Wright, “A Survey of Generator Back-Up Protection Practices: IEEE Committee Report,” IEEE Transactions on Power Delivery, vol. 5, issue 2, pp. 575–584, Apr. 1990.

[3] NERC System Protection and Control Subcommittee, Power Plant and Transmission System Protection Coordination – Technical Reference Document. North American Electric Reliability Council, December 2009. Available: http://www.nerc.com/filez/spctf.html.

[4] IEEE Guide for Abnormal Frequency Protection for Power Generating Plants, IEEE Standard C37.106-2003, 2004.

[5] Kudelina, K., Vaimann, T., Asad, B., Rassõlkin, A., Kallaste, A., & Demidova, G. (2021). Trends and challenges in intelligent condition monitoring of electrical machines using machine learning. Applied Sciences, 11(6), 2761.

[6] Jalayer, M., Orsenigo, C., & Vercellis, C. (2021). Fault detection and diagnosis for rotating machinery: A model based on convolutional LSTM, Fast Fourier and continuous wavelet transforms. Computers in Industry, 125, 103378.