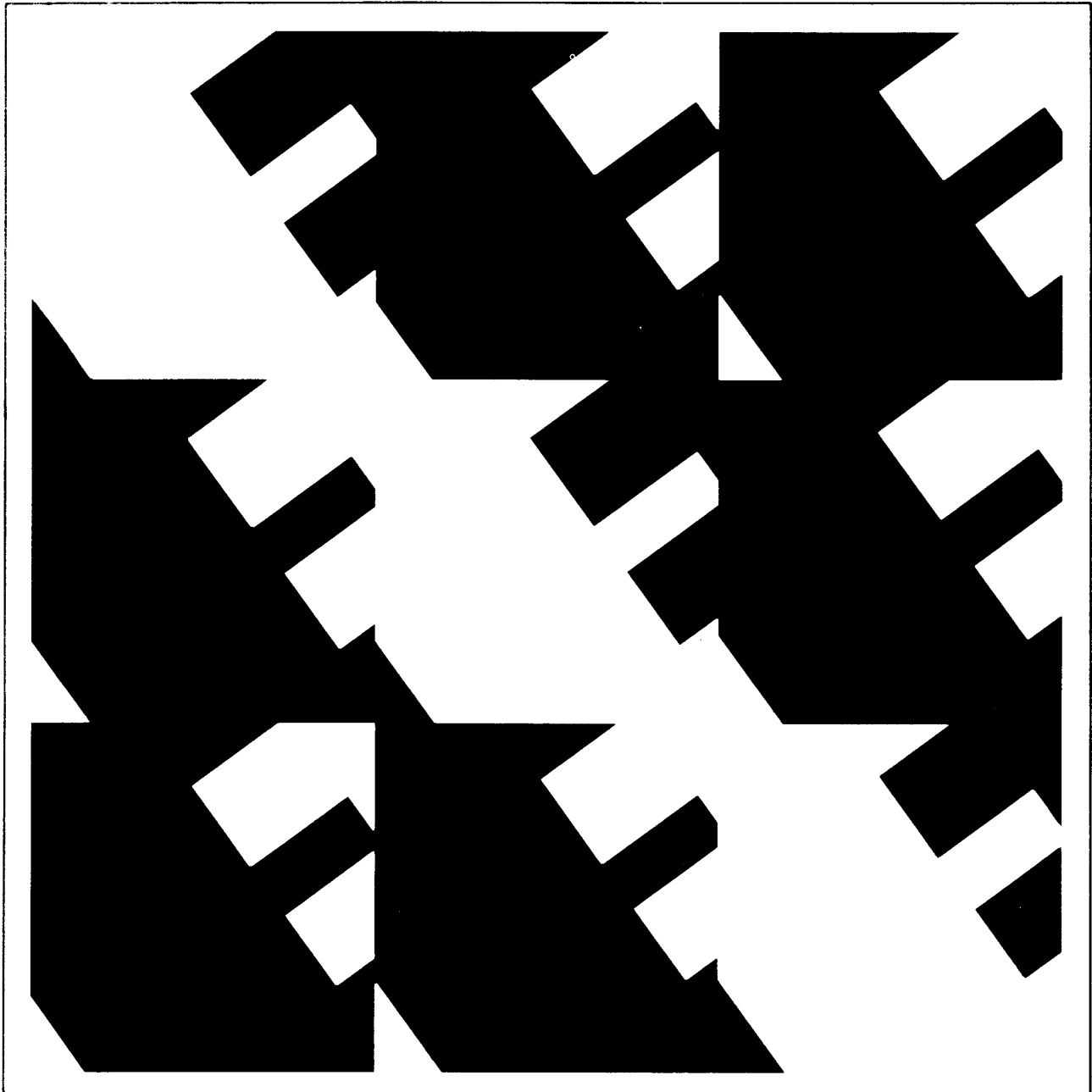


IEEE Guide for AC Generator Protection

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IEEE Guide for AC Generator Protection

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Foreword

(This foreword is not a part of IEEE C37.102-1987, IEEE Guide for AC Generator Protection.)

This guide was prepared by the AC Generator Protection Guide Working Group of the Rotating Machinery Protection Subcommittee of the Power System Relaying Committee of the IEEE Power Engineering Society.

The Institute is indebted to those individuals who gave so freely of their time and contributed so willingly and cooperatively to this guide. Particular credit goes to those past members of the working group (listed below) whose sustained efforts made this guide possible.

This guide is intended to enable determination of the protection requirements for a specific application.

At the time this guide was completed, the AC Generator Protection Guide Working Group had the following membership:

L. E. Landoll, *Chairman*

R. F. Arehart
D. M. Clark
L. H. Coe

R. W. Haas
J. R. Latham
H. O. Ohmstedt

A. C. Pierce
D. E. Sanford
C. L. Wagner

Past members who made contributions to the guide were:

F. G. Basso
J. Berdy*

R. I. Longwell

W. H. Van Zee
F. Von Roeschlaub

*Past chairman

The following were on the Rotating Machinery Protection Subcommittee of the IEEE Power System Relay Committee when it was approved:

G. R. Nail, *Chairman*

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Contents

SECTION	PAGE
1. Introduction	9
2. References	9
3. Description of Generators, Excitation Systems and Generating Station Arrangements	10
3.1 Generator Winding Design and Arrangements	10
3.2 Generator Grounding	10
3.3 Excitation Systems	13
3.4 Generating Station Arrangements	15
4. Protection Requirements	17
4.1 Generator Stator Thermal Protection	17
4.2 Field Thermal Protection	19
4.3 Generator Stator Fault Protection	21
4.4 Generator Rotor Field Protection	33
4.5 Generator Abnormal Operating Conditions	34
4.6 System Backup Protection	47
4.7 Generator Breaker Failure Protection	49
4.8 Excitation System Protection	50
5. Other Protective Considerations	52
5.1 Current Transformers	52
5.2 Voltage Transformers	52
5.3 Protection During Start-Up or Shut-Down	53
5.4 Protection for Accidentally Energizing a Generator on Turning Gear	55
5.5 Subsynchronous Resonance	57
5.6 Transmission Line Reclosing Near Generating Stations	57
5.7 Synchronizing Equipment	58
5.8 Incipient Fault Detection	58
6. Protection Specification	59
6.1 Protective Arrangements	59
6.2 Protective Functions	59
7. Bibliography	71
 FIGURES	
Fig 3.1 Winding Configurations	11
Fig 3.3.1 System with DC Generator Commutator Exciter	13
Fig 3.3.2 System with Alternator Rectifier Exciter and Stationary Rectifier	14
Fig 3.3.3 System with Alternator Rectifier Exciter and Rotating Rectifiers	14
Fig 3.3.4 System with Static Exciter	14
Fig 3.3.5 Static Excitation System with Internal Supply	15
Fig 3.4.1 Unit Generator—Transformer Configuration	16
Fig 3.4.2 Unit Generator—Transformer Configuration with Generator Breakers	16
Fig 3.4.3 Cross-Compound Generators	16
Fig 3.4.4 Generators Sharing a Transformer	17
Fig 3.4.5 Generators Connected Directly to a Distribution System	17
Fig 4.1-1 Turbine-Generator Short-Time Thermal Capability for Balanced 3-Phase Loading (from ANSI C50.13-1977 [1])	18
Fig 4.2-1 Generator Field Short-Time Thermal Capability	20
Fig 4.3.2-1 Variable Slope Percentage Differential Relay	21
Fig 4.3.2-2 High-Impedance Differential	21
Fig 4.3.2-3 Self-Balancing Protection Scheme (Single Phase Shown)	22

FIGURE	PAGE
Fig 4.3.2-4 Split-Phase Protection Using Separate Current Transformers	23
Fig 4.3.2-5 Split-Phase Protection Using a Single Window Current Transformer	23
Fig 4.3.2-6 Split-Phase Protection Using Double-Primary Single Secondary Current Transformer ..	23
Fig 4.3.2-7 Percentage Differential Relay Connection—Six-Bushing Wye-Connected Generator	24
Fig 4.3.2-8 Application of Split-Phase and Differential Relaying	24
Fig 4.3.2-9 Combination Split-Phase and Differential Relaying	24
Fig 4.3.2-10 12-Bushing Generator	25
Fig 4.3.2-11 Percentage Differential Relay Connection—Delta-Connected Generator	25
Fig 4.3.2-12 Generator Phase Fault Backup Overall Differential Scheme	26
Fig 4.3.2-13 Phase Fault Backup for a Two-Winding Generator	26
Fig 4.3.2-14 Phase Fault Backup for Cross-Compound Generator	26
Fig 4.3.3-1 Percent of Stator Winding Unprotected by Differential Relay for Phase-to-Ground Fault	27
Fig 4.3.3-2 Generator Ground Fault Protection for High-Impedance Grounded Generator	28
Fig 4.3.3-3 Backup Ground Overcurrent Protection	28
Fig 4.3.3-4 Ground Protection for a Two-Winding or Cross-Compound Generator	29
Fig 4.3.3-5 Third Harmonic Undervoltage Scheme for Generator Ground Fault Protection	29
Fig 4.3.3-6 Third Harmonic Overvoltage Scheme for Generator Ground Fault Protection	30
Fig 4.3.3-7 Third Harmonic Differential Scheme for Generator Ground Fault Protection	30
Fig 4.3.3-8 Subharmonic Voltage Injection Scheme for Generator Ground Fault Protection	30
Fig 4.3.3-9 Scheme for Removing Potential from Ground Fault Overvoltage Relay When Relay is Used to Alarm	31
Fig 4.3.3-10 Sensitive Ground Fault Protection	32
Fig 4.3.3-11 Ground Fault Protection with a Zigzag Grounding Bank	33
Fig 4.4-1 Rotor Ground Protection	33
Fig 4.4-2 Ground Detection Circuit	34
Fig 4.5.1-1 Loss-of-Excitation Characteristics for a Tandem Compound Generator	36
Fig 4.5.1-2 Generator Protection Using Two Loss-of-Excitation Relays	36
Fig 4.5.1-3 Loss-of-Excitation Relaying Scheme	36
Fig 4.5.2-1 Continuous and Short-Time Unbalanced Current Capability of Generators	38
Fig 4.5.2-2 Unbalanced Current Protection	39
Fig 4.5.2-3 (A) Typical Time-Overcurrent Curves for an Electromechanical Negative-Sequence Relay	39
(B) Characteristics of a Static Negative-Sequence Time-Overcurrent Relay	39
Fig 4.5.3-1 Loss of Synchronism for a Tandem Compound Generator—Voltage Regulator Out of Service	40
Fig 4.5.3-2 Single Blinder Scheme	40
Fig 4.5.4-1 Example of Dual Level Volts/Hertz Setting	42
Fig 4.5.4-2 Example of Inverse Volts/Hertz Setting	43
Fig 4.6-1 Application of System Back-up Relays—Unit Generator-Transformer Arrangement....	47
Fig 4.6-2 Application of System Back-up Relay—Generator Connected Directly to the System...	47
Fig 4.6-3 Complex System Configuration	49
Fig 4.7-1 Functional Diagram of a Generator Zone Breaker Failure Scheme	49
Fig 4.7-2 Modified Breaker Failure for Open Breaker Flashover Detection	50
Fig 5.2-1 Application of Voltage Balance Relay	53
Fig 5.2-2 Generator Zone Configuration that May Produce Voltage Transformer Ferroresonance	53
Fig 5.3-1 Relay Pick-up Versus Frequency	54
Fig 5.3-2 Protection During Low-Frequency Operation	54
Fig 5.4-1 Operating Areas of Directional Overcurrent Relays at Rated Voltage Shown on Typical Generator Capability Curve	56
Fig 5.4-2 Supplementary Protection for Accidentally Energizing a Generator on Turning Gear...	56

FIGURE	PAGE
Fig 5.4-3 Alternative Supplementary Protection for Accidentally Energizing a Generator on Turning Gear	57
Fig 6-1 Unit Generator-Transformer Configuration	61
Fig 6-1A Generator-Transformer Configuration DC Tripping Logic	62
Fig 6-2 Unit Generator-Transformer Configuration with Dual Generator Breakers.....	63
Fig 6-2A Unit Generator-Transformer Configuration with Dual Generator Breakers DC Tripping Logic	64
Fig 6-3 Cross-Compound Generators	65
Fig 6-3A Cross-Compound Generators DC Tripping Logic	66
Fig 6-4 Protection for Generators Sharing a Unit Transformer.....	67
Fig 6-4A Protection for Generators Sharing a Unit Transformer.....	68
Fig 6-5 Protection for Generators Connected Directly to a Distribution System.....	69
Fig 6-5A Protection for Generators Connected Directly to a Distribution System.....	70

IEEE Guide for AC Generator Protection

1. Introduction

This application guide for the relay protection of synchronous generators presents a review of the generally accepted forms of protection for the generator and its excitation system. It 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.

This guide is not a standard and does not purport to detail the protective requirements of all generators in every situation. Standby and emergency use generators are specifically excluded. The suggestions made pertain to typical 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 guide is divided as follows:

Section 3: Description of Generators, Excitation Systems and Generating Station Arrangements. Section 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 section is to present information that affects the protection arrangement and selection of protective relays.

A discussion of auxiliary system transfer and the possible negative impacts of misoperation and faults on these systems is beyond the scope of the generator protection guide.

The methods employed for grounding and fusing the secondary circuits of voltage transformers and the methods for grounding current-trans-

former secondary circuits are not generally the same for all installations. For this reason no secondary fuses or ground points are indicated in the figures throughout this guide. However, all current and voltage transformer secondary circuits should be grounded in a way that is consistent with accepted practices for personnel safety.

Section 4: Protection Requirements. Section 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 any specific situation.

Section 5: Other Protective Considerations. Section 5 presents a discussion of other forms of protection and factors that may be considered in the generator zone.

Section 6: Protection Specifications. Section 6 presents detailed tabulations and diagrams that are classified according to the method by which the generator is connected to the system. These tables and diagrams show the combination of relays (and their control function) often applied for generator and excitation system protection in accordance with good engineering practices. These tables and 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.

2. References

When the following American National Standards are superseded by an approved revision, the latest revision shall apply:

- [1] ANSI C50.13-1977, American National Standard Requirement for Cylindrical Rotor Synchronous Generators.¹
- [2] ANSI/IEEE C37.101-1985, IEEE Guide for Generator Ground Protection.²
- [3] ANSI/IEEE C37.106-1987, IEEE Guide for Abnormal Frequency Protection for Power Generating Plants.
- [4] ANSI/IEEE Std 67-1972, IEEE Guide for Operation and Maintenance of Turbine Generators.
- [5] ANSI/IEEE Std 502-1985, IEEE Guide for Protection, Interlocking, and Control of Fossil-Fueled Unit-Connected Steam Stations.
- [6] IEEE Std 143-1954, Application Guides for Ground-Fault Neutralizers, Grounding of Synchronous Generator Systems, and Neutral Grounding of Transmission Systems.
- [7] IEEE Committee Report. Out of Step Relaying for Generators, *IEEE Transactions on Power Apparatus and Systems*, vol 96, Sep/Oct 1977, pp 1556-1564.
- [8] IEEE Committee Report. Potential Transformer Application on Unit-Connected Generators, *IEEE Transactions on Power Apparatus and Systems*, vol 91, Jan/Feb 1972, pp 24-28.

3. Description of Generators, Excitation Systems and Generating Station Arrangements

3.1 Generator Winding Design and Arrangements. The stator windings of a three-phase synchronous generator consist of a number of single-turn or multitrn coils which 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.

¹ ANSI publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

² IEEE publications are available from the Sales Department, IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08854-1331.

The winding arrangements shown in Figs 3.1A and B are the configurations most commonly used for all types of generators. When more than one circuit is used per phase as shown in Fig 3.1B, 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 can 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 multitrn 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, current transformers can be provided in each phase group and in the leads to the external connections.

Figure 3.1C illustrates the wye-connected double-winding construction sometimes used in large steam-turbine generators. Each phase has two separate windings which 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, twelve-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 can accommodate three current transformers.

In the delta-connected generator, there may be one or more paralleled circuits per phase with two leads brought out to external connections. Current transformers can be provided inside the delta at the ends of each winding or outside the delta, or both.

3.2 Generator Grounding. 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

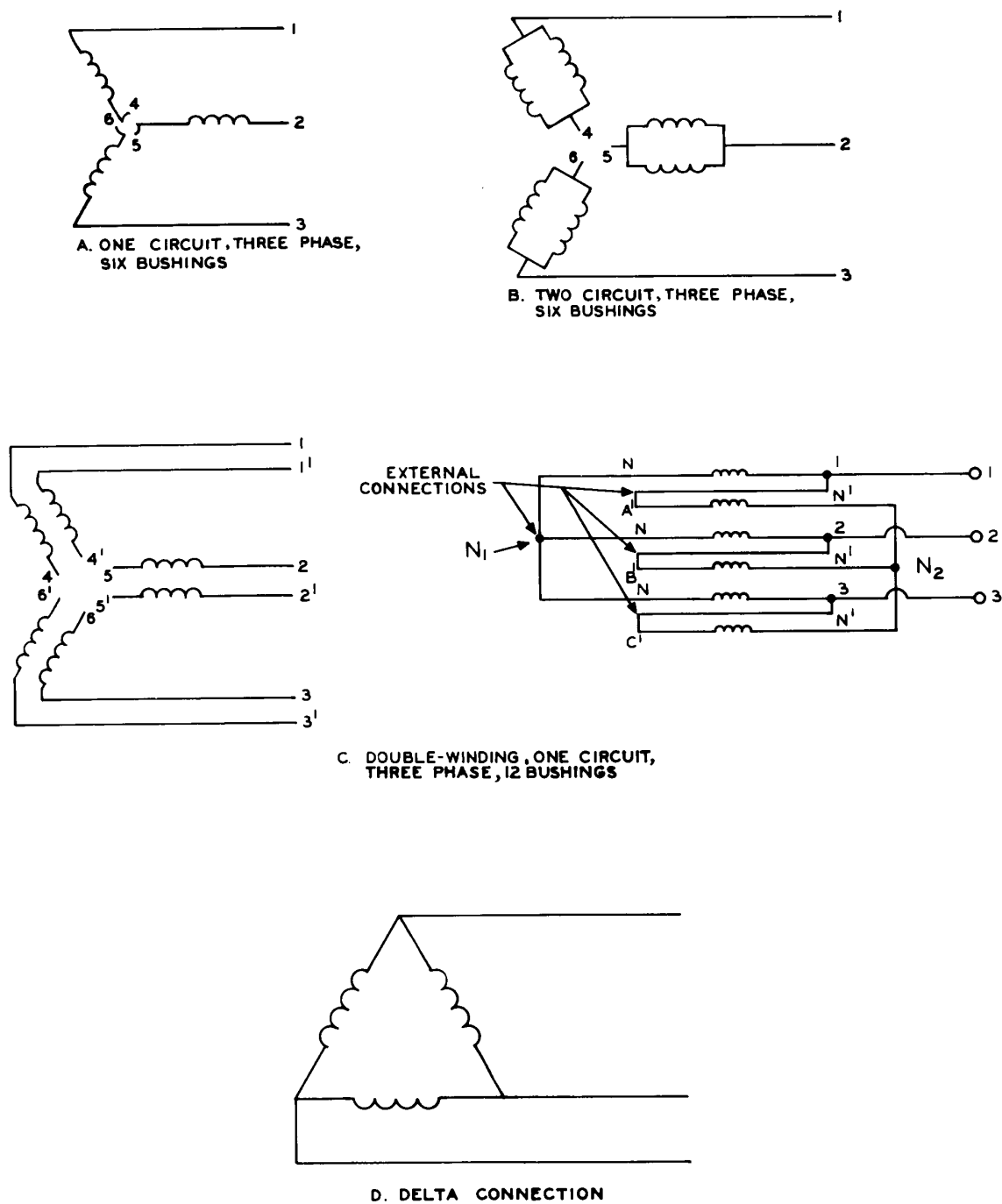


Fig 3.1
Winding Configurations

in ANSI/IEEE C37.101-1985 [2]³, and IEEE Std 143-1954 [6].

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

- (1) High-impedance grounding
- (2) Low-resistance grounding
- (3) Reactance grounding
- (4) Grounding-transformer grounding

Solid grounding of a generator neutral is not generally used since this practice can result in high mechanical stresses and excessive fault damage in the machine. According to ANSI C50.13-1977 [1], the maximum stresses that a generator is normally designed to withstand 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 must be 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 not often operated ungrounded. While this approach greatly limits the phase-to-ground fault currents, and consequently limits damage to the machine, it can produce high transient overvoltages during faults and also makes the fault location difficult.

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

3.2.1 High Impedance Grounding. Two types of high-impedance grounding are in common use today. These are as follows:

3.2.1.1 High-Resistance Grounding. In this method, a distribution transformer is connected between the generator neutral and ground and a resistor is connected across the secondary. The primary voltage rating of the distribution transformer is usually equal to or greater than rated generator line-to-neutral voltage, while the secondary winding rating is 120 or 240 V. The secondary 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 zero-sequence capacitive kVA to ground of the generator wind-

ings, and of all other equipment which may be connected to the machine terminals. With this resistor rating, the transient overvoltages during faults will be kept to safe values. This arrangement is considered high-resistance grounding. 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 to 25 A. If possible, the ground fault current level should be chosen to coordinate with the primary fuses (when used) of wye-wye connected voltage transformers with grounded neutrals. Note that distribution transformers with internal fuses or circuit breakers should not be used, as they could inadvertently be open and the grounding and protection scheme could be inoperative at the time of fault.

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 5–10 A. While this method of grounding is used in Europe, the physical size of the resistors, the required resistor insulation level, and the cost may preclude the use of this method.

3.2.1.2 Ground Fault Neutralizer Grounding (Tuned Inductive Reactor). In this grounding method, a distribution-type transformer with a ratio selected as above is used with a secondary tunable reactor. 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 zero-sequence capacitive reactance of 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. This type of grounding limits the single-phase-to-ground fault current to values that will not sustain an arc. It is applicable only where the zero-sequence capacitance of the circuit does not change significantly for different system conditions.

High-impedance grounding does not provide sufficient current for selective ground relaying of several machines connected to a common bus. Consequently, it is generally used with unit-system installations where a single generator is connected through its individual grounded wye-delta step-up transformer (or transformers) to the system.

In a few cases, this type of grounding has been used when two or more generators are connected to one step-up transformer. However, such a system is difficult to relay and may require shutting down all machines to isolate a fault.

³The numbers in brackets correspond to those of the references listed in Section 2.

3.2.2 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 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 above machine rated current.

This method of grounding is generally used where two or more generators are bussed at generator voltage and connected to a system through one step-up transformer or where the generator is connected directly to a distribution system having a low-impedance grounding source on the generator bus.

3.2.3 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. 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.

3.2.4 Grounding-Transformer Grounding. This method involves the use of a grounding transformer connected to the machine terminals or to the generator bus. The grounding may be provided by a zig-zag 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 zig-zag 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 secondary resistor. This method limits the single-phase-to-ground fault current to a range of 3–25 primary A.

A zig-zag 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 can also be used where several ungrounded-wye or delta-connected generators are bussed at generator voltage.

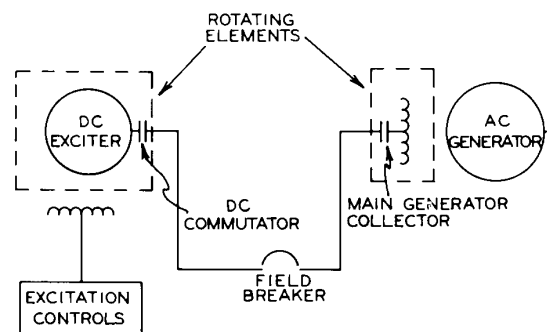
A grounded wye-broken delta transformer with a resistor across the corner of the broken delta may be used to provide a means for detecting ground faults in ungrounded-wye or delta-connected generators.

3.3 Excitation Systems. There are four basic types of excitation systems 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. While a detailed description of these systems is beyond the scope of this standard, their general characteristics will be briefly described in the following sections.

3.3.1 System with DC Generator-Commutator Exciter. Figure 3.3.1 shows a schematic of the primary elements of this system. Not shown on this diagram and the succeeding Figs 3.3.2 through 3.3.5 are the power supplies, such as pilot excitors, the current and potential intelligence inputs to the excitation control, etc, since they are essentially functionally the same for all systems.

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

Fig 3.3.1
System with DC Generator Commutator Exciter



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 can 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.

3.3.2 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 Fig 3.3.2 uses an alternator with a rotating dc field winding driven from the shaft of the main ac generator. 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.

3.3.3 System with Alternator Rectifier Exciter and Rotating Rectifiers. The system of Fig 3.3.3 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.

3.3.4 System with Static Exciter. The preceding schemes 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 Fig 3.3.4, external power current transformers or power voltage transformers (or both) feed rectifiers in the regulating system which, in turn, supply direct current to the main field winding of the generator through brushes and collector rings. Some systems use only potential transformers as input power, while some use additional current transformers to boost the input during fault conditions when the terminal voltage is reduced.

In Fig 3.3.5 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

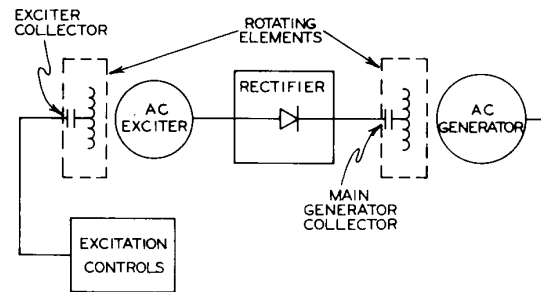


Fig 3.3.2
System with Alternator Rectifier Exciter and Stationary Rectifier

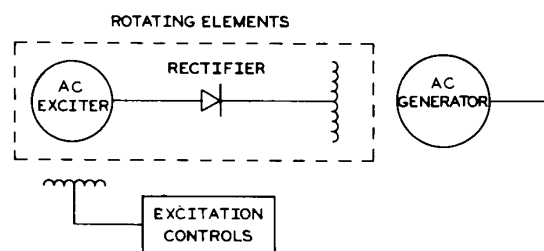


Fig 3.3.3
System with Alternator Rectifier Exciter and Rotating Rectifiers

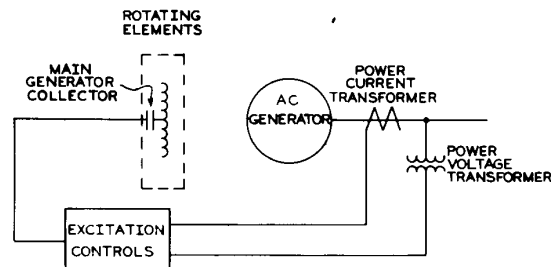


Fig 3.3.4
System with Static Exciter

stator winding slots (P bars in Fig 3.3.5). These potential windings are connected to each phase of an ungrounded-ye excitation transformer.

The current source is achieved by passing each of the three stator main winding leads through a window in each phase excitation transformer.

The output windings of the three single-phase excitation transformers are connected in delta to supply the external bridge rectifier circuits.

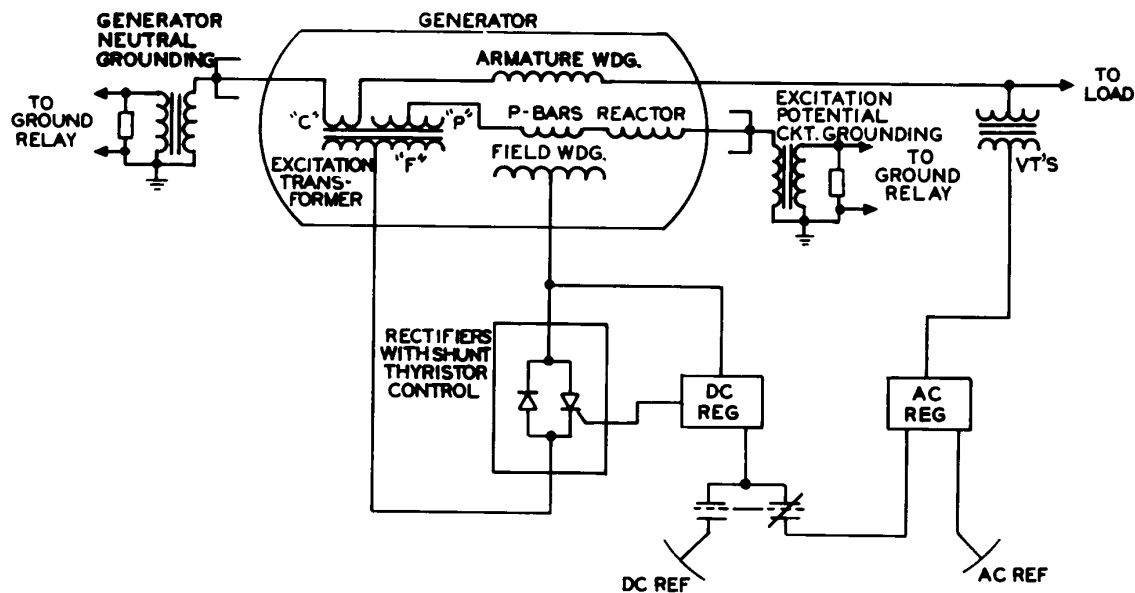


Fig 3.3.5
Static Excitation System with Internal Supply

As indicated in Fig 3.3.5, the potential windings in the stator are connected in wye through linear reactors. The neutral 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. 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:

- (1) Unit generator-transformer configuration
- (2) Unit generator-transformer configuration with generator breaker
- (3) Cross compound generators
- (4) Generators sharing a unit transformer
- (5) Generators connected directly to a distribution system

For the most part, the above configurations represent the most widely used generating station arrangements.

3.4.1 Unit Generator-Transformer Configuration. In this arrangement, a generator and its transformer (unit transformer) are connected as a unit to the system as shown in Fig 3.4.1. 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.

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

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

3.4.2 Unit Generator-Transformer Configuration with Generator Breakers. This arrangement, illustrated in Fig 3.4.2, has been used with large nuclear steam-turbine generators. The generator is wye-connected and high-resistance grounded through a distribution transformer. Two half-size grounded wye-delta connected unit transformers

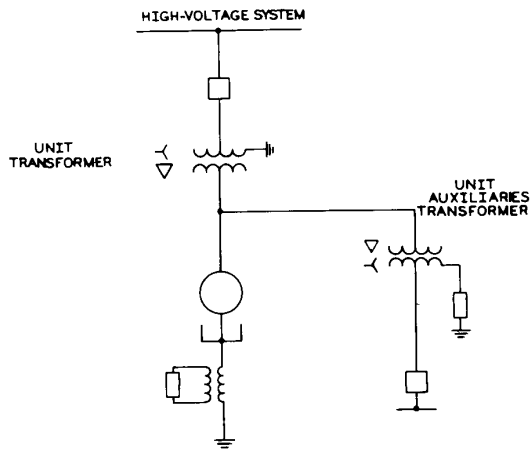


Fig 3.4.1
Unit Generator—Transformer Configuration

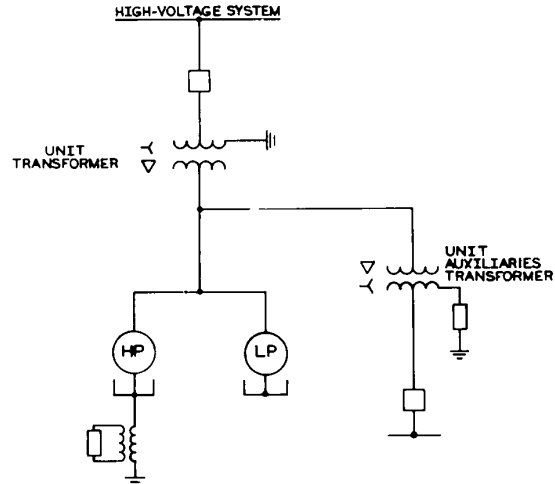


Fig 3.4.3
Cross-Compound Generators

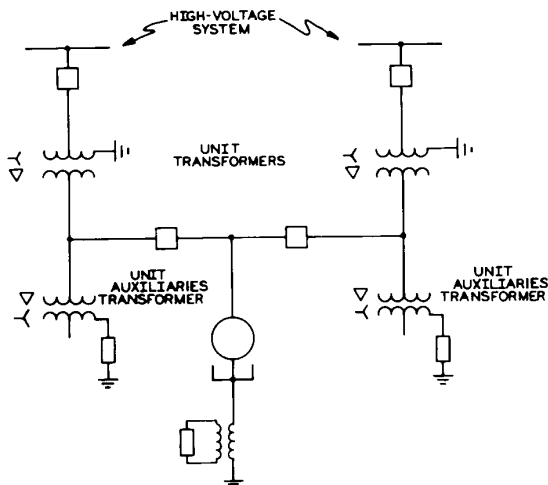


Fig 3.4.2
**Unit Generator—Transformer Configuration
with Generator Breakers**

are used to connect the generator to the system. As shown in this figure, two unit auxiliaries transformers are used in this arrangement.

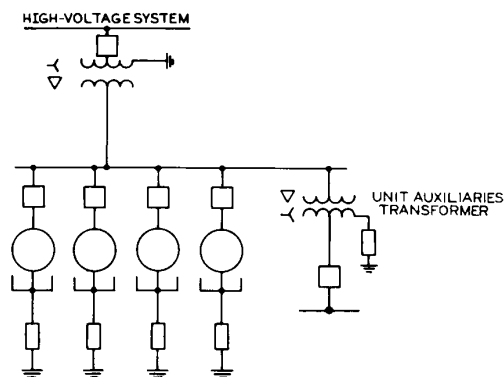
3.4.3 Cross-Compound Generators. The most common method for connecting a cross-compound generator to a system is shown in Fig 3.4.3. The low-pressure and the high-pressure units are bussed at generator voltage and connected to the system through a grounded wye-delta unit transformer. Both the low- and the high-pressure units are usually wye-connected, and it is recommended

practice to ground only one of the neutrals. High-resistance grounding through a distribution transformer is commonly used.

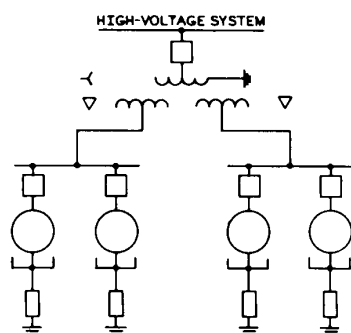
3.4.4 Generators Sharing a Unit Transformer. Figure 3.4.4 illustrates two methods for connecting two or more generators to a system using one step-up transformer. In Fig 3.4.4A, two or more generators are bussed at generator voltage and a two-winding grounded wye-delta unit transformer is used to connect the machines to the system. In Fig 3.4.4B, a number of generators are connected to the system through a three-winding grounded wye-delta-delta transformer. Either of these approaches may be used with small hydro or combustion-turbine generators.

In either approach, neutral-resistor grounding of the generators would 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 minimize damage due to phase-to-ground faults. However, this grounding method has the disadvantage that it does not provide sufficient current for selective relaying.

3.4.5 Generators Connected Directly to a Distribution System. Fig 3.4.5 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, or the neutral of the bus grounding transformer if the generator neutral is isolated (as noted in 3.2.4), will be grounded with a neutral



(A)



(B)

Fig 3.4.4
Generators Sharing a Transformer

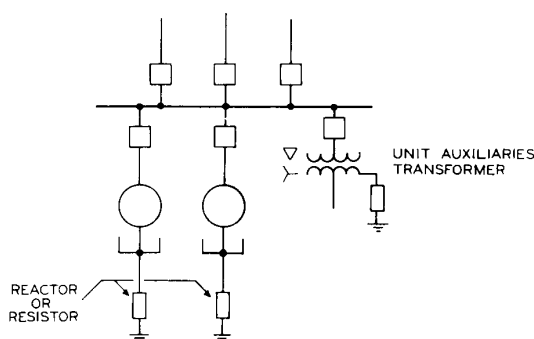


Fig 3.4.5
Generators Connected Directly to a Distribution System

inductive reactance. If the system is not effectively grounded, as for some three-wire distribution systems, the generator neutral or grounding transformer neutral will generally be grounded through a low ohmic value resistor.

4. Protection Requirements

4.1 Generator Stator Thermal Protection. Thermal protection for the generator stator core and windings may be provided for the following contingencies:

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

4.1.1 Generator Overload. The continuous output capability of a generator is expressed in kilovolt-amperes (kVA) available at the terminal 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 combustion-turbine generators, this capability is given at an inlet air temperature of 15 °C at sea level. In general, generators can 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. In accordance with ANSI C50.13-1977 [1], the armature winding short-time thermal capability is given by the following:

Time (seconds)	10	30	60	120
Armature current (percent)	226	154	130	116

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

A plot of this short-time capability is shown in Fig 4.1-1. Protective schemes to 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.

4.1.1.1 Winding-Temperature Protection.

Most generators are supplied with a number of resistance temperature detectors (RTDs) which are imbedded in the stator windings. As the name implies, the RTD detects temperature change by the change in resistance of the detector.

These RTDs are used to continuously monitor the winding temperatures. In attended generating stations, the RTDs may be connected to give an indication on an instrument, to provide an input to a data acquisition system or to actuate an alarm.

In unattended stations, the RTDs may be used with a relay to alarm, to initiate corrective action, or to trip the unit if a selected hot-spot temperature exceeds specified limits. The relay used for

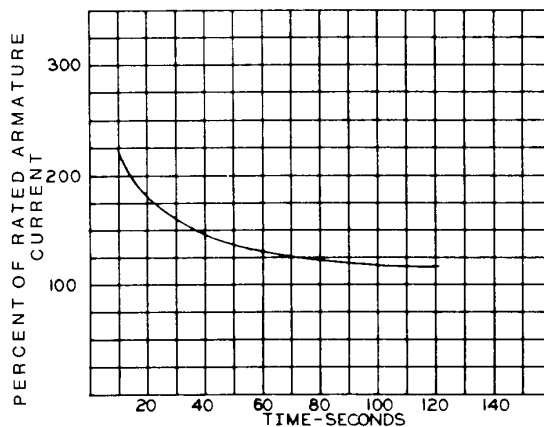


Fig 4.1-1
Turbine-Generator Short-Time Thermal
Capability for Balanced 3-Phase Loading
(from ANSI C50.13-1977 [1])

this function operates on a Wheatstone Bridge principle, where the RTD(s) and the relay unit are part of the bridge. When the temperature in the stator winding exceeds a specified limit, the change in RTD resistance unbalances the bridge and causes relay operation. The relay is generally designed to remain in the operated position until the temperature has decreased to a safe value.

This type of relay detects actual temperature, not temperature rise above ambient and, therefore, the relay has to be set to take into account the expected variation in ambient temperature. The selection of this type of temperature relay requires the following information:

- (1) RTD resistance
- (2) Temperature pickup range

In the US, the standard RTD resistance is $10\ \Omega$ at $25\ ^\circ\text{C}$ and most relays are designed to be used with this value. However, the user should check with the generator manufacturer in order to ascertain the ohmic value of the RTD element being supplied.

The required temperature pickup range will be a function of the class of insulation used in the generator. Again, the user should check with the manufacturer to ascertain the maximum permissible operating temperature.

4.1.1.2 Overcurrent Protection. In some instances, generator overload protection can be provided through the use of a torque controlled overcurrent relay that is coordinated with the ANSI C50.13-1977 [1] short-time capability curve of Fig 2.1-1. This relay consists of an instantaneous overcurrent 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 should be 95% or higher of pickup setting.

The time overcurrent unit is set to pick up at 75–100% of full-load current and a time setting is chosen so that the relay operating time is 7.0 s at 226% 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.

An overload alarm may be desirable to give the operator an opportunity to reduce load in an orderly manner. This alarm should not give nuisance alarms for external faults and 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 ANSI C50.13-1977 [1] 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 for its reduced capability when the ambient temperature is high.

4.1.2 Failure of Cooling Systems

4.1.2.1 General. Depending 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 (usually water) is in direct contact with the heat-producing members such as 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 can result in rapid deterioration of the stator core lamination insulation and/or stator winding conductors and insulation.

4.1.2.2 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 resistance temperature detectors (RTDs), thermocouples (TC), 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 safe levels, or to trip.

For a particular machine, the user should check with the generator manufacturer to ascertain the

temperature limits, the protection provided and the recommended operating procedures for a loss of coolant.

4.1.3 Core Hot Spots

4.1.3.1 General. Localized hot spots in the stator core can be produced by lamination insulation failure caused 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. 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 bore will result in a circuit for eddy currents. The shorting of laminations can cause melting of core steel that can be costly to repair.

4.1.3.2 Protection. The only means for detecting hot spots in air-cooled generators is through the use of resistance temperature detectors (RTDs) and/or thermocouples (TC) imbedded in the stator windings. Since it is not possible or practical to cover the entire core and windings with these detectors, this approach can 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 can be detected by the monitor. However, when overheating occurs, the thermal decomposition of organic material, epoxy paint, core lamination enamel or other insulating materials 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 can be determined by laboratory analysis of the particles and through the use of selective coatings on various parts of the machine.

At present, this type of protection is normally only supplied on large steam turbine generators and is connected to sound an alarm.

4.2 Field Thermal Protection. Thermal protection for the generator field may be divided into two categories:

- (1) Protection for the main field winding circuit
- (2) Protection for the main rotor body, wedges, retaining ring, and amortisseur winding

4.2.1 Field Winding Protection. The field winding can 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 must be reduced to keep the field current within these limits. The capability curves as defined in ANSI/IEEE Std 67-1972 [4] 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 as specified in ANSI C50.13-1977 [1]. In this standard, the field winding short-time thermal capability is given in terms of permissible field voltage as a function of time as noted below.

Time (seconds)	10	30	60	120
Field voltage (percent)	208	146	125	112

A plot of this short-time capability is shown in Fig 4.2-1. Protection schemes utilize this characteristic to prevent thermal damage to the field winding circuit.

4.2.1.1 Thermal Protection. Since it is not practical to put temperature sensors directly in the field windings, only indirect monitoring of the field winding temperature is normally possible. For excitation systems employing main field collector rings, the average temperature of the field winding can be approximated by calculating the field resistance using simultaneous field current and voltage readings. This resistance, in conjunction with the known cold resistance, is a measure of the operating temperature. This method, described in ANSI/IEEE Std 67-1972 [4], gives only an indication of the average temperature throughout the field winding and not the more important hot-spot temperature. Moreover, this method is not applicable with brushless excitation systems where the actual main field current and voltage are not available for measurement.

If a generator is equipped with a core monitor as described in 4.1.3, the monitor will also detect overheating of the field winding insulation and hot spots.

4.2.1.2 Protection for Field Overexcitation. Some form of overexcitation protection for the field winding is generally provided utilizing the short-time capability curve of Fig 4.2-1. Several different schemes are available using relays or excitation system control elements, or both.

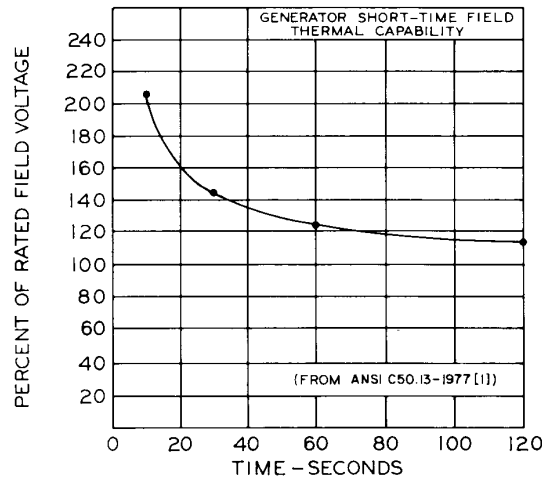


Fig 4.2-1

Generator Field Short-Time Thermal Capability

4.2.1.2.1 Fixed-Time Delay Relaying Scheme. The simplest form of field protection utilizes a contact making milliammeter or voltmeter connected in either the main field circuit or in the field of the ac exciter. This device is set to pick up when the field current exceeds its rated full-load value. When an overexcitation condition occurs, the device will pick up and perform the following functions:

- (1) Sound an alarm.
 - (2) Adjust field excitation to a preselected value corresponding to rated full-load level or less.
 - (3) After a fixed-time delay, trip the generator regulator or transfer to an alternate control.
 - (4) If overexcitation is not eliminated after some additional short-time interval, trip the unit.
- This scheme will protect the field for overexcitation conditions during system disturbances and for the rare occurrence of a faulty excitation system component. While simple in form, this scheme has the disadvantage that it will overprotect the machine, since the fixed time delay relay must be set for the maximum possible overexcitation condition that can occur. This means that for less severe overexcitation conditions, tripping will occur at shorter times than is required and, therefore, full advantage of the inverse-time thermal capability of the field winding characteristic cannot be obtained.

4.2.1.2.2 Inverse Time Delay Relay Scheme. This approach utilizes a voltage relay whose characteristic approximately matches the

inverse time characteristic of Fig 4.2-1. This relay may be connected at the terminals of an ac exciter alternator, in the main generator field or in the field of the ac exciter. When connected to a field circuit, a transducer is used to convert the dc signal to an ac quantity. The relay is normally set so that there is 5-10% margin between the relay characteristic and the field capability curve.

This relay, in conjunction with one or more timers, performs the same functions as the preceding scheme. For an overexcitation condition, it will:

- (1) Sound an alarm.
- (2) Adjust the field excitation to a preselected value corresponding to rated full-load level or less.
- (3) After some delay, trip the generator regulator or transfer to an alternate control.
- (4) If overexcitation is not eliminated, trip the unit.

This scheme provides protection for overexcitation conditions as well as for possible excitation system failures.

4.2.1.2.3 Voltage Regulator System. Modern excitation systems usually incorporate the field protective functions as well as the regulating function. These systems may have built-in circuitry that duplicates the fixed time and/or the inverse time relaying function. When an overexcitation condition occurs and field current exceeds a safe value for a specified period of time, these protective functions will reduce field current to the full-load value or to some other predetermined level. On some excitation systems, if the overexcitation condition persists after an attempt to reduce field current is made, the protective function will trip the regulator or transfer to an alternate exciter after a short period of time. If this does not eliminate the problem, the generator may be tripped. In this type of excitation system, the protective function is separate from the excitation function, and, therefore, can provide protection when there are failures in the regulating systems or when the regulator is not in the control circuit.

If the protective function is part of the regulating system, the protection would be eliminated when the regulator is tripped or is out of service. For this type of system, supplementary relay protection as described in the preceding can be provided.

4.2.2 Rotor Body. There are no simple methods for direct thermal protection of the rotor. Various indirect methods are used either to approximate rotor temperatures or to act directly

on the quantities that would lead to excessive rotor temperatures. Protection schemes for the rotor are, therefore, directed at the potential causes of thermal distress. For example, negative-sequence currents in the stator, loss of excitation or loss of synchronism can cause excessive rotor temperatures due to circulating currents in various paths of the rotor body. These phenomena and associated protective schemes are covered in 2.5 of this standard.

4.3 Generator Stator Fault Protection

4.3.1 General Consideration. Generator faults are always considered to be serious since they can cause severe and costly damage to insulation, windings, and the core; they can also produce severe mechanical torsional shock to shafts and couplings. Moreover, fault currents in a generator do not cease to flow when the generator is tripped from the system and the field disconnected. Fault current can continue to flow for many seconds because of trapped flux within the machine, thereby increasing the amount of fault damage.

As a consequence, for faults in or near the generator which produce high magnitudes of short-circuit currents, some form of high-speed protection is normally used to trip and shut down the machine as quickly as possible in order to minimize damage. Where external impedances are used to limit fault currents to a few amperes, slower forms of protection may be justified. In certain cases, it may be justified to consider the use of rapid de-excitation methods which produce a faster decay of fault currents.

4.3.2 Phase-Fault Protection. Some form of high-speed differential relaying is generally used for phase-fault protection of generator stator windings. Differential relaying will detect three phase faults, phase to phase faults, double-phase-to-ground faults and some single phase-to-ground faults, depending upon how the generator is grounded.

Differential relaying will not detect turn-to-turn faults in the same phase since there is no difference in the current entering and leaving the phase winding. Where applicable, separate turn fault protection can be provided with the split-phase relaying scheme. This scheme will be discussed subsequently.

4.3.2.1 Variable Slope Percentage Differential Relay. The variable slope percentage differential relay is the most widely used form of differential relaying for generator protection. In this type of relay, the percentage slope characteristic can vary from about 5% at low values of

through current up to 50% or more at high values of through current as illustrated in Fig 4.3.2-1. This characteristic results in a relay that is very sensitive to internal faults and insensitive to current transformer error currents during severe external faults.

Current transformers with identical characteristics are used in a generator differential scheme and it is preferable to avoid connecting other relays or devices in these current circuits.

4.3.2.2 High-Impedance Differential Relay.

As the name implies, this is a high-impedance relay connected in a differential circuit as shown in Fig 4.3.2-2. The relay discriminates between internal and external faults by the voltage which appears across the relay. On external faults, the voltage across the relay will be low, while for internal faults the voltage across the relay is relatively high. The relay may be set to operate for

Fig 4.3.2-1
Variable Slope Percentage Differential Relay

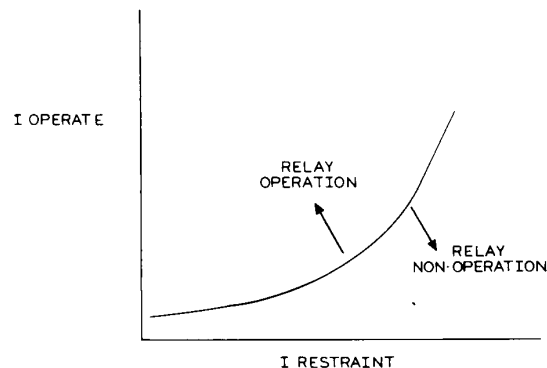


Fig 4.3.2-2
High-Impedance Differential

