

IEEE Guide for AC Generator Protection

IEEE Power and Energy Society

Developed by the
Power System Relaying and Control Committee

IEEE Std C37.102™-2023
(Revision of IEEE Std C37.102-2006)



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Power System Relaying and Control Committee
of the
IEEE Power and Energy Society

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IEEE SA Standards Board

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Abstract: This guide has been prepared to assist the protection engineer in applying relays for the protection of generators from damage caused by internal electrical faults, system faults, or abnormal operating conditions.

Keywords: abnormal operation, combined cycle, combustion, excitation control system, generator, ground fault, grounding, hydro, IEEE C37.102™, phase fault, steady-state stability limit, steam, subsynchronous resonance, synchronization, system faults, system operations, turbine

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Introduction

This introduction is not part of IEEE Std C37.102™-2023, IEEE Guide for AC Generator Protection.

This application guide for the protection of synchronous generators is a revision of IEEE Std C37.102-2006. It presents a review of the generally accepted forms of protection for the synchronous generator and its excitation system. It also summarizes the use of relays and devices and serves as a guide for the selection of equipment to obtain adequate protection. The guide is primarily concerned with protection against faults and abnormal operating conditions for large hydraulic, steam, and combustion turbine generators (CTGs). It also gives some consideration to security against operation due to events at the system level for which the generator is not taken out of service.

In this revision, the following notable changes have been made.

- Modified split-phase differential protection section to include information on impact of cutting out and bypassing the faulted coil of a hydrogenerator (4.3.2.6.2)
- Added section on turn-to-turn stator fault detection using negative sequence directional element (4.3.2.6.4)
- Added section on series fault protection (4.3.2.7)
- Emphasis on overall differential protection (4.3.2.8) and underreaching distance protection (4.3.2.9) for phase fault backup protection of the generator differential
- Included improvements for selective ground fault protection for multiple generators connected to a bus (4.3.3.2.2)
- Included section on improvements of high-impedance grounded stator ground fault-protection schemes (4.3.3.2.3)
- Removed information on power transformer protection and directed user to the appropriate guide (4.9)
- Included a section on voltage transformer (VT) grounding connections (5.2.3)
- Added section on supplemental inadvertent energization protection scheme (5.4.4)
- Provided additional information on subsynchronous resonance (SSR), including SSR studies (5.5.2)
- Expanded synchronizing section with focus on synchro-check supervision (5.7.4)
- Added section on dynamic simulation (5.9)
- Removed the clause “Multifunction generator protection system” (Clause 6 in the previous revision)
- Modified informative Annex A to use actual equipment datasheets and provide examples for the most commonly used protective functions
- Added informative Annex B, Deriving steady-state stability limit (SSSL) equations

This guide discusses general generator ground fault protection, while IEEE Std C37.101™⁶ provides detailed generator ground fault-protection guidance. This guide also discusses general volts-per-hertz (V/Hz) protection and provides some information about frequency protection. IEEE Std C37.106™ provides detailed guidance regarding both V/Hz and frequency protection for the generator.

⁶ Information on references can be found in Clause 2.

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IEEE Guide for AC Generator Protection

1. Overview

1.1 Scope

This application guide describes ~~for the relay protection of synchronous generators presents a review of~~ the generally accepted forms of protection for ~~the~~ synchronous generators ~~generator~~ and ~~their~~ ~~its~~ excitation systems ~~system~~. It summarizes the use and ~~of relays and devices and serves as a guide for the~~ selection of relays and other protective devices that provide generator ~~equipment to obtain adequate~~ protection. The guide is primarily concerned with protection against faults and abnormal operating conditions for large hydraulic, steam, and combustion turbine generators; (CTGs) ~~Basing generator protection on machine size is difficult because the desired protection may be determined more by the importance of the generator to the power system than by the size of the generator.~~

The guidance pertains ~~recommendations made pertain~~ to typical synchronous generator installations. However, sufficient background information relating to protection requirements, applications, and setting philosophy is given to enable the reader to evaluate the need, to select, and ~~to~~ apply suitable protection for most situations. The protective functions discussed in this guide may be implemented with a multifunction microprocessor-based protection system (digital system). The protection philosophy, practices, and limits are usually similar ~~essentially identical~~ to those of the implementation using discrete component relays. The algorithms used to perform some of the protection ~~functions~~ may be different, but typically provide equivalent ~~should produce equal~~ or better protection. The protection ~~However, the~~ performance and capability may be superior using ~~the~~ digital systems such as improved frequency response (bandwidth) and thresholds (pickup settings). Other additional features may be available from these digital systems that enhance the functionality such as monitoring and reporting.

This guide does not purport to detail the protective requirements of all generators in every situation. For example, standby and emergency-use generators are specifically excluded.

1.2 Purpose

This guide summarizes the use of relays and other protective devices such that the reader may select the necessary equipment to provide adequate protection for ac generators from short circuits and abnormal operating conditions.

1.3 Description of the guide

Clause 3 presents a brief description of typical generator design and connections, generator grounding practices, excitation systems design, and generating station arrangements. ~~The intent of~~ This clause intends ~~is~~ to present information that affects the protection arrangement and selection of protective relays.

A discussion of auxiliary systems ~~system transfer~~ and the possible negative impacts of misoperation and faults on these systems are beyond the scope of this guide.

The methods employed for grounding and fusing the secondary circuits of voltage transformers (VTs) and the methods for grounding current transformer (CT) secondary circuits are not generally the same for all installations. CT and VT secondary circuits may ~~should~~ be grounded in accordance with IEEE Std C57.13.3™.¹

Clause 4 briefly describes the damaging effects of faults and abnormal operating conditions and the type of devices and their settings commonly used to detect these conditions. A clear understanding of the effects of abnormalities on generators will assist the reader in evaluating the need for and the means of obtaining adequate generator protection in many situations ~~any specific situation~~.

Clause 5 presents a discussion of other forms of protection and factors that may be considered in the generator zone.

¹ ~~Information on references can be found in Clause 2.~~

~~Clause 6 describes multifunction generator protection systems (MGPS) and presents an application on a typical generating unit and includes information on testing of MGPS.~~

Clause ~~6~~ ⁷ presents detailed diagrams that are classified according to the method by which the generator is connected to the system. These diagrams show the combination of relays (and their control ~~functions~~ ~~function~~) often applied for generator and excitation system protection in accordance with good engineering practices. These diagrams also consider the protective devices on other equipment in or adjacent to the generating station that are connected to trip or shut down the generator.

Table 2 provides a summary of the protective elements and their subclause references.

Table 3 provides guidance on equipment to be tripped or alarm for the different protective elements and their subclause references.

Annex A describes sample calculations for settings of some common generator protection functions.

Annex B provides derivations for the steady-state stability limit (SSSL) equations.

Annex C provides the bibliography.

1.4 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall equals is required to*).^{7, 8}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should equals is recommended that*).

⁷ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may equals is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can equals is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

~~IEC 60034-1, Rotating Electrical Machines—Part 1: Rating and Performance.²~~

~~IEC 60034-3, Rotating Electrical Machines—Part 3: Specific Requirements for Cylindrical Rotor Synchronous Machines.~~

~~Std 67TM, IEEE Guide for Operation and Maintenance of Turbine Generators.^{3,4}~~

IEEE Std 421.1TM, IEEE Standard Definitions for Excitation Systems for Synchronous Machines.^{9,10}

² IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH 1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

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~~IEEE Std 142™, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book).~~

~~IEEE Std 502™, IEEE Guide for Protection, Interlocking, and Control of Fossil-Fueled Unit-Connected Steam Stations.~~

IEEE Std C37.91™, IEEE Guide for Protecting ~~Protective Relay Applications to~~ Power Transformers.

IEEE Std C37.101™, IEEE Guide for Generator Ground Protection.

IEEE Std C37.106™, IEEE Guide for Abnormal Frequency Protection for Power Generating Plants.

IEEE Std C37.110™, IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes.-

IEEE Std C50.12™, IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/-Motors for Hydraulic Turbine Applications Rated 5 MVA and Above.

IEEE Std C50.13™, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz, Synchronous Generators Rated 10 MVA and Above.-

~~IEEE Std C57.13™, IEEE Standard Requirements for Instrument Transformers.~~

IEEE Std C57.13.3™, IEEE Guide for Grounding of Instrument Transformer Secondary Circuits and Cases.

IEEE Std C62.92.2™, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part II—~~Grounding of~~ Synchronous Generator Systems.

3. Description of generators, excitation systems, and generating station arrangements_

3.1 Generator winding design and arrangements_

3.1.1 General

The stator windings of a three-phase synchronous generator consist of a number of single-turn or multi-turn coils that are connected in series to form a single-phase circuit. One of these circuits or several circuits connected in parallel are used to form a complete phase winding. The phase windings are normally connected in wye with the neutral grounded through some external impedance. Delta-connected phase windings are used occasionally but this is not a common connection. Figure 3-1 illustrates the possible winding arrangements and connections._

The winding arrangements shown in parts a) and b) of Figure 3-1 are the configurations most commonly used for all types of generators. When more than one circuit is used per phase as shown in part b) of Figure 3-1, these circuits will be connected in parallel inside the machine and two leads brought out to external connections. In general, up to three ~~current transformers~~ (CTs) may be provided at each end of the phase winding for relaying and instrumentation purposes._

In some hydrogenerator designs, there may be a number of circuits per phase and each circuit may consist of a number of multi-turn coils connected in series. In these machines, the parallel-connected circuits may be formed into two groups that are paralleled, and only two leads are brought out to external connections. There may be an equal or unequal number of circuits in each group. In this design, CTs may be provided in each phase group and in the leads to the external connections.

Part c) in Figure 3-1 illustrates the wye-connected double-winding construction sometimes used in large steam turbine generators. Each phase has two separate windings that are connected externally to form two wye connections. The high-voltage terminals of each phase are connected in parallel to form a single three-phase output. Separate wye connections are formed on the neutral end of each winding. These neutrals may be physically at opposite ends of the machine. This arrangement is sometimes referred to as the *double-ended, 12-bushing* machine and is used where the total full-load phase current exceeds the current carrying capability of a single bushing. The bushings at each end of the winding may accommodate three CTs.

Part d) in Figure 1 shows a ~~In the~~ delta-connected generator winding, where , there may be one or more paralleled circuits per phase with two leads brought out to external connections. CTs may be provided inside the delta, at the ends of each winding, ~~or~~ outside the delta, or both.

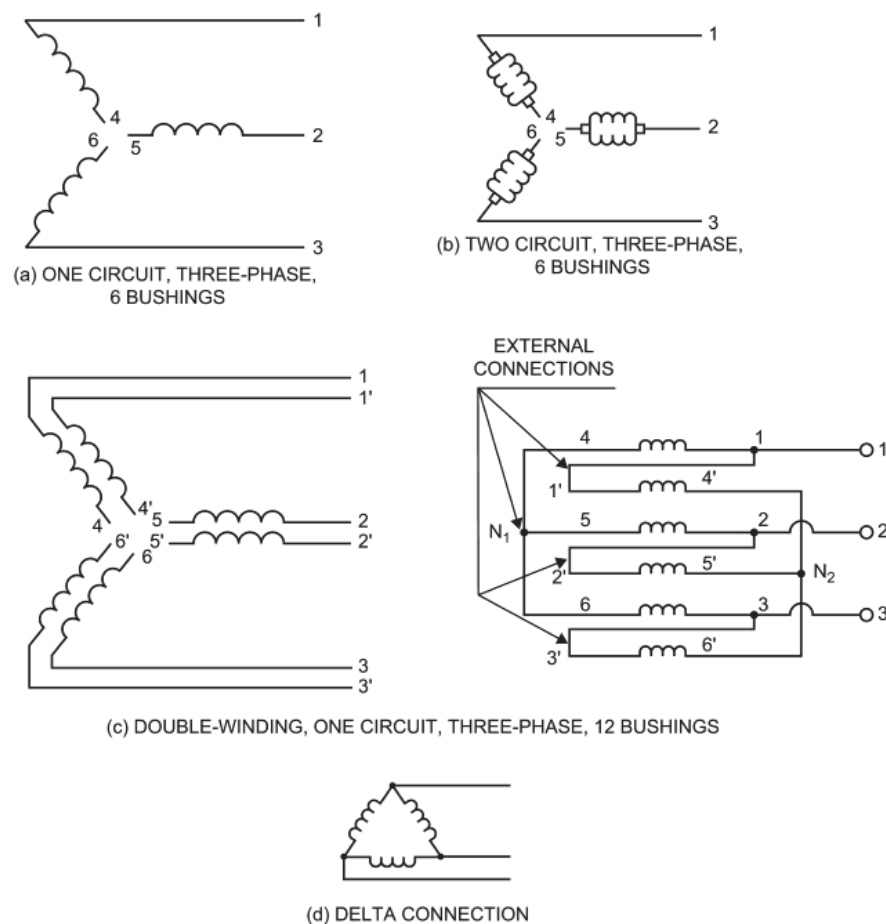


Figure 3-1 — Winding configurations

3.2 Generator grounding

3.2.1 General

It is common practice to ground all types of generators through some form of external impedance. The purpose of this grounding is to limit the mechanical stresses and fault damage in the machine, to limit transient voltages during faults, and to provide a means for detecting ground faults within the machine. A complete discussion of all grounding and ground protection methods may be found in IEEE Std C62.92.2TM and IEEE Std C37.101TM, respectively. ^{TM 1993 [B62].⁵}

The methods most commonly used for generator grounding will be discussed in this guide. They are listed in five ~~four~~ broad categories, as follows:

- a) High-impedance grounding (3.2.2)
- b) Low-resistance grounding (3.2.3)
- c) Reactance grounding (3.2.4)
- d) Grounding-transformer grounding (3.2.5)
- e) Hybrid impedance grounding (3.2.6)

Solid grounding of a generator neutral is not generally used since this practice may result in high mechanical stresses and excessive fault damage in the machine. According to IEEE Std C50.13TM, the maximum stresses that a generator is normally designed to withstand are ~~is that~~ associated with the currents of a three-phase fault at the machine terminals. Because of the relatively low zero-sequence impedance inherent in most synchronous generators, a solid phase-to-ground fault at the machine terminals will produce winding currents that are higher than those for a three-phase fault. Therefore, to comply with this standard, generators are grounded in such a manner to limit the maximum phase-to-ground fault current to a magnitude equal to, or less than, the three-phase fault current.

Generators are sometimes ~~not often~~ operated ungrounded. While this approach greatly limits the phase-to-ground fault currents, and consequently limits damage to the machine, it may produce high transient overvoltages during faults and also makes single line-to-ground ~~the~~ fault location difficult to determine due to only the stray capacitance in the circuit.

The following subclauses provide a very brief description and typical applications of the above grounding methods.

3.2.2 High-impedance grounding

3.2.2.1 General

Two methods of high-impedance grounding are most commonly in use today: high-resistance grounding and ground fault neutralizer grounding. In both methods, the primary of a distribution transformer is connected between the generator neutral and ground, while the secondary winding rating is 120 V or 240 V. Note that distribution transformers with internal fuses or circuit breakers are ~~should~~ not ~~be~~ used to disconnect the high-impedance grounding devices, as they could inadvertently be open and the grounding and protection scheme could be inoperative at the time of fault. The two methods differ in their secondary connection as shown in the following subclauses.

3.2.2.2 High-resistance grounding

The high-resistance grounding method utilizes a resistor connected across the secondary of the distribution transformer to limit the maximum ground fault current. The resistor is selected so that for a single-phase-to-ground fault at the generator terminals, the power dissipated in the resistor is equal to, or greater than, three times the total zero-sequence capacitive kilovolt-amperes (kVA) to ground.

The capacitive kVA to ground includes the generator windings and all other equipment connected to the machine terminals. With this resistor rating, the transient overvoltages during faults will be kept to safer ~~safe~~ values. For a single-phase-to-ground fault at the machine terminals, the primary fault current will be limited to a value in the range of about 3 A to 25 A. If possible, the ground fault current level ~~is~~ ~~should be~~ chosen such that ~~to coordinate with the~~ primary fuses (when used) of wye-connected VTs with grounded neutrals will operate before generator ground fault protection for faults in the VT circuit.

In some cases, the distribution transformer is omitted and a high value of resistance is connected directly between the generator neutral and ground. The resistor size is selected to limit ground fault current to the range of 3 A to 25 A. While this method of grounding is used in some parts of the world, the physical size of the resistors, the required resistor insulation level, and the cost may discourage the use of this method.

3.2.2.3 Ground fault neutralizer grounding (tuned inductive reactor)

The ground fault neutralizer grounding method utilizes a secondary tunable reactor to limit the maximum ground fault current. The ohmic value of this secondary reactor is selected so that, when reflected into the primary circuit, its reactance is equal to one-third of the total zero-sequence capacitive reactance. This capacitive reactance includes the generator and all equipment connected to the generator terminals up to and including the delta-connected windings of the main step-up and station service transformers. Losses in the grounding reactor circuit and dielectric losses in the system determine the equivalent 50 Hz or 60 Hz zero-sequence impedance and, thus, the ground fault current. The reactor coil constant (i.e., X/R ratio) is selected to strike a balance between limiting the ground fault current and avoiding potentially damaging overvoltages. This type of grounding limits the single-phase-to-ground fault current to 1 A or less. This low fault current will not sustain an arc or cause damage to the generator stator iron. ~~Therefore, ground fault neutralizer grounding may detect much higher impedance grounds than is possible with high resistance ground.~~ Ground fault neutralizer grounding may be used with all unit-system installations where a single generator is connected through its individual wye delta generator step-up (GSU) transformer ~~(or transformers)~~ to the system.

The use of ~~Also~~, ground fault neutralizer grounding also allows the detection of ~~may detect much~~ higher-resistance ground faults compared to ~~impedance grounds than is possible with~~ high-resistance grounding. For example, the calculated maximum detectable fault impedance for a ~~typical~~ nuclear unit of 975 MVA is 3.5 ~~MΩ~~ ~~M1~~ for ground fault neutralizer grounding (see Gulachenski and Courville, [B81]¹¹). The ~~calculated~~ ~~Calculated~~ maximum stator fault current for ~~the~~ ~~a typical~~ 975 MVA nuclear unit is 0.45 A. If this generator is grounded through a high-resistance grounding, the maximum fault impedance that may be detected is 67 ~~kΩ~~ ~~k1~~ (~~see Gulachenski and Courville [B82]~~). Along with these desirable features, there are several that may be considered undesirable:

~~If protection from iron burning and greater sensitivity of detecting incipient faults is deemed desirable (for example an existing older generator equipped with high resistance grounding), retrofitting with ground fault neutralizer grounding may be done by replacing the resistor with a reactor.~~

- a) If automatic tripping is used, coordination with generator VT fuses may not be possible. Faults on the secondary wiring may cause ground indications where wye-wye connected generator VTs are used. Coordination may be achieved by various methods, see IEEE Committee Report "Potential Transformer Application" [B97] and IEEE Power System Relaying Committee Working Group J12 Report [B119 B17].
- b) High zero-sequence voltages and phase-to-ground overvoltages on the generator system are possible if too high a reactor coil constant is selected for the neutralizer.
- c) If surge protective equipment is used on the generator, it is selected on the basis of possible higher temporary overvoltages during ground faults. Voltages may be kept ~~to~~ within reasonable limits by selecting a reactor coil constant in a range from 10 to 50 without reducing the sensitivity of the fault-detection system.

^{11 5} The numbers in brackets correspond to those of the bibliography in Annex C B.

3.2.3 Low-resistance grounding

In this method, a resistor is connected directly between the generator neutral and ground. The resistor is selected to provide sufficient current for selective ground relaying of several machines, feeders, or both. In general, the grounding resistor is selected to limit the generator's contribution to a single-phase-to-ground fault at its terminals to a value in the range of 200 A up to 150% of [the](#) rated full-load current. Resistor cost and size usually preclude the use of resistors to limit the current below 200 A or to permit currents [significantly](#) above machine-rated current.

This method of grounding is generally used where two or more generators are bused at generator voltage and connected to a system through one [GSU](#) ~~step-up transformer~~ or where the generator is connected directly to a distribution system having a low-impedance grounding source on the generator bus. [A disadvantage of this grounding method is increased damage due to a ground fault.](#)

3.2.4 Reactance grounding

This method uses an inductive reactance between the generator neutral and ground. The inductive reactance is selected to produce an X_0/X_1 ratio at the machine terminals in the range of 1 to 10; ~~Common practice is to maintain an effectively grounded system by keeping the X_0/X_1 ratio at 3 or less;~~ see IEEE Std C62.92.2. This method of grounding produces relatively high levels of phase-to-ground fault currents ranging from approximately 25% to 100% of the three-phase fault current.

This grounding method is generally used where the generator is connected directly to a solidly grounded distribution system.

3.2.5 Grounding transformer grounding

This method involves the use of a grounding transformer connected to the machine terminals or ~~to~~ the generator bus. [This method may be used in applications where two or more generators are bused at generator voltage and connected to a system through one GSU.](#) The grounding may be provided by a zigzag transformer or a grounded wye-delta transformer, or by a grounded wye-broken delta transformer with a resistor connected across a corner of the broken delta.

~~When a zigzag or a grounded wye-delta transformer is used, the effective grounding impedance is selected to provide sufficient current for selective ground relaying.~~

The grounded wye-broken delta transformer with ~~a~~ resistance in the corner of the broken delta is generally a high-resistance grounded system. The resistance would be selected in the same manner as for the distribution transformer with a secondary resistor. This method limits the single-phase-to-ground fault current to a range of 3 A to 25 A primary.

A zigzag or grounded wye-delta transformer may be used as an alternate grounding source when a generator with neutral reactor grounding is connected directly to a distribution system. This approach may also be used where several ungrounded-wye or delta-connected generators are bused at generator voltage.

A grounded wye-broken delta transformer with a resistor across the corner of the broken delta may be used to provide a means for detecting ground faults in ungrounded-wye or delta-connected generators.

3.2.6 Hybrid impedance grounding

Industrial generator applications may utilize a hybrid impedance grounding scheme, i.e., both high-impedance and low-impedance grounding. This is further discussed in 4.3.3.6.

3.3 Excitation systems

3.3.1 General

There are four basic types of excitation systems that are used to control the output of ac machines: the dc generator commutator exciter, the alternator rectifier exciter with stationary rectifier system, the alternator rectifier exciter with rotating rectifier system, and the static excitation system. In terms of response times, excitation systems fall into two categories: rotating and static. Rotating exciters respond slower than static exciters. The speed of response of the excitation system is commonly expressed in terms of the nominal response, which indicates the speed of response during a period of 0.5 s after a sudden 20% reduction in generator terminal voltage. Rotating exciters have a nominal response in the range of 0.5 per unit (pu) to 1.0 pu ~~per-unit~~ exciter volts per second. Static exciters have a nominal response in the range of 2.5 pu ~~per-unit~~ to 3.5 pu ~~per-unit~~ exciter volts per second. The detailed effects of the excitation system nominal response on the fault current characteristics of the generator are ~~is~~ beyond the scope of this guide but are ~~is~~ well-documented in Higgins, Holly, and Wall [B90 ~~B16~~]. While a detailed description of these systems is beyond the scope of this guide ~~standard~~, their general characteristics will be briefly described in the following subclauses._

Refer to the IEEE 421 series of standards on excitation systems, IEEE Std 421.1™ through IEEE Std 421.6™ for further guidance.

3.3.2 System with dc generator-commutator exciter_

Figure ~~3-2~~ shows a schematic of the primary elements of this system. Not shown in ~~on~~ this diagram or ~~and the succeeding~~ Figure ~~3-3~~, Figure ~~3-4~~, Figure ~~3-5~~, and Figure ~~3-6~~ are the power supplies, such as pilot exciters, the current and potential intelligence inputs to the excitation control, etc., since they ~~are~~ essentially function ~~functionally~~ the same for all systems.

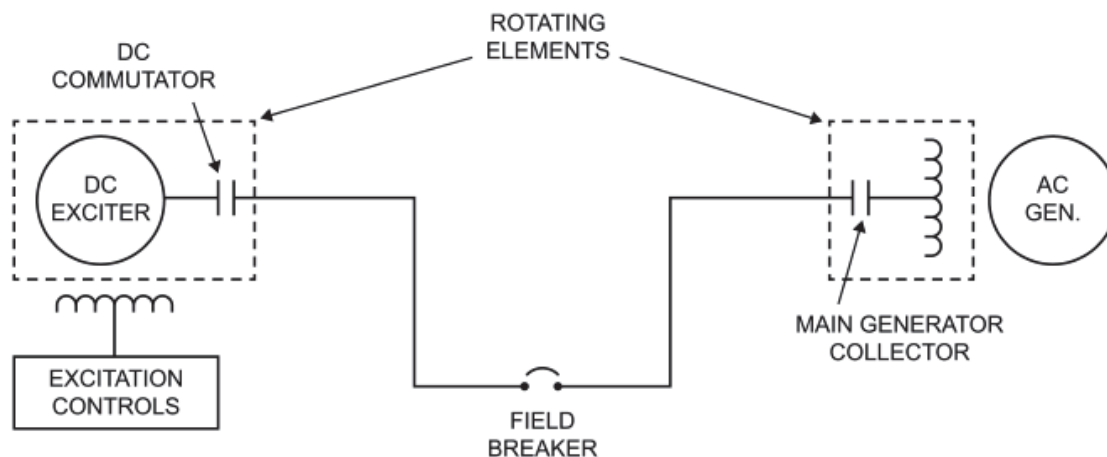


Figure 3-2—System with dc generator commuter ~~commutator~~ exciter

In this system, a dc control signal is fed from the excitation control to the stationary field of the dc exciter. The rotating element of the exciter then supplies a direct current through a field breaker to the field winding of the main ac generator. The rotating armature of the dc exciter is either driven from the same shaft as the rotating main field of the generator or may be on a separate motor-driven shaft. In either case, a dc commutator is required on the exciter, and brushes and collector rings are required on the rotating generator field to transmit the main generator field current. This system is used only on the smaller or older machines.

3.3.3 System with alternator rectifier exciter and stationary rectifiers

To eliminate the problems of high-current commutation for medium and large machines, the dc exciter is replaced by an alternator. The system of Figure 3-3 uses an alternator with a rotating dc field winding driven from the shaft of the main ac generator. The current for this field winding is obtained from the excitation controls through brushes and collector rings. The three-phase ac output of the alternator is rectified through a stationary three-phase diode bridge and the direct-current output is fed to the field winding of the generator through brushes and collector rings.

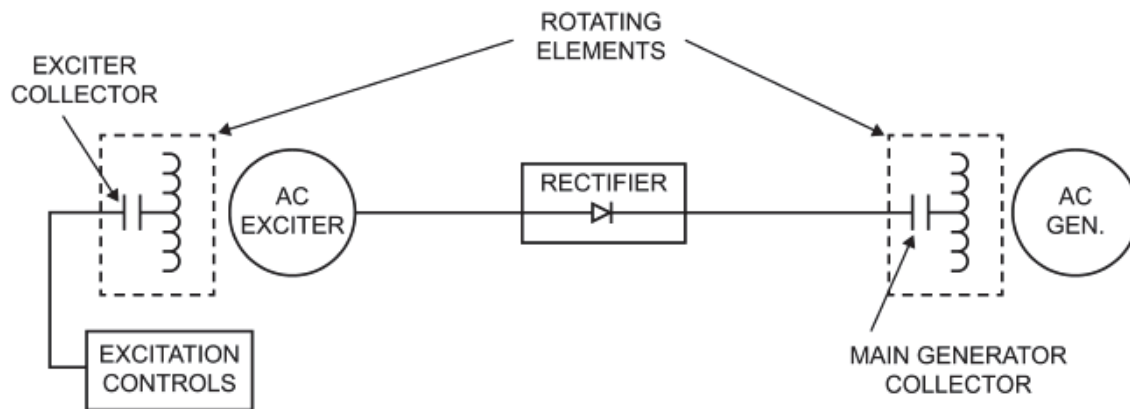


Figure 3-3 — System with alternator rectifier, ~~exciter and~~ stationary exciter and stationary rectifier

3.3.4 System with alternator rectifier exciter and rotating rectifiers (brushless exciters)

The system of Figure 3-4 again uses an alternator but by mounting the dc field winding on the stator of the exciter and the ac armature winding on the rotor, all brushes and commutators have been eliminated. In this system, the ac armature of the exciter, the rotating ~~three-phase~~ diode bridge rectifier, and the main field of the ac generator are all mounted on the same rotating shaft system. All electrical connections are made along or through the center of this shaft.

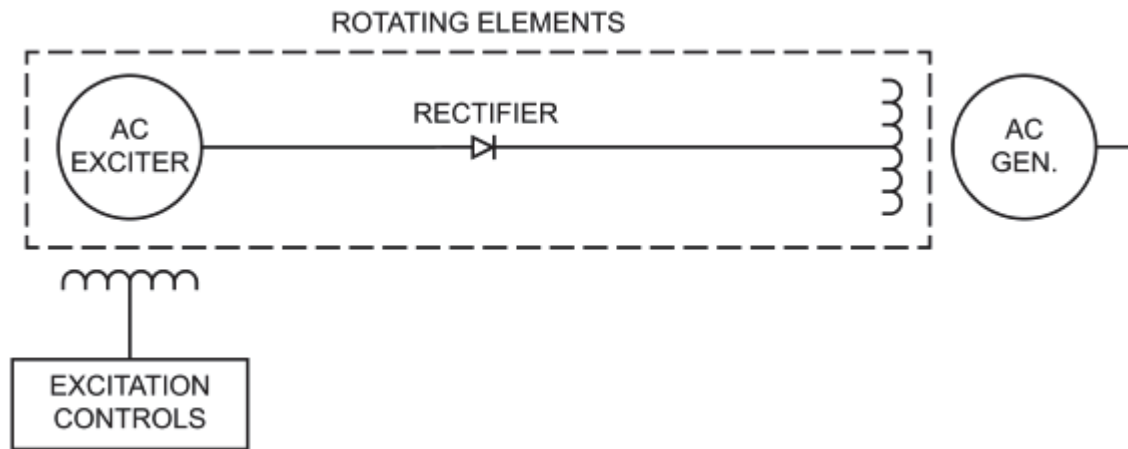


**Figure 3-4—System with alternator rectifier exciter and rectifiers
(brushless exciters)**

3.3.5 System with static exciter

The preceding schemes typically utilize the energy directly from the prime-mover shaft to obtain the required excitation power. Static excitation systems obtain this power from the electrical output of the generator or the connected system. In Figure 3-5, external power CTs or power potential transformers ~~VTs~~ (or both) feed rectifiers in the regulating system that, in turn, supply direct current to the main field winding of the generator through brushes and collector rings.

Some systems use only power potential transformers as input power, while some use additional power CTs to boost the input during fault conditions when the terminal voltage is reduced. During close-in faults, excitation systems using only potential transformers as input power may be unable to sustain fault currents long enough for the protective relaying to operate (see Higgins, Holly, and Wall [B90 B16]).

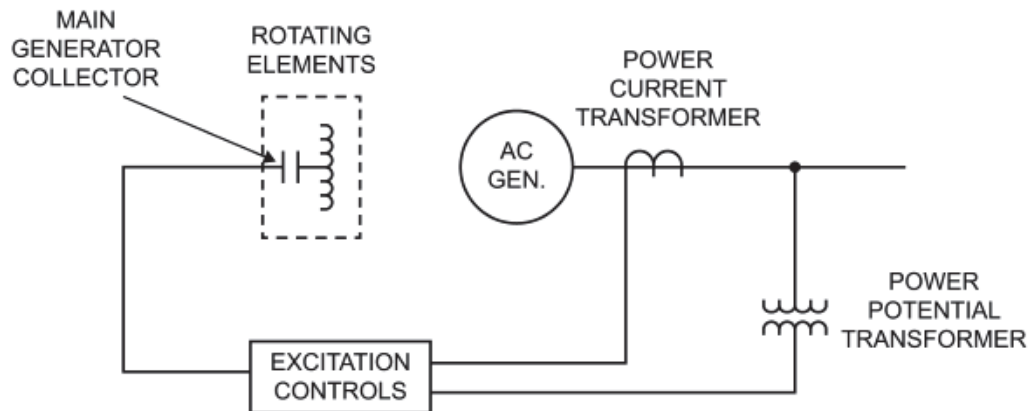


Figure 3-5.—System with static exciter

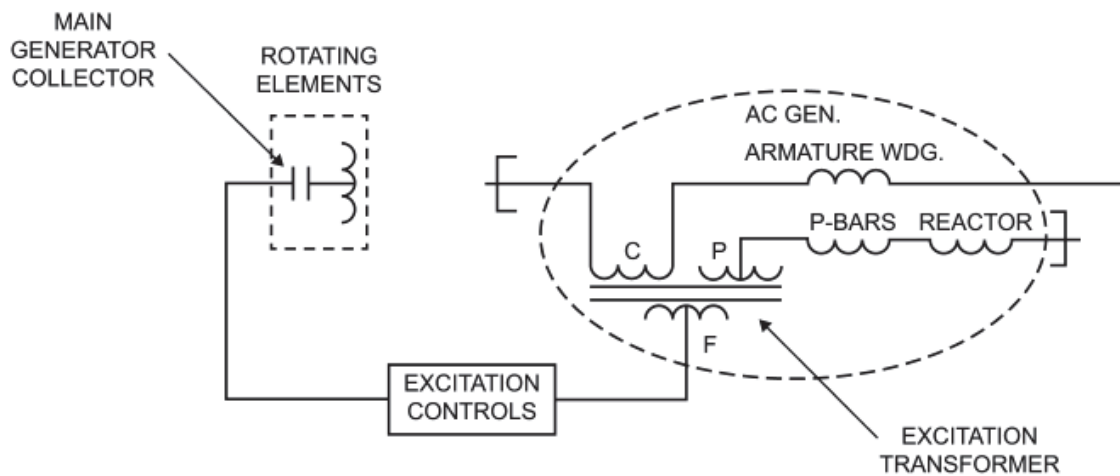


Figure 3-6.—Static excitation system with internal supply

In Figure 3-6 the excitation power is provided from a voltage and current source within the main generator. The voltage source is a set of three-phase windings mounted in three generator stator winding slots (P-bars in Figure 3-6). These potential windings are connected to each phase of an ungrounded-wye excitation transformer, [shown as the winding labeled "P."](#)

The current source is achieved by passing each of the three stator main [armature](#) winding leads through a window in each phase excitation transformer, ~~shown as the winding labeled "C."~~

The output windings of the three single-phase excitation transformers are connected in delta, [shown as the winding labeled "F,"](#) to supply the external bridge rectifier circuits. As indicated ~~in Figure 3-6,~~ the potential windings in the stator are connected in wye through linear reactors. The neutral [of the excitation system](#) is high-resistance grounded through a distribution transformer, thereby providing a means for detecting possible ground faults in the potential windings and excitation transformer.

3.4 Generating station arrangements

[3.4.1 General](#)

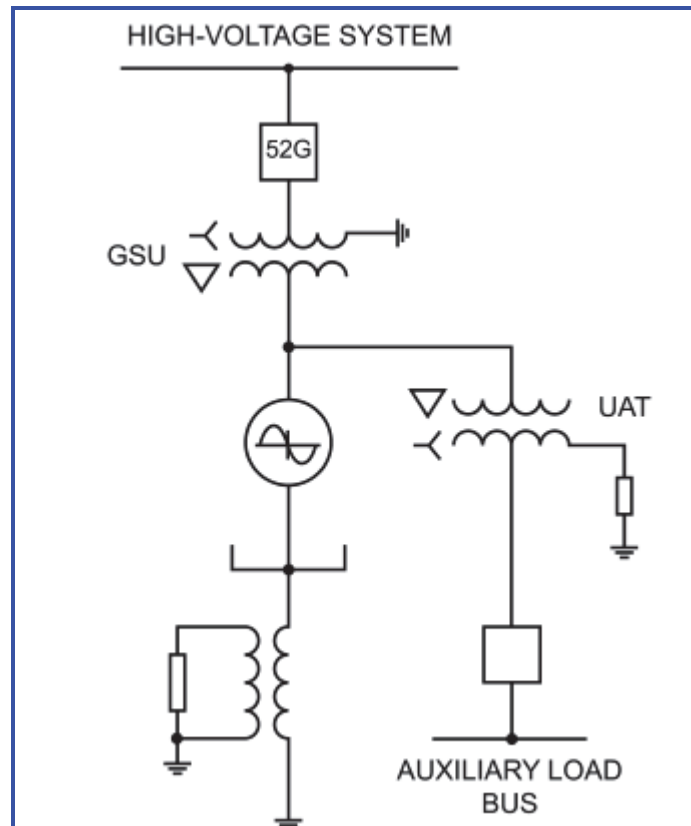
The selection and arrangement of protection for generators is influenced to some degree by the method in which the generators are connected to the system and by the overall generating station arrangement. For purposes of this guide, the following generator connections and station arrangements will be considered:

- a) Unit generator-transformer configuration
- b) ~~Unit~~ Generator-transformer configuration with [a generator breaker on the low-voltage side of the GSU](#)
- c) Cross-compound generators
- d) Generators sharing a [GSU](#) ~~unit transformer~~
- e) Generators connected directly to a distribution system

These configurations represent widely used generating station arrangements.

3.4.2 Unit generator-transformer configuration

In this arrangement, a generator and its [GSU](#) ~~transformer (unit transformer)~~ are connected as a unit to the system as shown in Figure 3-7. The generator is usually wye-connected and high-resistance grounded through a distribution transformer. The unit transformer is most commonly a grounded wye-delta connection.



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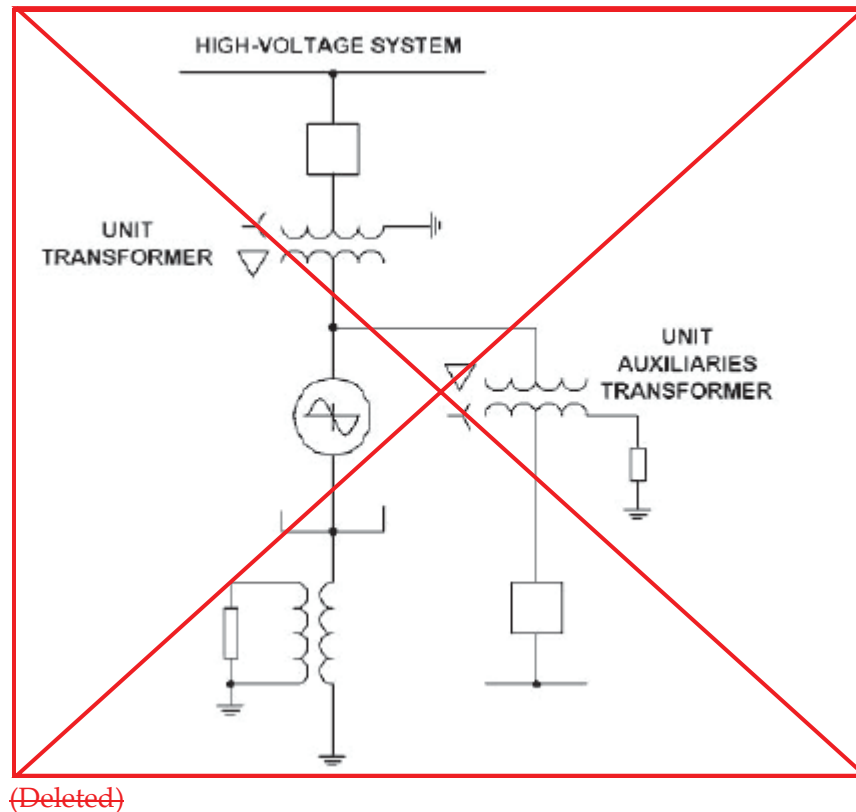


Figure 3-7 – Unit generator-transformer configuration

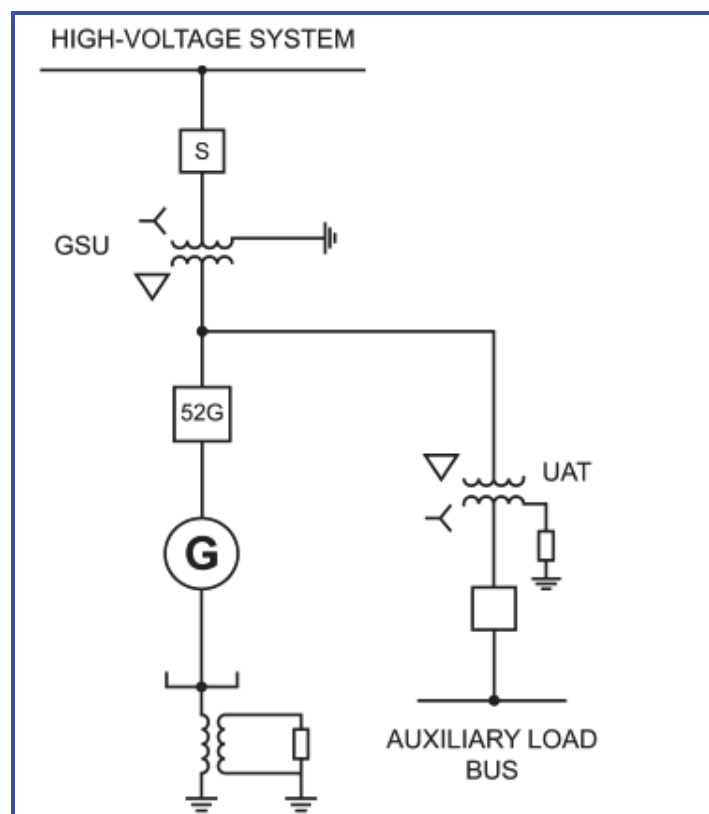
In some large steam turbine generator installations, the generator may be connected to the system through two parallel-connected GSUs ~~unit transformers~~, each transformer having one-half the total generator rating.

There may be one, two, or more ~~two~~ unit auxiliary ~~auxiliaries~~ transformers (UATs). These may be two-winding or three-winding transformers, depending on ~~upon~~ the size of the generator unit. In most instances, the UAT ~~unit auxiliaries transformer(s)~~ is connected delta-wye with the neutral of the wye connected to ground through some impedance.

3.4.3 ~~Unit~~ Generator-transformer configuration with a generator breaker on the low-voltage side of the GSU ~~breakers~~

This arrangement, illustrated in Figure 3-8, has been used with various size ~~some large~~ generators. The generator is wyeconnected and high-resistance grounded through a distribution transformer. ~~Two half-size grounded wyedelta connected unit transformers are used to connect the generator to the system. As shown in this figure, two unit auxiliaries transformers are used in this arrangement. For small and medium sized generators, a typical configuration is shown in Figure 7-6.~~

The benefits of this configuration are fast fault removal for ~~generator step up (GSU)~~ and UAT ~~auxiliary transformer~~ faults and it allows ~~to allow~~ the UAT ~~auxiliary transformer~~ to be used as a startup source.



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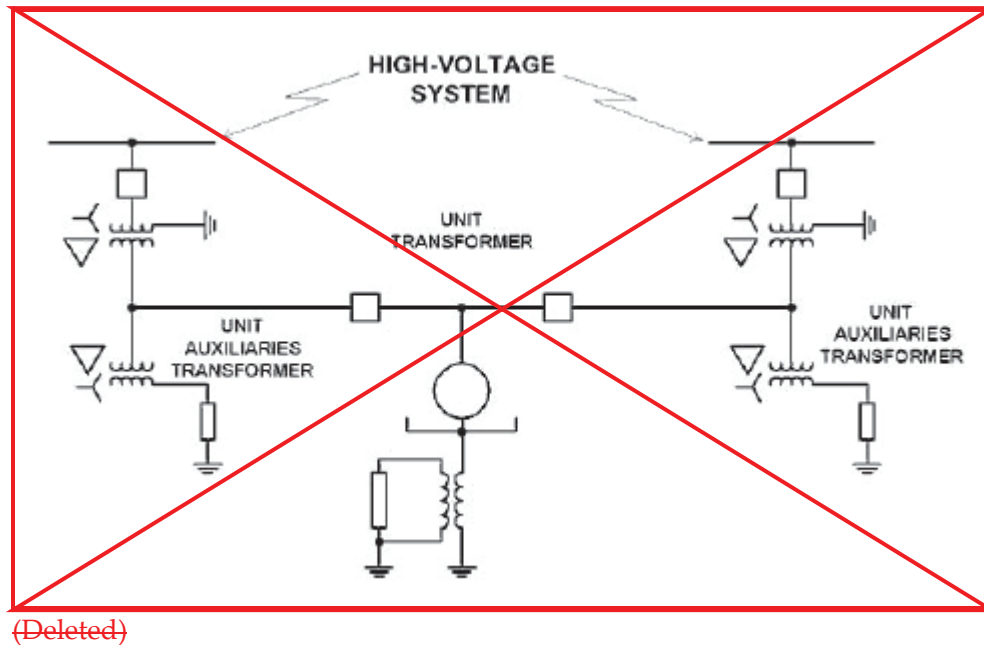
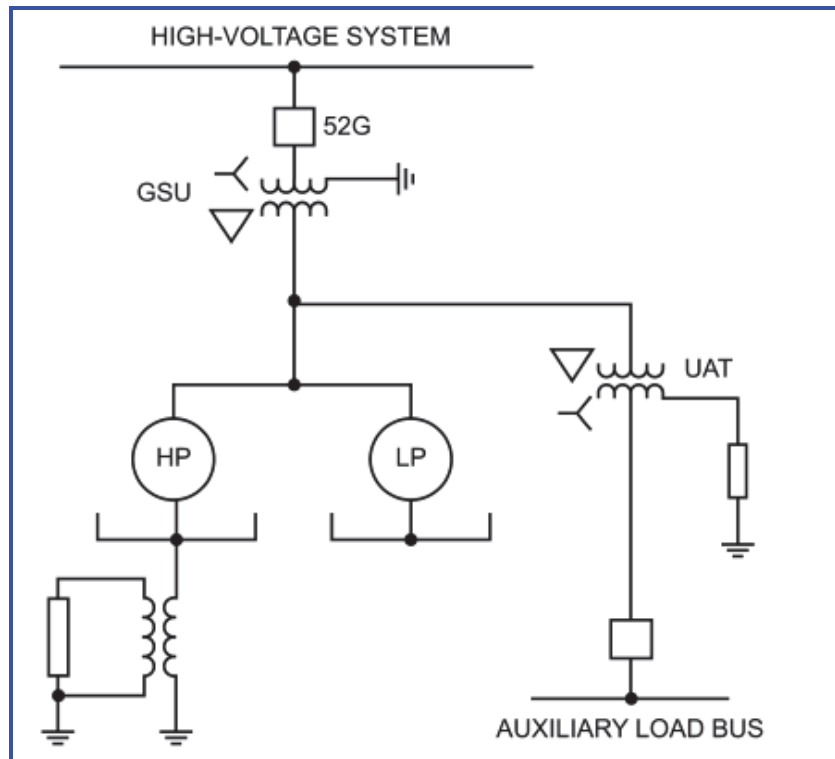


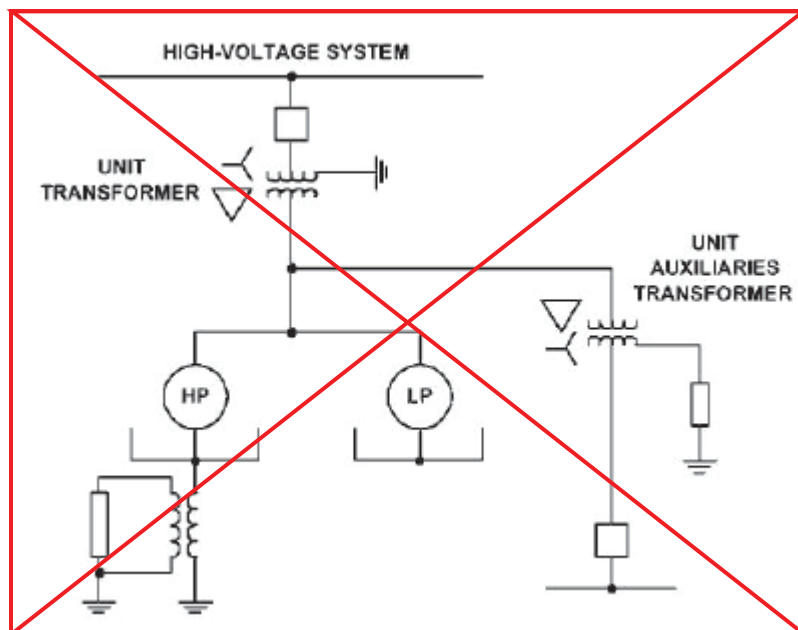
Figure 3-8—~~Unit~~ — Generator-transformer configuration with a generator breaker on the low-voltage side of the GSU ~~breakers~~

3.4.4 Cross-compound generators

A common method for connecting a cross-compound generator to a system is shown in Figure 3-9. ~~The~~ Low-pressure (LP) and ~~the~~ high-pressure (HP) units are bused at generator voltage and connected to the system through a grounded wye-delta GSU. LP unit transformer. ~~Both the low-pressure and HP high-pressure~~ units are usually wye-connected, and it is common ~~recommended~~ practice to ground only one of the neutrals. High-resistance grounding through a distribution transformer is commonly used.



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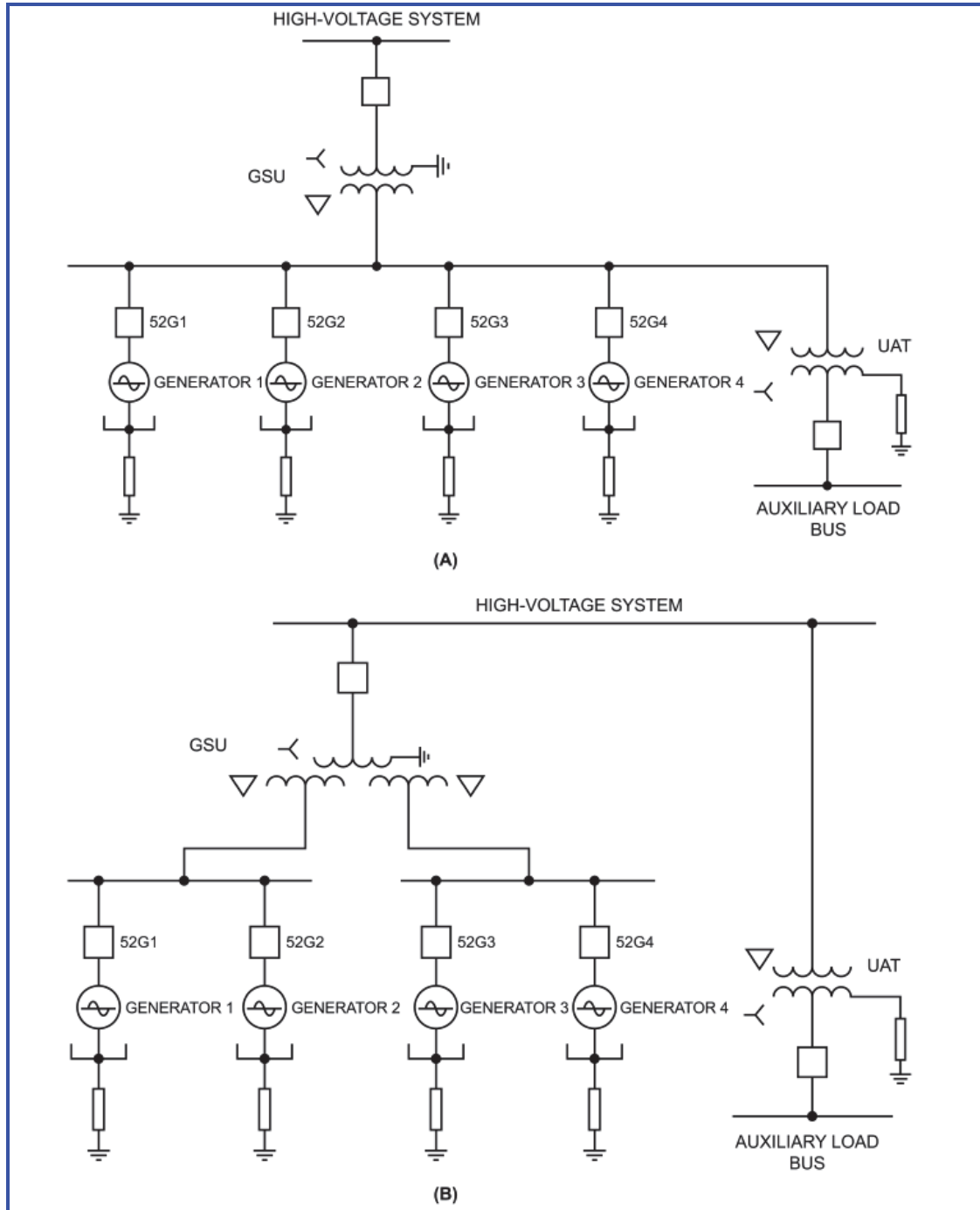
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Figure 3-9—Cross-compound generators

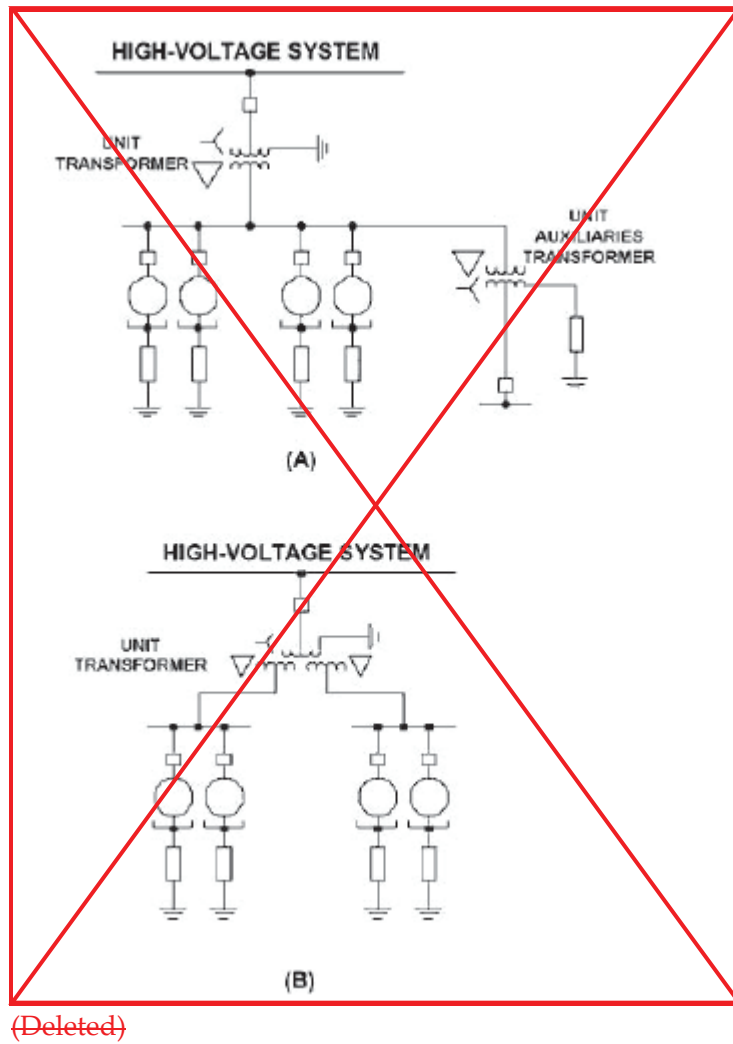
3.4.5 Generators sharing a GSU ~~unit-transformer~~

Figure 3-10 illustrates two methods for connecting two or more generators to a system using one GSU ~~step-up transformer~~. In part A of Figure 3-10, two or more generators are bused at generator voltage and a two-winding grounded wye-delta GSU ~~unit-transformer~~ is used to connect the generators ~~machines~~ to the system. In part B of Figure 3-10, a number of generators are connected to the system through a three-winding grounded wye ~~wyedelta~~-delta-delta GSU ~~transformer~~. Either of these approaches may be used with small hydraulic or ~~combustion turbine generators~~ (CTGs).

In either approach, neutral-resistor grounding of the generators can help provide ~~may be used in order to achieve~~ selective ground fault protection for ~~the~~ machines. In some instances, the generators may be high-resistance grounded through a distribution transformer ~~in order to~~ reduce ~~minimize~~ damage due to phase-to-ground faults. However, this grounding method has the disadvantage that it may not provide sufficient current for selective relaying.



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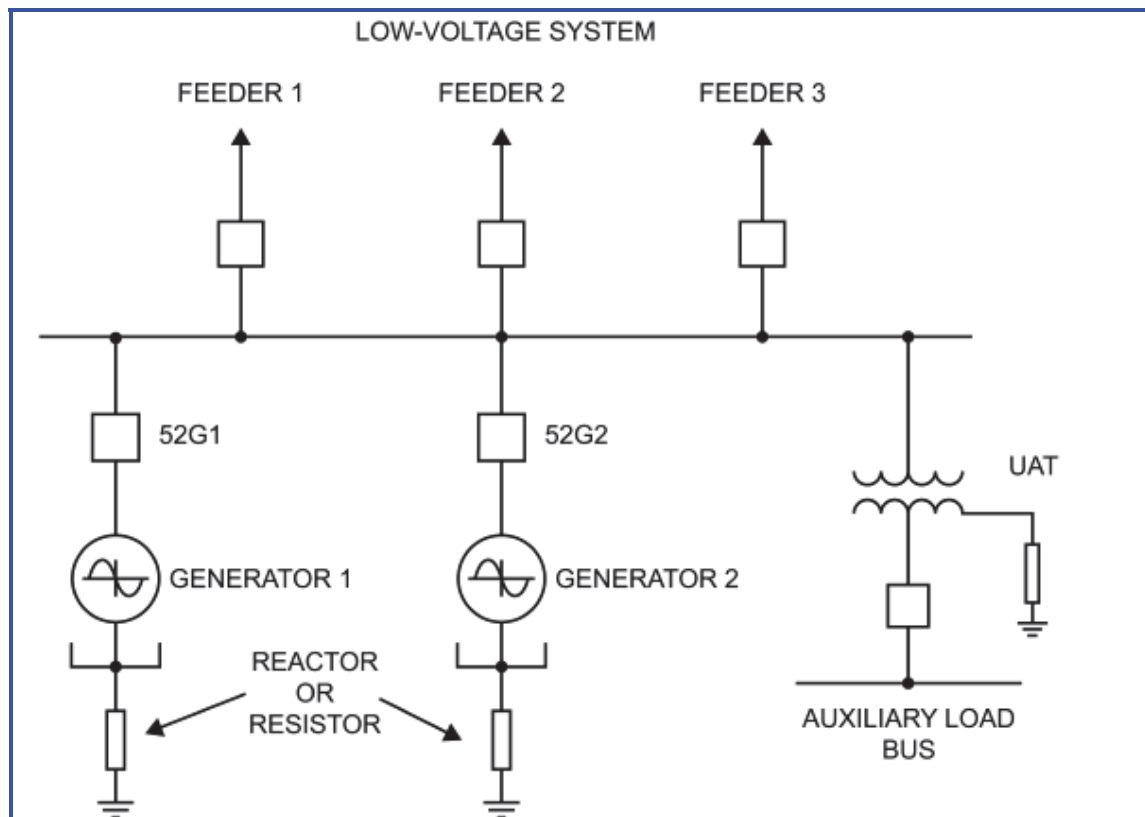


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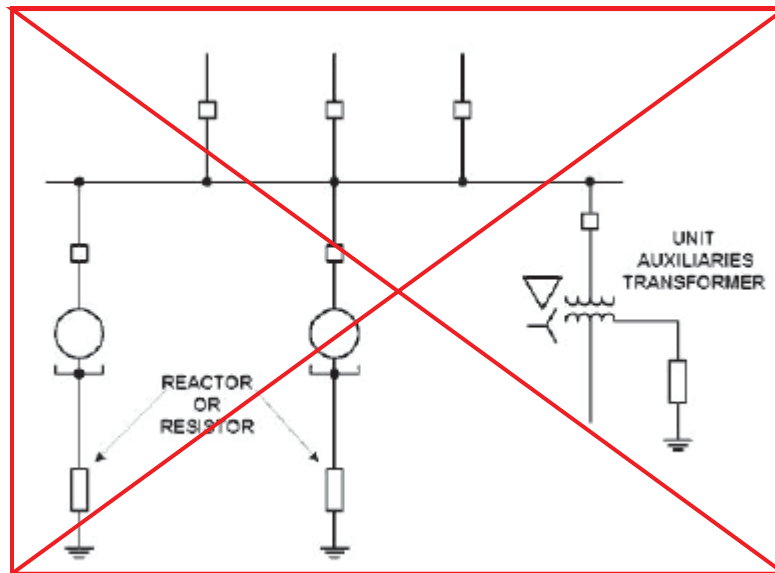
Figure 3-10 — Generators sharing a GSU transformer

3.4.6 Generators connected directly to a distribution system

Figure 3-11 shows a typical installation where generators are connected directly to a distribution system. If the system is effectively grounded ($X_0/X_1 \leq 3$, $R_0/X_1 \leq 1$), the generator neutral will be grounded with a neutral inductive reactance. As an alternative as noted in 3.2.5, 4 a bus-grounding transformer with a neutral reactor may be applied if the generator neutral is ungrounded. If the system is not effectively grounded, the generator neutral or grounding transformer neutral will generally be grounded through a low ohmic value resistor. Where this is used, the feeders connected to off-of the bus are shall-be of the three-wire type (four-wire connections are not used), and only three- no-phase loads are served (no single-phase line to ground loads) because the to-neutral resistor is not sized to serve continuous current. loads may be permitted.



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Figure 3-11— Generator connected directly to a distribution system

4. Protection requirements

4.1 Generator stator thermal protection

4.1.1 General

Thermal protection for the generator stator core and windings may be provided for the following contingencies:

- Generator overload
- Failure of cooling systems
- Localized hot spots caused by core lamination insulation failures or by localized or rapidly developing winding failures

4.1.2 Generator overload

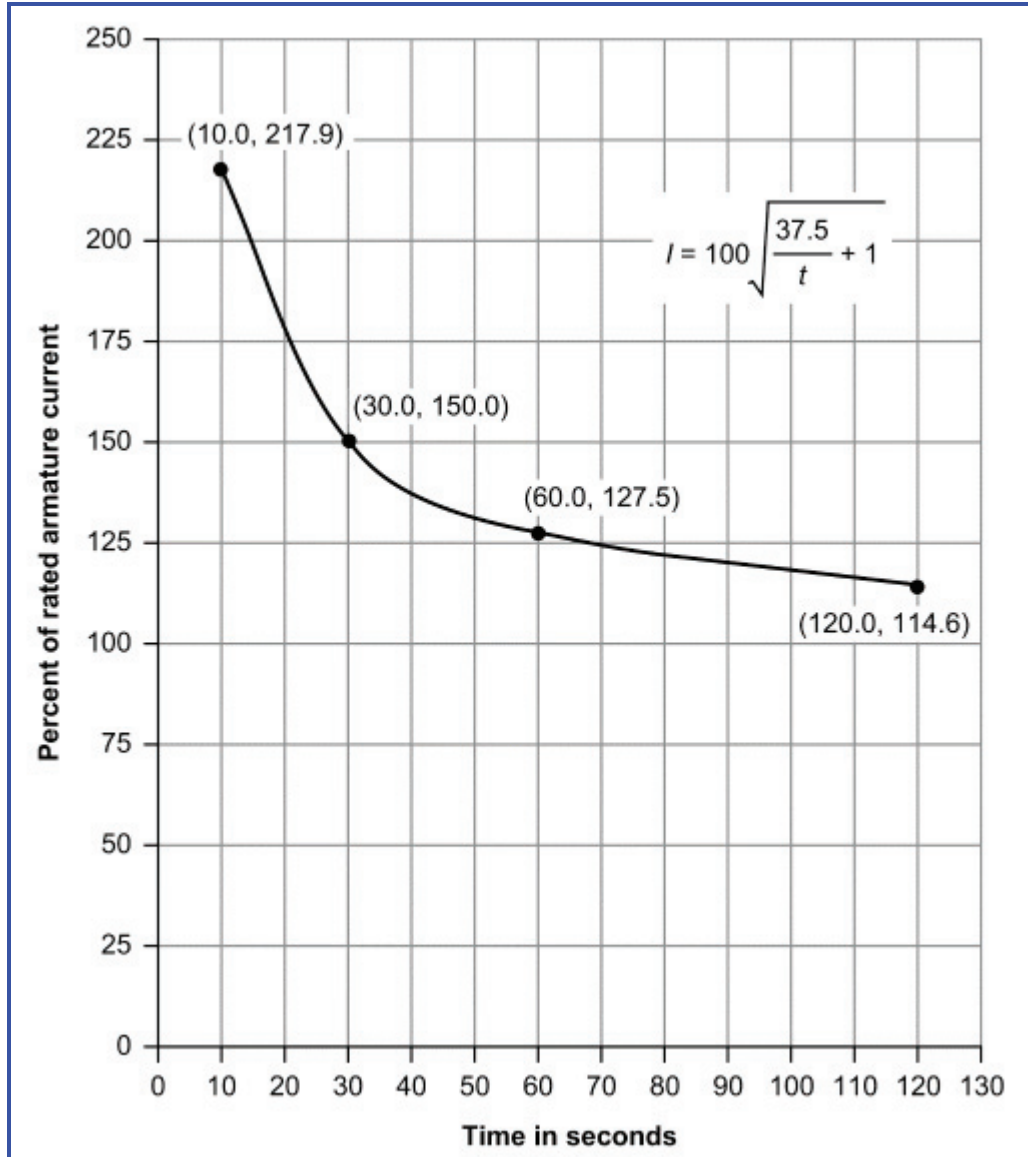
4.1.2.1 General

The continuous output capability of a generator is expressed in ~~kilovolt-amperes (kVA)~~ available at the terminals at a specified frequency, voltage, and power factor. For hydrogen-cooled generators, the output rating is usually given at the maximum and several lesser hydrogen pressures. ~~For CTGs, this capability is given at an inlet air temperature in the range of 20° C to 50° C.~~ In general, generators may operate successfully at rated kVA, frequency, and power factor for a voltage variation of 5% above or below rated voltage.

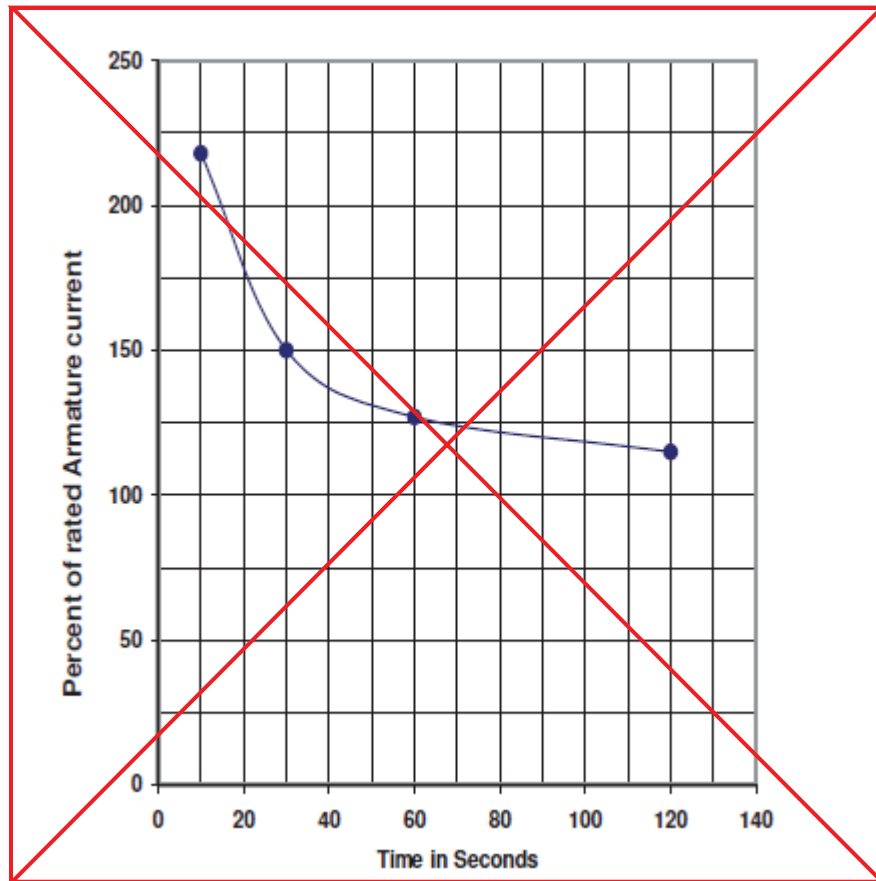
Under emergency conditions, it is permissible to exceed the continuous output capability for a short time. A plot of the stator short-time capability in accordance with IEEE Std C50.13 is shown in Figure 12. Protective schemes to help prevent thermal damage to the stator winding utilize winding temperature detectors or relays having time-current characteristics that conform to the short-time capability curve. ~~, the armature winding short time thermal capability is given by the following:~~

~~Time (seconds)~~	~~10~~	~~30~~	~~60~~	~~120~~
~~Armature current (percent)~~	~~218~~	~~150~~	~~127~~	~~115~~

~~(Deleted)~~



[\(New\)](#)



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Figure 12 4-1 — ~~Turbine~~-Generator armature short-time thermal capability for balanced three-phased loading

where 100% current is the rated current of the machine at maximum hydrogen pressure.

A plot of this short time capability is shown in Figure 4-1. Protective schemes to prevent thermal damage to the stator winding utilize winding temperature (curve drawn using data from IEEE Std C50.13) detectors or relays having time-current characteristics that conform to the short time capability curve.

4.1.2.2 Winding-temperature protection

Most generators are supplied with a number of temperature sensors to monitor the stator windings. These sensors are usually resistance temperature detectors (RTDs) and thermocouples (TCs). As the name implies, the RTD detects temperature by the change in resistance of the sensor. A TC detects temperature by the change in thermoelectric voltage induced at the TC junction.

These sensors are used to continuously monitor the stator winding. In attended generating stations, the sensors may be connected to a data acquisition system for recording or alarm purposes.

In unattended stations, the sensors may be used with a relay to alarm, ~~to~~ initiate corrective action, or ~~to~~ trip the unit if preset temperature limits are exceeded.

For generators with conventional (indirectly cooled) stator windings, RTDs embedded between the top and bottom bars are used to monitor winding temperatures. For generators with inner-cooled (directly cooled) stator windings, the stator bar coolant discharge temperature is used along with the embedded RTDs (if equipped) to monitor the winding temperature.

The generator manufacturer may ~~should~~ be consulted for specific recommendations on the preferred method of monitoring these sensors and temperature limits for alarm and trip purposes.

4.1.2.3 Overcurrent protection

In some instances, generator overload protection may be provided through the use of a torque-controlled overcurrent relay that is coordinated with the IEEE Std C50.13 short-time capability curve of Figure 12 ~~4-1~~ (curve drawn using data from IEEE Std C50.13). This relay consists of an instantaneous overcurrent (IOC) unit and a time-overcurrent unit having an extremely inverse characteristic. The instantaneous unit is set to pick up at 115% of full-load current and is used to torque control the time-overcurrent unit. The instantaneous unit dropout is set at ~~should be~~ 95% or higher of the pickup setting.¹²

¹² The terms *torque control*, *pickup*, and *dropout* were used for electromechanical relays and their usage has been retained for microprocessor-based relays.

The time-overcurrent unit is set to pick up at 75% to 100% of full-load current, and a time setting is chosen so ~~that~~ the relay operating time is 7.0 s at 218% of full-load current. With this approach, the relay is prevented from tripping for overloads below 115% of full-load current and yet provides tripping in a prescribed time for overloads above 115% of full-load current. The overcurrent relay settings are ~~should be~~ provided to transmission system protection personnel for coordination purposes.

An overload alarm may be desirable to give the operator an opportunity to reduce load in an orderly manner. This alarm is set such that it does ~~should~~ not give nuisance alarms for external faults and coordinates ~~should coordinate~~ with the generator overload protection if this protection is provided.

For air-cooled generators that may operate in a wide range of ambient temperatures, it is necessary to coordinate the IEEE Std C50.13 thermal capability and the relay setting with the increased capability of the turbine and the generator at reduced ambient temperature. Conversely, it may be difficult to protect the generator with ~~for~~ its reduced capability when the ambient temperature is high. See A.3.16 for a coordination example performed using a thermal model.

4.1.3 Failure of cooling systems

4.1.3.1 General

Depending on ~~upon~~ rating and design, the generator stator core and windings may be cooled by air, oil, hydrogen, or water. In direct-cooled (or so-called “conductor-cooled”) generators, the coolant is in direct contact with the heat-producing conductors (the coolant flows through a hollow space inside the conductor) of the stator winding. In indirectly or conventionally cooled generators, the coolant cools the generator by relying on heat transfer through the insulation. For any type of generator, a failure of the cooling system may result in rapid deterioration of the stator core lamination insulation and/or stator winding conductors and insulation. Current-or load-based overload protection cannot protect for this sort of overloading condition.

4.1.3.2 Protection

In general, the generator manufacturer provides all of the necessary protection for the cooling system. This protection is in the form of sensors such as RTDs, TCs, and flow and pressure sensors. These devices are used to monitor the winding temperatures or the coolant temperature, flow, or pressure. They may be connected to alarm, to automatically reduce load to safer ~~safe~~ levels, or to trip.

For a particular machine, the user can ~~should~~ check with the generator manufacturer to ascertain the temperature limits, the protection provided, and the recommended operating procedures for a loss of coolant.

4.1.4 Core hot spots

4.1.4.1 General

Localized hot spots in the stator core may be produced by lamination insulation failure caused by misoperation (such as excessive leading power factor operation or overfluxing), by vibration due to looseness (wear of insulation or fatigue of laminations), by foreign objects left in the machine, by damage to the core during installation or maintenance, or by objects that are normally a part of the machine (such as a nut, wedge, etc.), but become detached from their normal position and move to the core.

The hot spots are the result of high eddy currents, produced from core flux, that find conducting paths across the insulation between laminations. In some designs, stator laminations are electrically shorted together on the outer diameter of the core where it attaches to the stator frame. Any contact between laminations on the inner core ~~bore~~ will result in a circuit for eddy currents. The shorting of laminations may cause melting of core steel that may be costly to repair.

4.1.4.2 Protection

A means for detecting hot spots in air-cooled generators is through the use of RTDs and/or TCs embedded in strategic locations. Since it is not possible or practical to cover the entire core and windings with these detectors, this approach may provide only partial detection of hot spots.

On hydrogen-cooled generators, the presence, but not the exact location of local hot spots, may be detected by the use of a generator core (or condition) monitor. The core monitor is an ion particle detector that is connected to a generator in a manner that permits a constant flow of cooling gas to pass through the monitor. Under normal conditions, the gas coolant contains no particles that may be detected by the monitor. However, when overheating occurs, the thermal decomposition of organic material, epoxy paint, core lamination enamel, or other insulating material produces a large number of particles. These particles are of submicron size and are detected by the monitor.

The general location of the hot spot may be determined by laboratory analysis of the particles and through the use of selective coatings on various parts of the machine.

In the past ~~At present~~, this type of protection has been ~~is normally~~ supplied on large steam turbine generators and is connected to sound an alarm.

4.2 Field thermal protection

4.2.1 General

Thermal protection for the generator field may be divided into two categories, as follows:

- a) Protection for the main field winding circuit
- b) Protection for the main rotor body, wedges, retaining ring, and amortisseur winding

4.2.2 Field winding protection

4.2.2.1 General

The field winding may operate continuously at a current equal to or less than that required to produce rated kVA at rated power factor and voltage. For power factors less than rated, the generator output ~~is should be~~ reduced to keep the field current within these limits. The estimated capability curves as defined in IEEE Std 67 are determined on this basis.

Under abnormal conditions, such as short circuits and other system disturbances, it is permissible to exceed these limits for a short time. IEEE Std C50.13 lists the short-time thermal capability for cylindrical-rotor machines. In this standard, the field winding short-time thermal capability is given in terms of permissible field current as a function of time as follows :

Time (seconds)	10	30	60	120
Field current (percent)	209	146	125	113

~~(Deleted)~~

A plot of this short-time capability is shown in Figure ~~13~~ 4-2 (curve drawn using data from IEEE Std C50.13). Protection schemes utilize this characteristic to help prevent thermal damage to the field winding circuit.