ANSI/IEEE
C37.101-1985

An American National Standard

IEEE Guide for Generator Ground Protection

Sponsor

Power System Relaying Committee of the
IEEE Power Engineering Society

Secretariat

Institute of Electrical and Electronics Engineers, Inc
National Electrical Manufacturers Association

Approved December 17, 1981
IEEE Standards Board

Approved February 4, 1983
American National Standards Institute

The Institute of Electrical and Electronics Engineers, Inc
345 East 47th Street, New York, NY 10017, USA

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least once every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
345 East 47th Street
New York, NY 10017
USA

Foreword

(This Foreword is not a part of ANSI/IEEE C37.101-1985, IEEE Guide for Generator Ground Protection.)

This guide was prepared by the Generator Ground Protection Working Group of the Rotating Machinery 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 K. Winick and G. Paradis, past Chairman of the working group, whose sustained efforts made this guide possible.

This guide is intended to enable one to determine the protection requirements for a specific application.

The Standards Committee on Power Switchgear, C37, which reviewed and approved this guide, had the following personnel at the time of approval:

C.L. Wagner, *Chairman* **John D. Hopkins**, *Secretary*

J.E. Beehler, *Executive Vice-Chairman of High-Voltage Switchgear Standards*
W.E. Laubach, *Executive Vice-Chairman of Low-Voltage Switchgear Standards*
S.H. Telender, *Executive Vice-Chairman of IEC Activities*

Organization Represented	*Name of Representative*
Association of American Railroads	*Vacant*
Association of Iron and Steel Engineers	J.M. Tillman
Electric Light and Power Group	K.G. Adgate
	J.E. Beehler
	R.L. Capra (*Alt*)
	H.G. Darron
	H.F. Frus
	K.D. Hendrix
	R.L. Lindsey (*Alt*)
	E.E. Ramm (*Alt*)
	F.R. Solis
Institute of Electrical and Electronics Engineers	M.J. Beachy (*Alt*)
	R.N. Bell (*Alt*)
	H.H. Fahnoe
	R.E. Friedrich
	M.J. Maier
	C.A. Mathews (*Alt*)
	D.C. Musgrave (*Alt*)
	G.W. Walsh
	H.F. White
National Electrical Manufacturers Association	A.P. Colaiaco
	R.W. Dunham
	D.G. Portman
	G.A. Wilson
	W.R. Wilson
Tennessee Valley Authority	Robert C. St. Clair
Testing Laboratory Group	L. Frier
	E.J. Huber
	R.W. Seelbach (*Alt*)
US Department of the Army	Robert H. Bruck
US Department of the Interior, Bureau of Reclamation	Edward M. Tomsic
US Department of Defense, Defense Communications Agency	*Vacant*
US Department of the Navy, Naval Facilities Engineering Command	D.M. Hannemann

At the time this guide was approved the members of the Generator Ground Protection Working Group were as follows:

A.C. Pierce, *Chairman*

H. DiSante
E.J. Emmerling
C.H. Griffin
C.L. Wagner

At the time this guide was approved, the members of the Rotating Machinery Protection Subcommittee were as follows:

R.F. Archart, *Chairman*
G.R. Nail, *Vice Chairman/Secretary*

M.S. Baldwin
F.G. Basso
J. Berdy
J.L. Blackburn
B. Bozoki
E.J. Emmerling
R.J. Fernandez
J.A. Imhof
L.E. Landoll*
J.R. Latham
N.E. Nilsson**
G.C. Parr
C.J. Pencinger
A.C. Pierce
C.M. Shuster
W.H. VanZee
F. VonRoeschlaub
C.L. Wagner†
J.E. Waldron
R.C. Zaklukiewicz

*Liaison to Rotating Machinery Committee
**Liaison from Rotating Machinery Committee
†Liaison to Power Generation Committee

When the IEEE Standards Board approved this guide on December 17, 1981 it had the following membership:

Irvin N. Howell, Jr, *Chairman*
Irving Kolodny, *Vice Chairman*

Sava I. Sherr, *Secretary*

G.Y.R. Allen
J.J. Archambault
James H. Beall
John T. Boettger
Edward Chelotti
Edward J. Cohen
Len S. Corey
Jay Forster
Kurt Greene
Loering M. Johnson
Joseph L. Koepfinger
John E. May
Donald T. Michael*
John P. Riganati
Frank Rosa
Robert W. Seelbach
Jay A. Stewart
William E. Vannah
Virginius N. Vaughan, Jr
Art Wall
Robert E. Weiler

*Member emeritus

Contents

FIGURES

SECTION PAGE

TABLE

APPENDIXES

APPENDIX FIGURES

An American National Standard

IEEE Guide for Generator Ground Protection

1. Introduction

This guide has been prepared to aid in the application of relays and relaying schemes for the protection of synchronous generators for single-phase-to-ground faults in the stator winding. The guide is not intended for the selection of generator or ground connection schemes.

The information included in the main body is limited to those generator connections, grounding practices, and protective schemes generally used in North America.

Appendix A provides information on some of the protective schemes in use elsewhere in the world and on schemes which are not in widespread use throughout North America.

Appendix B provides examples of how to calculate ground overcurrent and overvoltage relay settings for the various protective schemes and how to coordinate them with voltage transformer secondary fuses.

Appendix C is a bibliography of available literature on the ground-fault problem from which source material was drawn.

Recommended protective schemes and the arrangements in which they may be applied are indicated in Table 1. The use of this table is described in Section 3 with supporting information provided in subsequent sections.

2. References

When the following standards are superseded by an approved revision, the latest revision shall apply.

[1] ANSI/IEEE C37.2-1979, IEEE Standard Electrical Power System Device Function Numbers.

[2] IEEE Std 143-1954, IEEE Application Guides for Ground-Fault Neutralizers, Grounding of Synchronous Generator Systems, Neutral Grounding of Transmission Systems.

[3] GROSS, E.T.B. Sensitive Generator Ground-Fault Protection, *Proceedings American Power Conference*, vol 36, 1974, pp 1031-1035.

[4] GROSS, E.T.B., and GULACHENSKI, E.M. Experience of the New England System with Generator Protection by Resonant Neutral Grounding. *IEEE Transactions on Power Apparatus and Systems*, vol 92, Jul/Aug, 1973, pp 1186-1194.

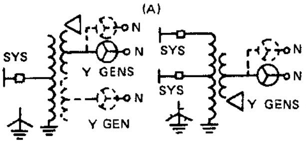
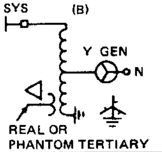
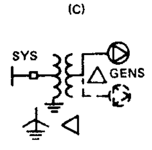
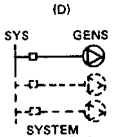
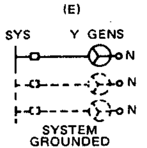
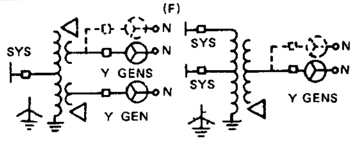
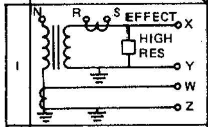
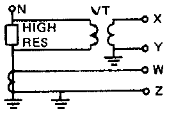
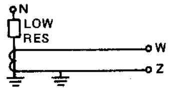
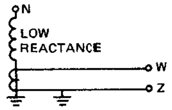
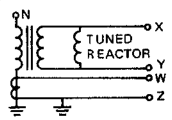
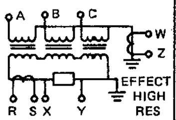
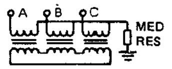
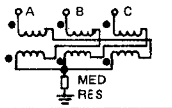
[5] IEEE COMMITTEE REPORT. Potential Transformer Application on Unit Connected Generators. *IEEE Transactions on Power Apparatus and Systems*, vol 91, Jan/Feb 1972, pp 24-28.

3. Summary of Protection Schemes

A summary of recommended protective schemes is given in Table 1, which is a matrix of generator connections, generator grounding methods, and the scheme numbers which identify the protective schemes. The following explanation has been prepared as an aid for its use.

Across the top of the table, heading the six columns (A–F), are one-line diagrams covering most, if not all, of the significant variations of generator-transformer-bus circuit-breaker arrangements that might be encountered in a present-day electric utility or industrial power system. These diagrams are discussed in Section 4 of this guide. Vertically, along the left

Table 1
Generator Connections, Generator Grounding Methods, and Protective Scheme Numbers

	GENERATOR CONNECTIONS → / GROUNDING METHODS ↓	(A) 	(B) 	(C) 	(D) 	(E) 	(F) 
I		[1,7,10] 2,3,4,9,11 5S,8S				[12,15] 13 5S,8S	[1,7,10] 2,3,4,9,11 5S,8S
II		[1,7,10] 2,3,4,11 5S,8S				[12,15] 13 5S,8S	[1,7,10] 2,3,4,11 5S,8S
III			10,11,15,16			[14,16] 10,11,15	
IV			10,11,15,16			10,15,16	
V		[6]					6,10,11 5S
VI	GENERATOR LEADS 			[1,9,10] 2,3,4,11 5S	[12,17] 13 5S		
VII	GENERATOR LEADS  GENERATOR LEADS 				12,13	12,13	
VIII	UNGROUNDED		[12.15] .13 8S		[12.17] .13 8S	[12.15] .13 8S	

[ ] MOST WIDELY USED SCHEMES S SUITABLE DURING STARTUP OR SHUTDOWN

side of the table, heading the eight rows (I–VIII), are one-line diagrams of approved grounding methods for electric generators covered in IEEE Std 143-1954 [2].[1] These diagrams will be explained and discussed subsequently. The individual boxes in Table 1 list by scheme number (1, 2, 3, etc), the different applicable ground-fault protective schemes that apply for a given generator connection, and a given grounding method. For example, the box under column E and row III indicates that protective schemes 10, 11, 14, 15, and 16 may be applied for single-phase-to-ground fault protection of a wye-connected generator. The neutral is grounded through a *low* resistance, and the main leads are connected directly to a grounded system through a circuit breaker.

Those boxes which are crossed out and contain no protection scheme numbers represent cases that are either not practical or not recommended. For example, under column D, a delta-connected generator has no neutral available, so boxes under column D (associated with rows I, II, III, IV, and V) are crossed out. Also, the box under column E (and associated with row V) is crossed out because the use of a tuned-resonant grounding method, in the neutral of a wye-connected generator directly connected to a grounded system, is a misapplication.

The protective scheme numbers in the boxes refer to protective schemes that are completely illustrated and described in Section 6 of this guide. In some boxes, there are some numbers that are followed by the suffix S, such as 5S in box (D–VI). The suffix S indicates that the protective scheme represented by that scheme number designation is suitable for use only when the machine is running and disconnected from the system, but with field excitation applied. This type of protection utilizes protective devices that are not tuned to normal system frequency, so that they offer sensitive protection over a wide range of frequencies. Thus, schemes designated with the suffix S are suitable for the protection of machines during startup and shutdown. Protective scheme numbers without the suffix S represent schemes that are indexed to provide protection only during operation at rated frequency. For example, in the case of the generator connection illustrated in the diagram of column A with the grounding connection of row I, scheme 8S is intended to detect any single-phase-to-ground fault in the generator or its leads during startup or shutdown procedures while field excitation is applied, but with the main circuit breaker open. In the box (D–VIII) the protective scheme represented by scheme 17 is intended for protection during the time that the main breaker is closed and the machine is running normally. In general, startup and shutdown proctection for single-phase-to-ground faults is indicated only in those applications where a high-impedance grounded or an ungrounded generator is connected directly to a grounded system, or where excitation is applied to a machine early in the startup cycle or is removed late in the shutdown cycle. This startup and shutdown protection is generally not intended to coordinate properly with system protection. For this reason, it should be removed from service at the time the unit is synchronized to the system. This is usually performed automatically when the main breaker is closed.

The protective scheme numbers in Table 1 are arranged in the boxes with the running protective schemes listed first, and the startup protective schemes—where they apply—listed last. Within each box, the schemes within the brackets are the most widely used and recommended. The remainder of the schemes are listed in numerical sequence.

It should be recognized that the bracketed recommendations are based on the anticipated performance of the schemes and not on other factors that might relate to the integrity of the generator itself. For example, while schemes 1 and 7 in box (A-I) could provide essentially the same order of protection for generator single-phase-to-ground faults, the fact that scheme 7 requires voltage transformers on the generator leads may reduce the overall reliability of the generator. Thus, scheme 1 might be more desirable than scheme 7, but they are both indicated in the table to have the same order of merit as far as the protection afforded for single-phase-to-ground faults is concerned.

No attempt is made in Table 1 to indicate primary or backup schemes. It is suggested that descriptions of all schemes applicable to a given situation be considered, and, unless overriding circumstances dictate otherwise, that one of

---

[1] The numbers in brackets correspond to the references listed in Section 2 of this guide.

the bracketed schemes be used for the primary protection, and another high-rated scheme be used for backup or alternate protection.

The generator connections illustrated in column F are very similar to those in column A. The difference is only in the use of low-side circuit breakers in the diagram of column F. A comparison of the applicable protective schemes between columns A and F will indicate that they are nearly all the same. Because of the low-side circuit breakers in the diagrams of column F, field excitation might normally be applied to the unit when it is turning at, or very near to, rated frequency. Under these conditions, the need for startup or shutdown protection is minimized.

Section 5 describes grounding methods I–VIII. The different grounding methods head up the rows in Table 1 along the left-hand side. The diagrams in the column are intended to indicate the different grounding methods and the means for interfacing with the protective relay schemes. The diagrams in row I have both a neutral point N and a ground point in the primary circuit, as do those in rows II–V. The point N in the grounding method diagram connects to the point N in the generator-connection diagram with which it is applied. For example, if any grounding method, I–V, is used with any generator connection illustrated in columns A, B, E, or F, the generator neutral N in question is grounded through the neutral connection shown in the grounding method diagram. In the case of the delta-connected machines of columns C and D, no neutral point exists, so grounding method VI or VII should be used. This includes a wye-broken delta-connected distribution-transformer bank with a secondary resistor. The wye (Y) windings are connected to the associated-generator main leads. Finally, row VIII indicates an ungrounded machine which is grounded only through the system to which it may be connected.

In Table 1, the diagram for grounding methods also indicates the interface between the primary circuits and the protective schemes. An example of this is that grounding method I shows a distribution transformer with a secondary resistor. In series with the secondary of the distribution transformer is a current-transformer primary winding. The secondary winding of this current transformer terminates at terminals labeled R and S. A current-operated relay, connected to these two terminals, will measure the current in the resistor during a ground fault in the generator stator or its associated circuits.

In this same diagram, terminals designated X and Y are connected across the resistor. If the operating coil of a voltage relay is connected to these terminals, it will measure the voltage developed across the resistor (which is proportional to the current through the resistor) during ground faults in the generator-stator winding or its associated circuits.

Again, in grounding method I, the current transformer in the neutral lead of the generator ground connection (in series with the primary winding of the distribution transformer) has its secondary winding terminating at points W and Z. A current-operated relay, connected to these terminals, will measure the current in the generator neutral during ground faults in the generator-stator winding or its associated circuits. The terminal points R. S, X. Y, W, and Z are the interface connections to the protective schemes. The same is true in grounding methods II–VI. Reference to these connections will show that not all the grounding methods provide the same opportunities for protection. For example, in method IV, only a neutral-current transformer is indicated with secondary connections to terminals W and Z.

The diagrams for each of the protective schemes in Section 6 indicate to which terminal points (R, S. W, etc) they connect. For example, protective scheme 1 will be found to have input connections labeled X and Y. This indicates that protective scheme 1 is always connected to terminals X and Y, regardless of the grounding method with which it is used. From Table 1, it will be noted that protective scheme 1 may be used with grounding methods I, II, and VI, since all of these have interfacing terminals labeled X and Y. Similar comments apply to the other protective schemes and the interfacing terminal designations.

4. Generator Connections

The six different classes of generator connections illustrated in Table 1 are intended to be representative of connections in common use today. While the connections of the two diagrams in column A are different, the arrangements are such that the same protective schemes may be applied to both. The criteria here is that a single-phase-to-ground fault in a generator will not produce any significant zero-sequence current or voltages in the system, nor will a similar fault in the system produce any significant zero-sequence quantities in the generator circuit.

In connection A, if two units are paralleled on one transformer delta winding (as in the case of a cross compound machine, or machines with two-stator windings per phase), the same kind of protective schemes could be used as if only one unit were connected to the transformer. In general, for these applications, only one neutral is grounded. Where machines are connected to separate low-voltage transformer windings, each unit is grounded separately and has its own protective scheme. If tripping is employed, each protective scheme should initiate shutdown of all generators connected to a common transformer.

The generator connections of column B indicate that the unit stepup transformer is any autotransformer, with either a wound-delta tertiary or a phantom tertiary. In either case, the autotransformer provides a direct zero-sequence connection between the generator and the system so that the system grounding will provide zero-sequence current for ground faults in the generator. Also, the generator will provide zero-sequence current for faults on the system.

It is important to recognize in connection B that the wound or phantom tertiary of the main transformer will be a source of ground-fault current for generator faults. With this arrangement, even with the generator-neutral ungrounded and the main circuit breaker open, substantial fault current could flow for a ground fault in the stator when the generator is running with field excitation applied.

Connection C is similar to A, except that the generator(s) is connected in delta (Δ) rather than in wye (Y). Here, as in connection A, the delta-connected winding of the power transformer provides zero-sequence isolation between the generator and the system. Such delta-connected generator units have no neutral available, so that grounding is obtained by the use of a scheme as illustrated in Table 1, method VI. In general, one common grounding equipment is employed regardless of the number of generator units that are connected to a given transformer winding.

The circuit arrangements of connection D and E indicate generators connected directly to the system bus without any interposing stepup transformer. In general, these will be relatively small generators and they will be connected to a grounded (in contrast to an ungrounded) power system. As indicated in Table 1, the delta machine of connection D requires the scheme of method VI or VII for grounding while that of connection E uses a suitable neutral grounding method. In these applications, each machine has individual protection.

The circuit arrangements in the diagrams of connection F are the same as those in A, except that the former utilize individual generator circuit breakers on the low side of the power-transformer banks. Here again, the delta-wye (Δ–Y) connections of the transformers provide zero-sequence isolation between the generators and the system. In general, each generator will have individual grounding and protection. While the low-side circuit breakers permit switching of individual generators, the protective schemes available cannot distinguish between faults in the different generators connected to a common delta winding. However, if different time delay settings are utilized on the individual ground relays, the units will be sequentially tripped until the fault is cleared. This will establish the fault location. For this reason, a fault in any one machine may result in the loss of all generators connected to a common delta winding.

5. Grounding Methods

This guide describes protection for six of the seven grounding categories covered in IEEE Std 143-1954 [2]. The seven categories described in IEEE Std 143-1954 [2] are: solid, resistor, reactor, distribution transformer, ground-fault neutralizer, grounding transformer, and ungrounded. Protection for solidly grounded generators is not considered in this guide. These machines can be protected for ground faults by conventional differential and overcurrent relays. IEEE Std 143-1954 [2] considers high-, medium-, and low-resistance grounding as a single category. This guide lists them as separate grounding methods, since each requires a different type of protective scheme. Thus there are eight grounding methods given in Table 1. They are

I Distribution-Transformer Grounded (High Resistance)
II Neutral-Resistor Grounded (High Resistance)
III Neutral-Resistor Grounded (Low Resistance)
IV Neutral-Reactor Grounded (Low Inductive Reactance)
V Ground-Fault Neutralizer Grounded (Tuned Inductive Reactor)
VI Grounding-Transformer Grounded (High Resistance)
VII Grounding-Transformer Grounded (Medium Resistance)
VIII Ungrounded

5.1 Method I, Distribution-Transformer Grounded (High Resistance). Grounding Method I utilizes a distribution transformer with a primary-voltage rating equal to, or greater than, the line-to-neutral voltage rating of the generator, with a secondary rating of 120 V or 240 V. The distribution transformer should have sufficient overvoltage capability so that it does not saturate on phase-to-ground faults with the machine operated at 105% rated voltage. Secondary resistors are usually selected so that for a single-phase-to-ground fault at the terminals of the generator, the power dissipated in the resistor is equal to, or greater than, the zero-sequence reactive voltampere loss in the zero-sequence capacitance of the generator windings, its leads, and the windings of the transformers that are connected to the generator terminals. This arrangement is considered to be high-resistance grounding, and it limits the maximum single-phase-to-ground fault current to a value in the range of approximately 3–25 primary amperes. This is not of sufficient magnitude to operate standard generator differential relays. In general, the W–Z current transformer will have a ratio of unity and the R–S current-transformer ratio is usually selected so that its secondary current will be approximately equal to the primary current in the generator neutral.

5.2 Method II, Neutral-Resistor Grounded (High Resistance). Grounding Method II is functionally equivalent to that of Method I. In Method II, the resistor is sized directly to limit the single-phase-to-ground fault current to the same magnitude as in Method I, without the use of a distribution transformer. However, the voltage transformer voltage ratings are selected on the same basis as those for the distribution transformer in Method I. The W–Z current-transformer ratio is generally selected to be unity.

5.3 Method III, Neutral-Resistor Grounded (Low Resistance). Method III illustrates a low-resistance grounding arrangement. This type of grounding method permits fault current many times higher than those produced by methods I and II. In the case of the low-resistance grounding methods, the single-phase-to-ground fault current is high enough to operate the standard generator differential relays for faults in the stator, except for those near the neutral end of the machine.

5.4 Method IV, Neutral-Reactor Grounded (Low Inductive Reactance). Method IV illustrates a low inductive-reactance grounding arrangement. This type of grounding method permits fault current many times higher than those produced by Methods I and II. In the case of low inductive-reactance grounding methods, the single-phase-to-ground fault current is high enough to operate the standard generator differential relays for faults in the stator, except for those near the neutral end of the machine.

5.5 Method V, Ground-Fault Neutralizer Grounded (Tuned Inductive Reactor). Method V illustrates the ground-fault neutralizer arrangement. In this grounding method, a distribution type transformer with a ratio selected, as in Method I, is used with a secondary reactor. The ohmic value of this secondary reactor is selected so that, when reflected into the primary circuit, its reactance is equal to $\frac{1}{3}$ of the zero-sequence capacitive reactance of the circuit from (and including) the generator, to (and including) the delta windings of the associated power 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. Thus, it may not be readily applied to units arranged as in Fig F, such as when low-side breakers are applied.

5.6 Method VI, Grounding Transformer Grounded (High Resistance). Grounding Method VI uses three distribution transformers with ratios selected as in Method I. The primary windings of these are connected to the generator leads in Y, while the secondaries are connected in broken Δ with a resistor. As in the case of Method I, the resistor is selected so that, for a single-phase-to-ground fault at the terminals of the generator, the power dissipated in the resistor is equal to, or greater than, the 3-phase zero-sequence reactive voltampere loss in the zero-sequence capacitance of the generator windings, its leads, and the windings of the transformers connected to the generator terminals. This grounding method is used on Δ-connected generators.

5.7 Method VII, Grounding Transformer Grounded (Medium Resistance). Grounding Method VII uses either a zig-zag transformer or a Y–Δ transformer. The primary windings of these are connected to the generator leads, with a resistor connected from the transformer neutral to ground. The effective grounding impedance is selected to provide sufficient current for selective ground relaying.

5.8 Method VIII, Ungrounded. Finally, if no grounding of any sort is employed on the leads or neutral of the generator, this is termed *ungrounded* and is noted in row VIII.

In grounding Methods I–V, the neutral-current transformer is shown to be connected between the fault-limiting device and ground. This current transformer could be located on either side of the fault-limiting device, depending on the preference of the user. The insulation level of the current transformer should be compatible with the possible voltage to which it may be exposed.

6. Protective Schemes

The protective schemes listed by number in Table 1 are illustrated and described in the following pages. The electrical characteristics of the relays represented by the device function numbers in the figures illustrating each scheme are defined in Section 7.

The methods employed for grounding and fusing the secondary circuits of voltage transformers and the methods for grounding current-transformer secondary circuits are not generally the same for all installations. For this reason no secondary fuses or ground points are indicated in the illustrated figures. However, all current and voltage transformer secondary circuits should be grounded in a way that is consistent with accepted practices for personnel safety.

Protective schemes that are used to protect generators employing high resistance and resonant grounding methods (grounding methods I, II, V, and VI) are generally sensitive enough to detect phase-to-ground faults in the secondary, and in the primary circuits of voltage transformers connected to the generator leads. If the wye-connected secondary circuit of these voltage transformers is grounded at one of the phase leads, rather than at the neutral point, and if the neutral point is not wired out, the possibility of a phase-to-neutral fault is extremely remote. If this is the case, the relays employed in these protective schemes need not be coordinated with the voltage-transformer secondary fuses. However, coordination with the primary fuses is still required.

A complete discussion of voltage-transformer fusing is given in [5], Appendixes B3, and B4.

Usually, a generator is cleared without any intentional delay once the ground fault is detected. The risk of continuing operation with low-impedance grounding is extensive core damage, while the risk with high-impedance grounding is the possibility of a second fault.

The majority of existing generators having resonant-grounding methods are not tripped immediately, but an alarm is actuated and an orderly shutdown is started. Field experience of over 385 years with generators (prior to 1979) has shown no case of a second fault developing even though there have been at least seven ground faults, all of which were allowed to exist during a delayed tripping. See [3] and [4].

When immediate tripping is used, it includes the main and field circuit breakers, and the turbine stop valve or gates. Because a sudden, complete shedding of load can be a severe shock to the mechanical systems of the unit, including the steam system, it is sometimes necessary to employ an orderly shutdown rather than an immediate trip. In such cases, upon detection of a stator ground fault, the generator is either automatically or manually unloaded at a safe rate before tripping the circuit breakers. All the protective schemes that follow — except schemes 2, 3, 4, and 6 — indicate complete and immediate shutdown of the unit. Schemes 2, 3, and 4 illustrate three possible variations in the shutdown procedures that may be employed to effect an orderly shutdown. While the use of these schemes can significantly increase the possibility of extensive damage to the generator, they can be used where necessary. However, they should only be used in conjunction with high-resistance or resonant-grounding methods, where ground fault current is severely limited.

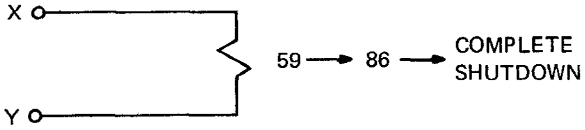
In some instances, such as in cross-compound machines, field excitation is applied as these machines are brought up to speed. In these applications, or where field excitation is permitted to remain on the unit as it is shut down, or both, additional protection may be required during these periods. Schemes intended for use in such applications are designated with the suffix S. Table 1 indicates where these schemes may be applied when necessary.

6.1 Scheme 1, Ground Overvoltage—Complete Shutdown. Protective scheme 1 may by used for single-phase-to-ground fault detection on high-resistance grounded generators that are connected to the system through Δ–Y-connected transformers. Table 1 indicates that this includes grounding methods I and II for Y-connected generators and grounding method VI for Δ-connected generators.

All three of these grounding methods limit the available fault current for single-phase-to-ground faults in the generator stator windings, the generator leads, and the delta windings of the associated transformers to extremely low levels. The voltage measured across the grounding resistors at terminals X–Y provides an indication of the existence of a fault in this zone.

Fault detection in these applications is achieved by connecting the operating circuit of a very sensitive overvoltage relay (device 59) across terminals X–Y. The magnitude of the voltage seen by this device depends on the fault location and the ratio of the distribution transformer in the case of grounding methods I and VI, or the ratio of the voltage transformer in the case of grounding method II.

Fig 1
Scheme 1, Ground Overvoltage—
Complete Shutdown



For the case of grounding method I, a single-phase-to-ground fault at the generator terminals will produce full phase-to-neutral voltage across the primary of the distribution transformer. For the case of grounding method II, this same fault will produce the same voltage across the neutral resistor. For the case of grounding method VI, the phasor sum of the phase-to-ground voltages applied to the primary windings of the three distribution transformers during a single-phase-to-ground fault at the terminals of the generator will be equal to three times the full phase-to-neutral voltage of the generator. In every case, the voltage appearing at the terminals of the operating circuit of device 59 will be the primary voltage divided by the voltage transformer ratio or the distribution transformer ratio. Since the voltage rise from the generator neutral to its terminals is uniformly distributed, the voltage appearing across the grounding device for a single-phase-to-ground fault on a stator winding will be roughly proportional to the distance from the neutral as a percentage of the total winding.

The voltage pick-up setting of device 59 shall be high enough so that it will not operate on fundamental frequency voltages produced by normal system imbalances, or 3rd harmonic voltages generated by the machine under full-load conditions. So as to permit a sensitive pick-up setting for device 59 it should be insensitive to 3rd harmonic voltages by design. In general, relays are available that make it possible to safely set device 59 to detect single-phase-to-ground faults as close as 2% to 10% from the neutral end of the winding, depending on the ratio of the voltage or the distribution transformers that are used. To ensure that the relay will not operate on the system imbalance, the relay voltage should be measured at machine full load.

Phase-to-ground faults on the transmission system produce zero-sequence voltage in the grounded-Y-connected high-voltage winding of the main power transformer. This voltage is capacitively coupled to the generator zero-sequence network by the interwinding capacitance of the transformer. If the transformer is solidly grounded, the zero-sequence voltage in the Y-connected winding will be quite low. Because the impedance of the generator-grounding device is small (in comparison to that of the interwinding capacitance), most of this voltage will be across the transformer interwinding capacitance and very little of it across the generator grounding device.

Phase-to-ground faults on the station-service distribution system will also be capacitively coupled to the generator zero-sequence network. However, because the auxiliary transformer is small and the distribution voltage is low, coupled zero-sequence voltage from this source is seldom a problem, even though these systems are typically high-resistance grounded.

If the main power transformer is not solidly grounded, or the effect of inter-winding coupling cannot be evaluated, some short time delay should be used to prevent false generator trips for faults on the transmission system. In any case, time delay will be required to coordinate with the generator-voltage transformer fuses for phase-to-ground faults in the voltage transformers (VTs) or their secondary leads. Appendix B provides an example of relay-fuse coordination. Device 59 should be capable of withstanding the maximum applied voltage for the time required to shut down the generator.

During a ground fault, device 59 operates and energizes a lockout relay, device 86. The lockout relay initiates a complete shutdown, which includes tripping the main and field breakers and closing the turbine stop valves or gates.

For the case of two generators, where each is connected directly to a separate delta winding of a common step up transformer, separate relays are required. Each relay should shut down both machines. For the case of cross-compound machines, or machines with double stator windings, only one stator winding is normally grounded and only one relay is required. When two or more machines, with each having its own low-side circuit breaker, are connected to the same transformer primary Δ winding, each machine is usually grounded so that one relay is required for each machine. Each relay trips only its associated unit. It is advisable to provide a protective scheme such as that illustrated in scheme 7, so as to protect the transformer Δ winding. This relay should trip the transformer high side and all the generator breakers. In such applications, a fault in any machine, or the Δ winding of the transformer, will be detected by all the relays, so that complete selectivity is not generally possible. Some users apply all the generator relays at the same pickup setting but adjusted to operate with different time delays. The scheme 7 relay is set less sensitively and with the longest time delay. If a fault occurs in the protected zone, the generators are tripped in sequence until the faulted unit is removed. The remaining units, if any, are permitted to continue in service. If the fault is in the transformer Δ winding, all the units and the transformers are ultimately tripped. This type of application often helps to pinpoint the fault location. As an alternate method, all generator relays may be set alike. Reports on such applications indicate that, for some faults in the generator windings, the relay associated with the faulted generator will operate to clear the unit before any of the others can trip. However, for faults near the terminals of a generator, this approach can result in tripping all the units.

A third approach is to supervise the tripping of the relay in the broken Δ with the auxiliary contact of the generator breakers, such as in scheme 8S. For faults in either generator, only the generators are tripped. For faults on the bus or in the transformer, the broken-Δ relay trips the transformer high-side breakers after both generator breakers trip.

In general, the overvoltage relay employed in protective scheme 1 will not provide sensitive protection at frequencies significantly below rated frequency. Thus, if field excitation will be applied during the periods when the machine is brought up to speed or shut down, a protective scheme similar to that described under scheme 5S or 8S should be considered in addition to scheme 1.

The major advantage of scheme 1 is that, due to its sensitive relay settings, ground faults in the stator may be detected to within 2% of the neutral point. The major disadvantage of this scheme is that it can respond to faults in the voltage transformer primary and secondary circuits, and total coordination with the associated fuses may not be possible. An example related to the application of scheme 1—including coordination between the voltage transformer fuses and the protective relay—is provided in Appendix B.

6.2 Scheme 2, Ground Overvoltage—Permissive Shutdown. This variation of schemes 1 and 7 utilizes the same 59 and 86 devices and settings, but tripping of the main and field circuit breakers is supervised by position switches on the turbine stop valves. The advantage of this scheme is that it prevents full load rejection

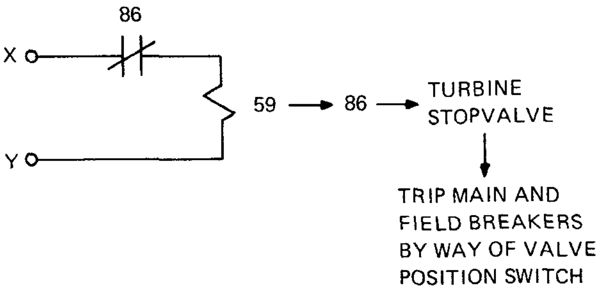


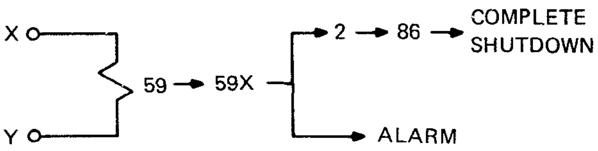
Fig 2
Scheme 2, Ground Overvoltage—Permissive Shutdown

with its accompanying overspeed condition. The fact that it permits a longer fault duration and the additional complexity of its tripping circuits are its disadvantages. This arrangement may result in considerably more than rated voltage applied to the 59 device for a prolonged period of time. Because of this, a contact on device 86 is employed to interrupt the circuit to the overvoltage relay.

6.3 Scheme 3, Ground Overvoltage—Alarm and Time-Delay Shutdown. This variation of schemes 1 and 7 utilizes the same overvoltage relay but provides for an immediate alarm with a prolonged time-delay trip. If device 59 cannot continuously withstand the maximum voltage to which it may be subjected during a single phase-to-ground fault at the generator terminals, then this scheme shall be modified by the inclusion of a 59H device as in the case of scheme 4.

If a more orderly shutdown is desired, device 86 is connected to trip the turbine stop valve, which in turn, by way of a valve position switch, trips the main and field breakers as in scheme 2.

Fig 3
Scheme 3, Ground Overvoltage—Alarm and Time-Delay Shutdown

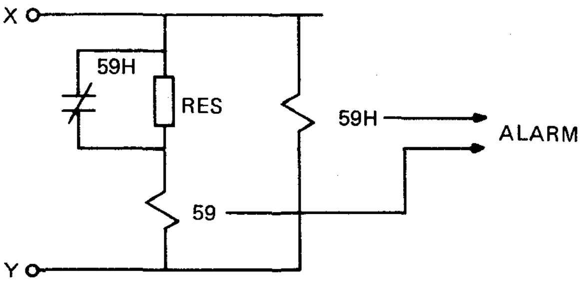


6.4 Scheme 4, Ground Overvoltage—Alarm. This variation of schemes 1 and 7 utilizes the same 59 device but provides only for alarm. Because this arrangement may result in considerably more than rated voltage applied to device 59 for an extended period of time, an additional, less sensitive, but higher rated 59H device is also employed.

The 59 relay should be set exactly as in scheme 1 or 7. Device 59H should be set to pick up at a voltage level below the continuous rating of device 59. Also, the continuous rating of the 59H device shall be capable of continuously withstanding the voltage it will be subjected to for a single-phase-to-ground fault at the generator terminals. With this arrangement, if the fault voltage on device 59 exceeds its capabilities, the 59H device will operate to insert a resistor and reduce the voltage on device 59 to a safe value.

NOTE: If device 59 can withstand the maximum fault voltage to which it may be continually exposed, a 59H device is not required.

Fig 4
Scheme 4, Ground Overvoltage—Alarm



6.5 Scheme 5S, Startup Ground Overvoltage—Complete Shutdown. As indicated by the suffix S, this scheme is intended for stator ground-fault detection during the time that the protected machine is disconnected from the system and running with field excitation applied. It serves a particularly important function when applied to high-resistance or resonant-grounded Y or Δ-connected units (see Table 1), because the single-phase-to-ground fault protection normally provided for these applications is relatively insensitive except at frequencies at or near rated value. Device 59S, used in scheme 5S, should have a relatively constant volts-per-hertz response down to its dc pickup. As a result the relay will be more voltage sensitive as the frequency is decreased. Such a device will tend to provide the same level of protection over a wide range of frequencies as the generator is brought up to speed or shut down, while maintaining an essentially constant volts-per-hertz.

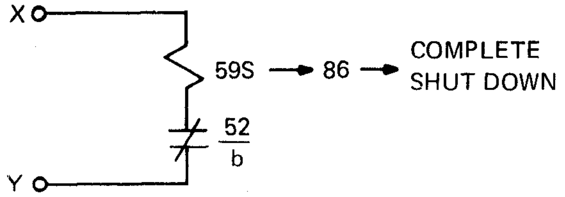


Fig 5
Scheme 5S, Startup Ground Overvoltage—Complete Shutdown

The operating coil circuit of the sensitive instantaneous overvoltage relay (device 59S) may be connected to terminals indicated as X–Y in grounding methods I, II, V, and VI illustrated in Table 1. The relay operating circuit is connected by way of an auxiliary switch (52/b) on the associated circuit breaker, so that the protection is in service only during the time that the circuit breaker is open.

NOTE: In ring bus and breaker-and-a-half arrangements, auxiliary switches from each of the two associated circuit breakers shall be connected in series.

Because the protection afforded by this scheme is available only during those periods that the generator breaker(s) is open, there is no need for coordination with other protective devices during external faults. Also, the relatively constant volts-per-hertz sensitivity of the relay tends to provide immunity to small magnitudes of 3rd harmonic voltages that might be present during startup or shutdown procedures. The combination of these two effects permits the use of a sensitive setting on device 59S. Typical pickup settings are in the range of 3% to 5% of the maximum voltage that can be developed for a solid single-phase-to-ground fault at the terminals of the generator. A relay setting example is given in Appendix B.

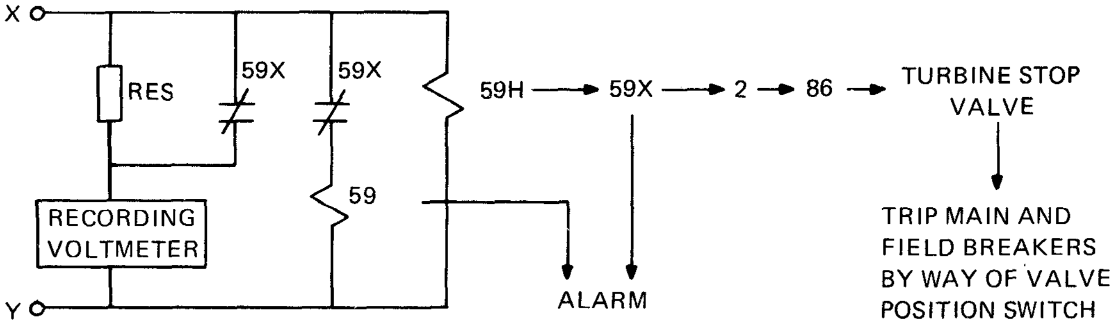
If the 59S device is not capable of withstanding the maximum voltage to which it may be subjected for the time duration required to shut down the unit, some arrangement should be used to de-energize 59S after device 86 has operated. A contact on device 86 could serve this purpose.

This scheme has the advantage of providing high speed sensitive protection during startup and shutdown procedures that may otherwise not be obtainable. It has the minor disadvantage that it will generally not coordinate with voltage transformer fuses. However, because the machine is not loaded during the period of time that this protection is in service, this limitation should not be a major consideration.

6.6 Scheme 6, Ground-Fault Neutralizer Overvoltage—Alarm and Time-Delay Orderly Shutdown. This scheme is generally employed for the protection of units that are grounded by means of the ground-fault neutralizer method. This is indicated as grounding method V in Table 1.

The ground-fault neutralizer method of grounding limits the single-phase-to-ground fault current in the machine stator windings and connected equipment to magnitudes so low that an arc cannot be maintained. This grounding method severely restricts fault damage, so that long time delays, permitting orderly shutdown of faulted units, are deemed justifiable. However, it should be recognized that this grounding scheme in no way alters

Fig 6
Scheme 6, Ground-Fault Neutralizer Overvoltage—Alarm and Time-Delay Orderly Shutdown



the probability of a second ground fault occurring prior to shutdown. A second fault could produce high fault current.

Protective scheme 6 is a variation of protective scheme 1. It employs the same 59 device as scheme 1, and all the comments regarding settings and sensitivities made in scheme 1 apply equally to scheme 6. Because of the absence, or near absence, of fault current, device 59 only operates an alarm. However, because device 59 may not be able to withstand prolonged operation with significant overvoltage applied, device 59H is included. Device 59H is an instantaneous overvoltage relay, which is not as sensitive as device 59, and it can withstand higher voltages continuously. Device 59H is set to pick up at a voltage level somewhat below the continuous rating of device 59.

Because of the higher setting, operation of device 59H indicates a fault that is significantly remote from the neutral of the generator. For such a fault, both the 59 and 59H devices pick up and sound an alarm. However, device 59H energizes auxiliary relay 59X which in turn de-energizes the voltage operating circuit of device 59, energizes a timer (2), and continues the alarm. The timer, set to operate in approximately 1 h, is intended to permit an operator to affect an orderly shutdown of the unit before any automatic action is taken by way of device 86. The recording voltmeter in this scheme monitors the small but discernible zero-sequence voltage that is always present across the neutralizing reactor. Reductions in this voltage (from normal readings) indicate short circuits to ground at or near the generator neutral terminal. An increase in voltage readings indicates insulation deterioration and a probable incipient fault. Operation of 59H inserts a resistor in series with the recording voltmeter to change the scale so that the higher fault voltages can be recorded.

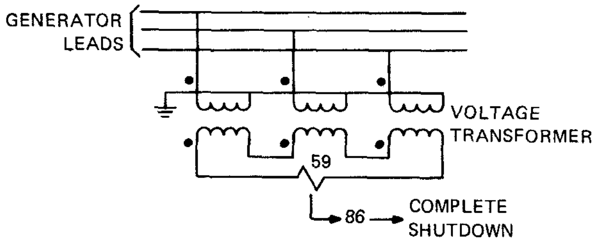
The advantages of this scheme are essentially the same as those afforded by scheme 1. However, with a ground-fault neutralizer, the impedances of the zero-sequence network will reduce to a parallel circuit of Z_x and Z_c, where Z_x is comprised of the reactive component of the tunable reactor shunted by a resistive component R_x which is representative of the reactor losses [3]. The phase-to-ground capacitive impedance, Z_c, of the system is comprised of an imaginary component which represents the phase-to-ground capacitive reactance, in parallel with a resistive component R_c which represents the losses associated with the capacitance of the system. In practice, R_x is appreciably greater than R_c. When the tunable reactor is adjusted so that the reactance of the tank circuit becomes almost infinite, then the zero-sequence network is reduced to: $Z_o = R_c = R$.

The zero-sequence network impedance of the ground-fault neutralizer is 30–50 times greater than the resistance used in high-resistance grounding. For a line-to-ground fault, the zero-sequence network reduces to the grounding impedance R in series with the arc fault impedance, $3R_f$. Since the per-unit voltage appearing across the grounding device is $R/(R + 3R_f)$, it can be seen that, for the same relay setting, the resonant grounding system will detect much higher resistance faults.

6.7 Scheme 7, Wye-Broken-Delta Voltage Transformer (VT) Ground Overvoltage—Complete Shutdown. This protective scheme should not be confused with grounding method VI illustrated in Table 1. Grounding method VI employs three distribution transformers connected grounded wye-broken-delta with a resistor in the broken-delta circuit. This grounding arrangement acts to provide a high-resistance ground for delta-connected generator, its leads, and the primary windings of the two transformers connected to it. On the other hand, the ground-fault detection illustrated in scheme 7 is intended to detect ground faults in the generator stator winding and the associated circuits rather than to provide a ground for the system.

Protective scheme 7 is a variation of protective scheme 1. It employs the same 59 device as scheme 1, and all comments regarding settings, sensitivities, advantages, and disadvantages

Fig 7
Scheme 7, Wye-Broken-Delta VT, Ground Overvoltage—Complete Shutdown



made in scheme 1 apply equally to scheme 7. The basic difference in the two schemes is that in scheme 1, a fault is sensed by the voltage across the neutral-grounding device, whereas in scheme 7, the voltage measured across the broken-delta secondary windings of the voltage transformer provides this indication. For example, during a single-phase-to-ground fault on the generator leads, the phasor sum of the phase-to-ground voltages applied to the primary windings of the three voltage transformers will be equal to three times the phase-to-neutral voltage of the generator. The voltage appearing at the terminals of the 59 device operating circuit will be the primary voltage, divided by the voltage transformer ratio.

Protective scheme 7 could be used instead of scheme 1 in any system using grounding methods I and II and generator connections A and F. Its use is generally limited to the case where two or more machines, each with its own low-side circuit breaker, are connected to the same transformer primary delta winding. Scheme 1 is usually used for the individual machine protection, while scheme 7 is used for the protection of the delta transformer winding and the associated bus. This application is discussed under scheme 1, and a relay setting example is given in Appendix B.

As Fig 7 indicated, device 59 is connected to a separate set of broken-delta secondary windings of the voltage transformers, whose primaries are connected to the generator terminals. If such separate secondary windings are not available, a set of auxiliary voltage transformers, connected grounded wye-broken-delta may be used in conjunction with the normally available wye-connected windings of the voltage transformers. It should be noted that full line-to-line voltage appears across each voltage transformer (VT) during a ground fault; therefore, they shall be rated accordingly. A loading resistor may be placed across the broken delta to prevent possible ferroresonance.

6.8 Scheme 8S, Startup Wye-Broken-Delta Voltage Transformer (VT), Ground Overvoltage—Complete Shutdown. This scheme is identical in purpose and function to scheme 5S, except that it is used when scheme 7 is used instead of scheme 1 for primary ground-fault protection. As indicated by the suffix S, it is inteded for stator ground-fault detection during the time that the protected machine is disconnected from the system and running with field excitation applied.

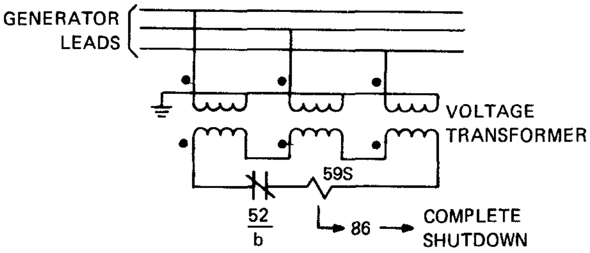


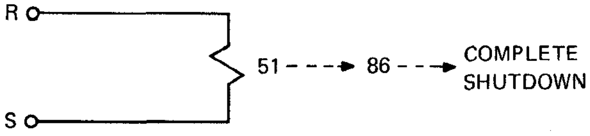
Fig 8
Scheme 8S, Startup Wye-Broken-Delta VT, Ground Overvoltage—Complete Shutdown

6.9 Scheme 9, Secondary Connected Current Transformer (ct), Time-Delay Ground Overcurrent—Complete Shutdown. Protective scheme 9 may be used for single-phase-to-ground fault detection on generators that are high-resistance grounded through distribution transformers and are connected to the transmission system through delta-wye connected transformers.

Scheme 9 measures the current through the secondary resistor (instead of the voltage across the resistor as in scheme 1) to detect generator ground faults. A very inverse time-delay overcurrent relay is connected to the secondary terminals R-S of a current transformer, which is connected in series with the resistor as shown in grounding methods I and VI. A 5 kV or 15 kV current transformer (ct) with a C100 relaying accuracy classification will provide a conservatively rated current source. The current transformer ratio is usually selected so that relay current is approximately equal to the current in the generator neutral.

Since the current through the resistor is directly proportional to the voltage across the resistor, schemes 1 and 9 should be equal in sensitivity. However, the voltage relay used in

Fig 9
Scheme 9, Secondary Connected ct, Time-Delay Ground Overcurrent—Complete Shutdown



scheme 1 is, by design, very insensitive to harmonic voltages, while the overcurrent relay of scheme 9 is not. Therefore, the overcurrent relay of scheme 9 shall be set somewhat less sensitively than the scheme 1 voltage relay. However, this disadvantage is offset by the fact that the overcurrent relay will provide some protection at reduced frequencies, while the tuned overvoltage relay will not.

Scheme 9 is essentially a variation of scheme 1 and the application discussion for scheme 1 also applies to scheme 9. Appendix B provides an example of relay setting calculations and voltage transformer fuse coordination for both schemes.

6.10 Scheme 10, Primary Connected Current Transformer (ct), Time-Delay Ground Overcurrent—Complete Shutdown. Scheme 10 is a variation of scheme 9, except that the current transformer supplying current to the generator ground relay is connected in series with the generator grounding impedance, instead of in the secondary of a distribution transformer. It will be noted that this scheme may be used with a wide variety of grounding methods such as high resistance, low resistance, low reactance, and tuned reactance.

If the generator being protected is isolated from the network by the delta winding of the generator stepup transformer, and if the grounding impedance is high so that the maximum ground fault is limited to 25 A or less, then the same principles of protection described under schemes 1 and 9 are applicable to scheme 10. In this scheme, a high-accuracy current transformer with a 5/5 ratio should be used so as to match the ground relay current to the generator neutral current; the setting calculation example of Appendix B will apply. Scheme 10 may be applied in conjunction with scheme 1 and will provide an excellent backup for the failure of device 59 or its associated auxiliary tripping relay 86.

Certain low-impedance grounding applications of scheme 10 may permit ground-fault current of hundreds or even thousands of amperes. This is particularly true in those cases in which the generator is connected to the system, as in Table 1, col E. If grounding method III is utilized, it may mean that the generators are the only source of ground-fault current on the system, and the generator grounding resistors may be sized to limit the maximum ground fault to some value less than the maximum phase-to-phase fault. If so, the generator neutral-current transformer ratio will be relatively high (typically 400/5), and the generator ground relay shall be coordinated with the other system ground relays. This method will permit sensitive high-speed ground relaying for feeder faults, but has the disadvantage of allowing the possibility of serious generator damage.

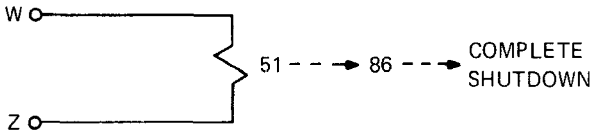


Fig 10
Scheme 10, Primary Connected ct, Time-Delay Ground Overcurrent—Complete Shutdown

These same comments apply generally to column B, if the machine is grounded using the low-reactance grounding method IV. Since there is a direct path for zero-sequence current from the generator neutral through the autotransformer to the system, the generator ground relay should be set somewhat insensitively. This prevents incorrect operations for system faults. Since the fault-current levels may be high, this may result in considerable damage when a ground occurs near the high-voltage terminals of the unit being protected. This damage may be reduced if a scheme 11 instantaneous ground overcurrent unit is included as an integral part of the generator overcurrent ground relay.

6.11 Scheme 11, Instantaneous Ground Overcurrent—Alarm or Complete Shutdown, or Both. Scheme 11 is an instantaneous overcurrent relay that may be used in conjunction with either scheme 9 or 10. When used in conjunction with scheme 9, this device will provide for high-speed tripping of all ground faults in the transformer delta windings and bus work connected to the generator terminals. It also provides high-speed protection for all faults in the first 50% to 70% of the generator stator winding, measured from the high-voltage end of the machine. Thus, device 50H may be valuable in limiting machine damage, particularly in the case of nearly simultaneous ground faults on two different phases. However, if it is desired to coordinate the generator ground relaying with the generator voltage transformer

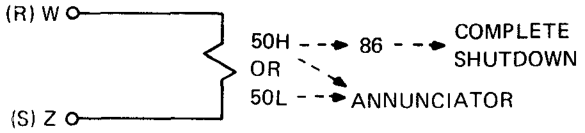


Fig 11
Scheme 11, Instantaneous Ground Overcurrent—Alarm or Complete Shutdown, or Both

fuses, scheme 11 may have to be connected to the alarm only. This will still serve the purpose of assisting in the determination of fault location, since any fault that does not operate scheme 11 is probably located inside the generator itself, and not in any externally connected equipment.

To prevent incorrect operation for faults on the high-voltage side of the generator main step-up transformer, device 50H should be set for not less than three times the scheme 9 overcurrent relay tap setting. If device 50H is connected to trip, it should be connected to the same auxiliary tripping relay as device 51 of scheme 9.

It should be noted that on most generators, even when a ground fault is *cleared* with high speed, ground-fault current may continue to flow for several seconds, due to the slow rate of generator voltage decay. If the fault is external to the generator, however, and a generator breaker is provided (column F), then operation of scheme 11 will isolate and clear the fault. This could prove to be of great value in preventing machine damage in the case of a phase-to-phase-to-ground fault in a main step-up or station service transformer.

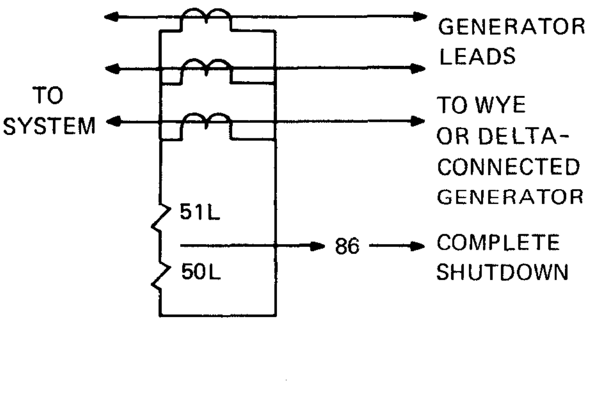
If scheme 11 is used in conjunction with scheme 10, it should, in general, be used for alarm purposes only, particularly in those cases where the generator ground relay shall be coordinated with other ground relays external to the generator protective zone. For example, if the generators of column E are grounded using method III, the time overcurrent relay (51) of scheme 10 may be set somewhat insensitively so as to coordinate properly with feeder ground relays. If so, some restricted faults may not be detected, and the generator ground relay will not trip. Device 50L of scheme 11 can usually be set to detect these faults. When an alarm is received (due to a scheme 11 relay operation), the operator may take such action as is required. When device 50L is applied in this manner, it will not only detect faults near the generator neutral that may not be sensed by device 51 of scheme 10, but will also serve as an alarm for feeder faults. This may be useful in some instances, particularly in the case of a stuck breaker. These same comments apply generally to other generator connections, such as in column B, where the machine is not isolated from the system by means of the delta winding of a generator stepup transfromer.

6.12 Scheme 12, Generator Leads Ground Overcurrent—Complete Shutdown. Protective scheme 12 may be used for ground detection for generators that are connected at generator potential to a grounded system. Table 1 indicates that this includes grounding methods I, II, VII, and VIII for wye-connected generators, and grounding methods VI, VII, and VIII for delta-connected generators. Scheme 12 may also be used for ground detection on ungrounded generators (grounding method VIII) that are connected to the system through an autotransformer with either a wound delta tertiary or a phantom tertiary.

Unit ground-fault protection is provided by an instantaneous and an inverse time overcurrent relay. They are supplied from current transformers in each phase which, connected in parallel, provide a residual current to the relays. The current transformers are positioned on the generator side of the generator synchronizing breaker.

There are two system conditions which should be satisfied with this relay application. First, with the three individual current transformers summed, some lack of symmetry is inevitable. This false residual current should be considered

Fig 12
Scheme 12, Generator Leads Ground Overcurrent—Complete Shutdown



when selecting and setting the overcurrent relays. The relays should coordinate for the maximum values of residual current possible during an external system phase fault with maximum infeed from the generator. Secondly, the relays should coordinate for the generator zone capacitance to ground-current contribution during an external system ground fault.

The pickup of the instantaneous relay 50L shall be set above the maximum current possible from either of the aforementioned. This restriction does not apply to the inverse time overcurrent relay 51L because of its inherent time-delay characteristics. This instantaneous relay will operate faster than the time overcurrent relay; however, it shall be set less sensitively.

The fault current detected by this scheme is the system contribution to a generator fault and not the contribution from the generator itself. When the unit is operating while disconnected from the system, the ground-fault current is limited below damage levels by the high-resistance grounding method. It is not feasible to attempt to recognize a ground fault in the zone under these conditions by overcurrent relaying which is supplied from residually connected current transformers sized to carry generator full-load current. Consequently, a voltage relay across the ground resistor, connected to the alarm or trip is more appropriate.

The advantage of scheme 12 is that the three separate current transformers can also be used for phase overcurrent relaying for overload or phase-fault protection.

6.13 Scheme 13, 3-Wire Generator Leads Window Current Transformer (ct) Instantaneous Ground Overcurrent—Complete Shutdown.

This relay scheme is a variation of scheme 12 but makes use of a window-type current transformer which surrounds the phase leads to the generator. This limits the scheme to relatively small generators based on the availability of window current transformer sizes. The current transformer (ct) measures the ground (zero squence) current in the generator leads during a ground fault. Unbalanced current in the generator leads which do not contain any ground (zero sequence) current will not appear in the current transformer output. This type of application has the advantage of allowing a ct ratio less than the ct rating required to carry generator full load. Another important advantage is that a window ct is subject to negligible secondary residual error current. The ct window should be physically sized to be no larger than needed to accommodate the generator leads. This reduces any error current to a negligible value from flux unbalance in the ct. Experience indicates that precise centering of the generator leads in the centroid of the ct is not critical.

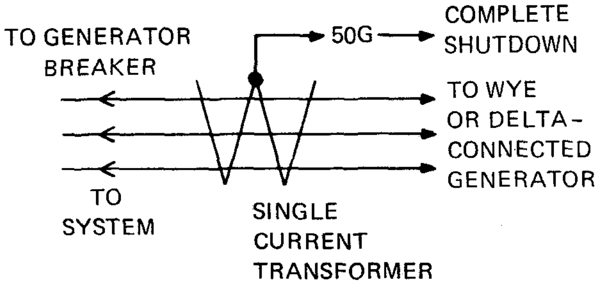


Fig 13
Scheme 13, 3-Wire Generator Leads Window ct, Instantaneous Ground Overcurrent—Complete Shutdown

With the system grounded, and the generator ungrounded or high-resistance grounded, the generator will contribute very little or no ground-fault current to an external fault. Therefore, the instantaneous relay device 50G can be set safely to a low value. A medium accuracy class ct with a ratio of 50/5 or 100/5 is typical. An instantaneous relay setting of 10-15 primary amperes has been found to be secure for ungrounded generators. A slightly higher setting may be required for a high-resistance grounded generator. For a ground fault on the generator side of this ct, the grounded system will provide current to operate the instantaneous relay. In this case, ct output results from the ground current in one generator lead producing flux in the ct which is not balanced out by the corresponding flux produced by current in the other generator leads.

The ability of this scheme to recognize ground faults at various locations in the generator stator, relative to the generator neutral, is related to the type of system grounding. For example, if the system limits the available ground current to 400 primary A, and if the instantaneous relay is set for 10 primary A, the relay can see a generator stator winding fault to within 2.5% of the neutral. If the available ground-fault current from the system is higher, the relay can see generator stator faults even closer to the neutral. However, it is important to note that the instantaneous relay is essentially a definite time device while heating at the fault is proportional to I^2t. Thus, greater sensitivity to stator faults near the generator neutral is obtained at the expense of increased burning for ground faults near the generator terminals due to higher fault current.

During external ground faults, capacitive ground current (zero-sequence current) will flow in the relay. The capacitance between the ct and the generator is usually small, but it should be considered. This may have an influence on the relay's pickup and therefore the sensitivity of the scheme. The major capacitance to ground considerations are cables, buses, surge capacitors, and the generator windings. If this capacitive ground current is significant, a time overcurrent relay, device 51G, should be used. This will provide the same primary ampere sensitivity with a short time delay.

It is important to note that window type cts (sometimes called *doughnut* cts) used in this type of application do not have much iron. The purpose for that is to keep the physical size of the ct small, so as to fit into certain space limits in switchgear. As a result, such cts have a poor saturation characteristic. It is necessary to test such a ct with its associated relay burden to determine the primary ampere pickup sensitivity of the package. For example, one supplier's package, which consists of an instantaneous plunger type relay and a 10/1 turns-ratio window ct, is guaranteed to pick up at 15 primary A with the relay set for 0.5 secondary A. Ideally, the primary ampere pickup is $0.5 \cdot 10/1 = 5$ primary A. Also, it is very important to note that when an induction overcurrent relay is used, the published time-current characteristics of the relay are not valid for this application. Here again, device 51G should be tested as a system to determine its actual time-current characteristics. This is particularly important when coordinating a device 51G relay, with backup ground relays so that for ground faults in the generator device 51G will operate first. The backup ground relays usually are connected to higher accuracy cts that permit the published time-current characteristic curves to be followed.

6.14 Scheme 14, 4-Wire Generator Leads Window Current Transformer (ct) Instantaneous Ground Overcurrent—Complete Shutdown. This relay scheme, often referred to as a generator *self-balancing* differential ground relay scheme, makes use of a window-type current transformer which surrounds the generator phase leads and the generator neutral lead. This scheme is similar in principle to scheme 13. The generator neutral lead passes through the current transformer, and is connected to point N toward the generator breaker side of the ct. Point N is then connected to the particular method of generator neutral grounding. With this arrangement, the ct output to device 50G is a measure of the ground current coming from the system and the generator for a ground fault in the generator. For a ground fault in the system external to the generator, current will not flow in device 50G.

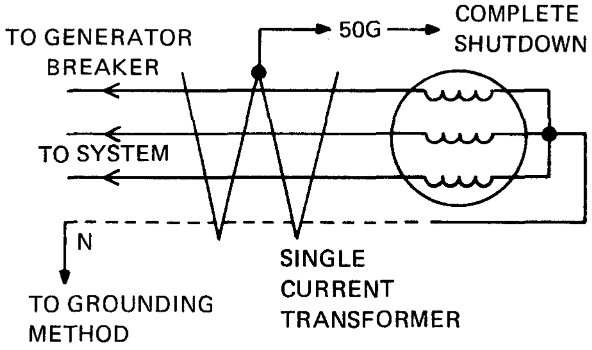


Fig 14
Scheme 14, 4-Wire Generator Leads Window ct, Instantaneous Ground Overcurrent—Complete Shutdown

6.15 Scheme 15, Generator Percentage Differential—Complete Shutdown. Protective scheme 15 is the conventional generator percentage differential protection for phase-to-phase faults. If the generator is connected to a solidly grounded system—either directly or through an autotransformer—10% generator differential relays will detect phase-to-ground fault within 10% to 15% of the generator neutral.

6.16 Scheme 16, Generator Percentage Differential and Polarized Neutral Overcurrent—Complete Shutdown. Protective scheme 16 is the conventional generator percentage-differential protection with the addition of a current polarized product type overcurrent relay. The relay is connected with its operating coil in the neutral of the differential relay circuit, and its

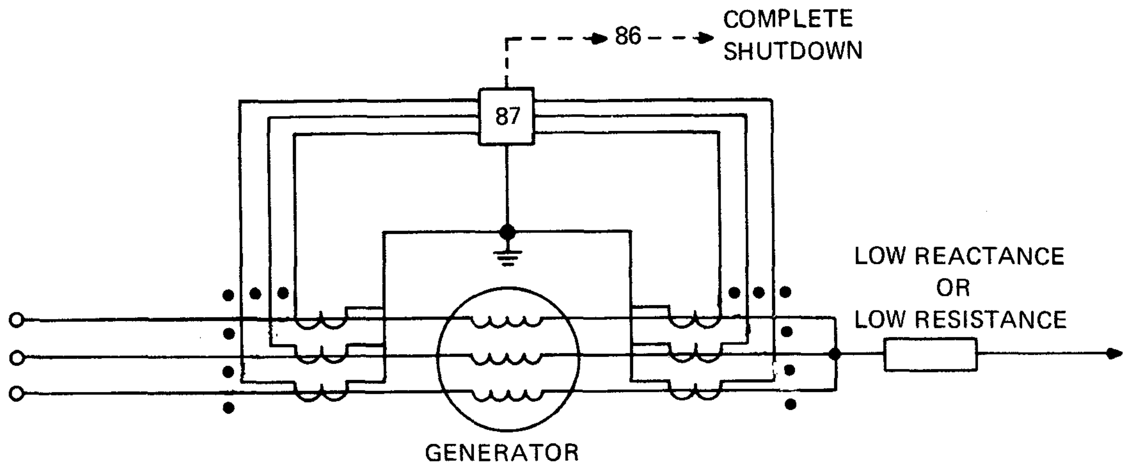
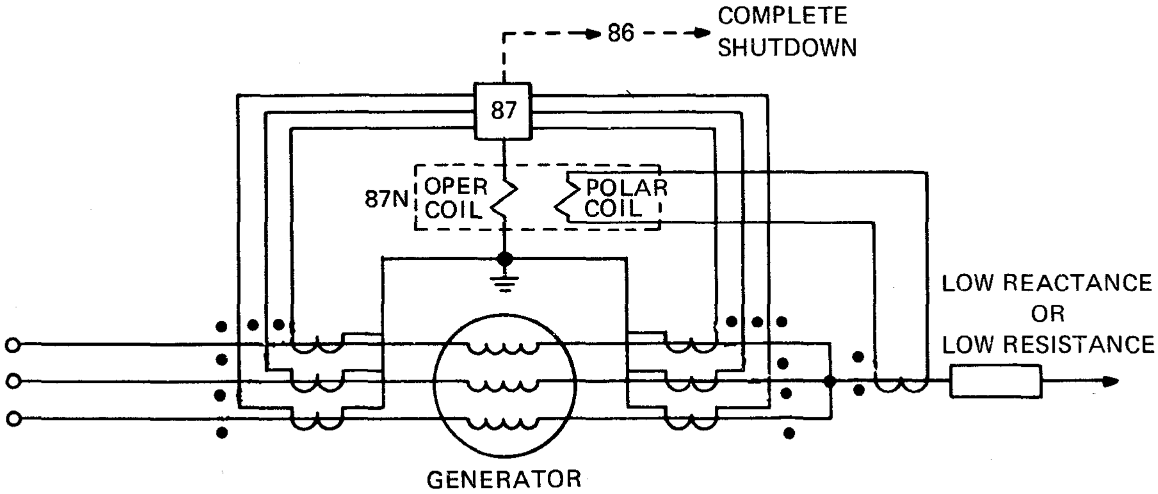


Fig 15
Scheme 15, Generator Percentage Differential—Complete Shutdown

polarizing coil is energized from a current transformer in the generator neutral. This relay provides additional sensitivity for phase-to-ground faults in the generator stator winding and prevents operation on current transformer error current for external phase-to-phase and three-phase faults. A polarized relay provides greater sensitivity without excessive burden to the operating coil.

6.17 Scheme 17, Delta-Connected Generator, Generator Percentage Differential—Complete Shutdown. Protective scheme 17 is the conventional differential protection for a delta-connected generator. If the generator is connected to a solidly grounded system that ensures sufficient ground current to reliably operate the differential relays, no other ground-fault protection is required. However, if under contingency system conditions, sufficient ground current cannot be ensured, differential protection should be supplemented by sensitive ground-fault protective schemes such as scheme 12 or 13. Scheme 5S or 8S may be used to detect generator grounds when the machine is running with its circuit breaker open.

Fig 16
Scheme 16, Generator Percentage Differential and Polarized Neutral Overcurrent—Complete Shutdown



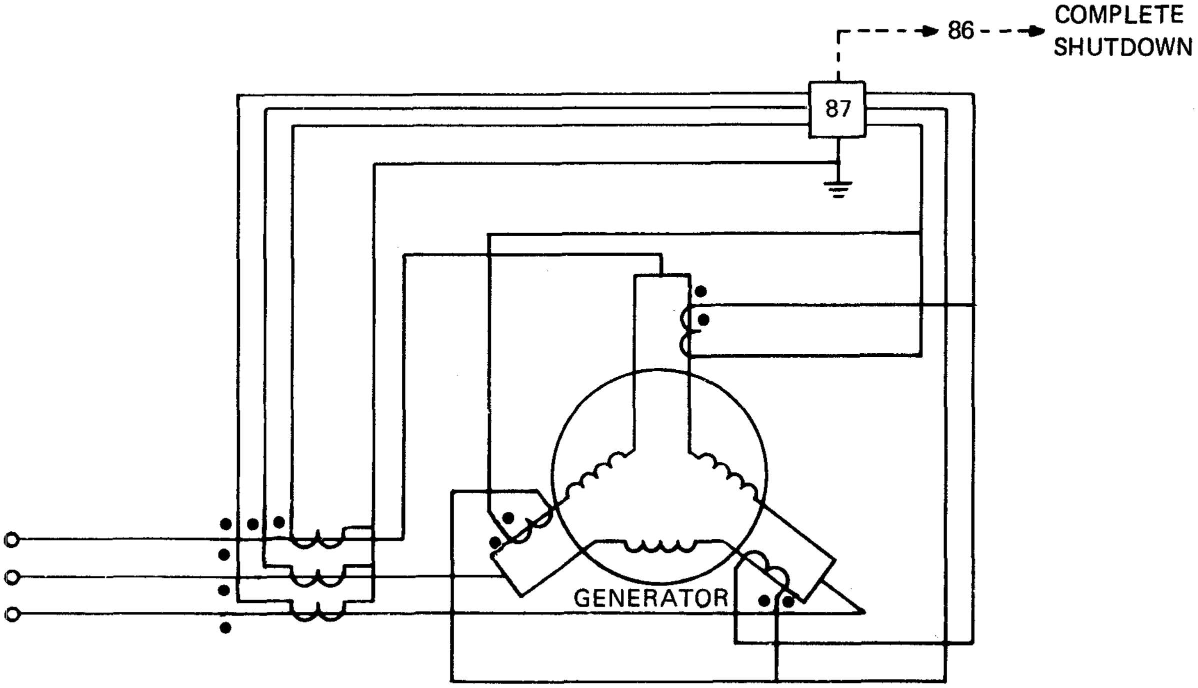


Fig 17
Scheme 17, Delta-Connected Generator, Generator Percentage Differential—Complete Shutdown

7. Protective Device Function Numbers

All of the different protection schemes illustrated in Figs 1-17 and described in Section 6 utilize protective relays that are represented or designed by device function numbers. It is the purpose of this section to define, in broad terms, the required characteristics of the relays designated by these numbers. Specific definitions for device numbers are found in ANSI/IEEE C37.2-1979, [1].

Device 2. This is a dc operated auxiliary time-delay relay. The range of adjustment, if any, should be selected to accommodate the desired time delay.

Device 27. This is an instantaneous 3rd harmonic undervoltage relay.

Device 50G. This is an instantaneous overcurrent relay that is designed in coordination with the associated toroidal current transformer to have a very sensitive pickup capability.

Device 50H. This is an instantaneous overcurrent relay having a pickup range that encompasses the magnitude of fault current that would result for a single-phase-to-ground fault at the terminals of the generator. There is no need to desensitize this device to 3rd harmonic current because of its relatively high pickup setting.

Device 50L. This is a standard instantaneous overcurrent relay. Its range of pickup adjustment is such that it can be set to pick up above any false residual current resulting from current transformer saturation during faults beyond the generator main circuit breaker.

Device 51. This is a sensitive time overcurrent relay, the time delay of which is inversely related to the magnitude of the input current to the device. The sensitivity of this device to fundamental current is such that, in conjunction with the current transformer to which it is connected, it will detect single-phase-to-ground faults in the generator stator winding to within a few percent of the distance to the neutral of the winding. The sensitivity of this relay to 3rd harmonic current should be such that the maximum 3rd harmonic current that flows in the generator should not cause it to operate. This relay should be capable of coordinating with the primary and secondary fuses that are used with any voltage transformers connected to the generator leads, where such coordination is desired. Examples of fuse and relay coordination are found in Appendix B.

Device 51I. This is a time delayed overcurrent device that is only sensitive to lower than fundamental frequencies.

Device 51L. This is a standard time overcurrent relay, the time delay of which is inversely related to the magnitude of the input current. The pickup range is such that the relay can be set to pick up above any false residual current resulting from current transformer saturation during faults beyond the main circuit breaker of the generator.

Device 59. This is a time delay overvoltage relay that is designed to be very sensitive to fundamental frequency voltage but insensitive to 3rd and higher harmonics. The sensitivity to fundamental frequency voltage should enable the device to detect single-phase-to-ground faults to within a few percent of the distance to the neutral end of the winding. In general, the relay will not be suitable to detect faults at, or very close to, the neutral point. Because this relay will be able to detect phase-to-ground faults in the primary and secondary circuits of any voltage transformer connected between the generator leads and ground, the time delay associated with it should be suitable to coordinate with the voltage transformer primary and secondary fuses. In some cases, because of the sensitivity of this relay, it may not be able to withstand, for a prolonged period, the maximum value of voltage to which it may be exposed in the event of a single-phase-to-ground fault at the generator terminals. This should be investigated if this device is used for alarm purposes, or if the tripping is delayed by some external time delay for any reason.

Device 59C. This is an ordinary instantaneous overvoltage relay having a pickup range of 50% to 70% of nominal terminal voltage. Its purpose is to monitor fundamental frequency voltage at the terminals of the generator to determine when the main generator breaker has closed or when field excitation has been applied.

Device 59D. This is an instantaneous 3rd harmonic voltage differential relay.

Device 59H. This is an overvoltage relay with no intentional time delay required. It should have a pickup range at a fundamental frequency voltage somewhat lower than the continuous rating of the associated 59 device. It should not operate as a result of the maximum zero-sequence harmonic voltage present during normal conditions. The purpose of the 59H device is to protect the associated device 59 during a single-phase-to-ground fault that produces voltage in excess of its continuous rating.

Device 59I. This is an instantaneous overvoltage relay, very sensitive to the fundamental frequency voltage and to somewhat lower frequencies, but insensitive to the 3rd and higher harmonics. See Device 59 for additional information.

Device 59S. This device is intended to provide for protection against single-phase-to-ground faults during the time that the generator is not connected to the system. This includes those intervals when the machine is being brought up to speed or being shut down, with field excitation applied. During these periods the machine voltage magnitude and frequency will be below normal. For this reason the 59S device should have a pickup characteristic that is essentially proportional to frequency. Because the relay is only in service when the main circuit breaker of the machine is open, no coordination with other protective devices is required, and a high speed, sensitive relay may be applied. A device having a constant volts/hertz pickup is desirable for this application.

Device 59T. This is an instantaneous overvoltage relay sensitive to the 3rd harmonic component.

Device 59X. This is an ac operated, self-reset multicontact auxiliary relay.

Device 86. This is a hand reset, multicontact, dc operated auxiliary relay.

Device 87. This is a conventional generator percentage differential relay.

Device 87H. This is a very sensitive, high-impedance phase and ground differential relay, whose sensitivity is independent of the load current and requires no coordination with external relays and devices.

Device 87N. This is basically a sensitive, short-time, product-type time overcurrent relay with two coils: an operating coil, and a polarizing coil. The relay operates when the current in the two coils have the proper relative phase angle, and the magnitude of the product of the current in the two coils exceeds the pickup setting.

Device 87NH. This is a very sensitive, single element, high-impedance differential relay measuring the residual ground differential quantity. The relay sensitivity is independent of load current and requires no coordination with external relays and devices.

Appendixes

(These Appendixes are not a part of ANSI/IEEE C37.101-1985, IEEE Guide for Generator Ground Protection.)

Appendix A
Generator Ground Protection; Other Practices

It is the purpose of this Appendix to identify briefly other reported generator ground-fault protective relay schemes which are nonstandard, special, unique, or not extensively used in the United States at this time. These schemes are interpretations of available documentation or combinations thereof, and are included as a matter of information only.

Where explicit application details may be missing in this Appendix, it is anticipated that the interested reader will pursue necessary application details from other sources. The listed references from which the information included in this Appendix has been drawn, provide some guidance for that purpose.

A1. Ground-Fault Relays for the Complete Generator Stator Winding

In the group of generator protective ground relays that are covered by this Appendix, there are schemes that provide 100% coverage of the stator winding for ground faults. These designs use different measuring quantities in addition to, or in lieu of, those previously discussed in the guide. They do not necessarily use the generator ground-fault current contribution for detection of the ground fault. For example, the lack of generator 3rd harmonic neutral voltage or an increase in the terminal 3rd harmonic residual voltage, or both, are used in some of these relay schemes to detect ground faults or deterioration of the insulation close to the neutral. In other schemes, an additional voltage source is connected to the generator neutral to produce a detectable flow of current upon the occurrence of a ground fault anywhere in the generator stator winding.

The importance of detecting ground faults close to the neutral point of the generator is not dependent on the need to trip because of fault-current magnitude, since it may be negligible and will not, in general, cause immediate damage. If a second ground fault occurs, the two ground faults combined can cause severe damage to the machine because the second ground fault can give rise to a short-circuit current not limited by the normal grounding impedance. This condition is aggravated if the first ground fault occurs close to, or at, the neutral of the generator, as all ground relays operating from the neutral point voltage or current become inoperative. Furthermore, if the second ground fault occurs in the same winding, the generator differential relay may also become inoperable since this condition can be regarded as an internal turn-to-turn fault. This fault is detected, for example, by a negative sequence current relay and—if large enough—by overcurrent back-up relays. Although desirable, instantaneous detection is not generally available for this type of fault.

The schemes reviewed involve the use of

(1) Third harmonic neutral voltage

(2) Third harmonic terminal to ground residual voltage

(3) Third harmonic ratio differential quantities

(4) Neutral or residual voltage injection

There are often differences in tripping philosophy for 100% relays versus other ground-fault relays with respect to the fault location. These practices consider the amount of ground-fault current flowing and the capability of the machine to cope with the fault current. Some utilities may elect to trip the machine regardless of the location of the ground fault in the stator winding or the size of the machine. Others may trip large baseload units with the conventional ground-fault relay only, and the alarm with the relay that detects faults in the neutral region, so as to permit inspection and possible repair during normal shutdown for maintenance.

If a second ground fault develops, the risk of more severe damage is accepted in order to maintain service. However, it is generally desirable to trip the machine regardless of fault location if there are no means for instantaneous detection and tripping of double ground faults.

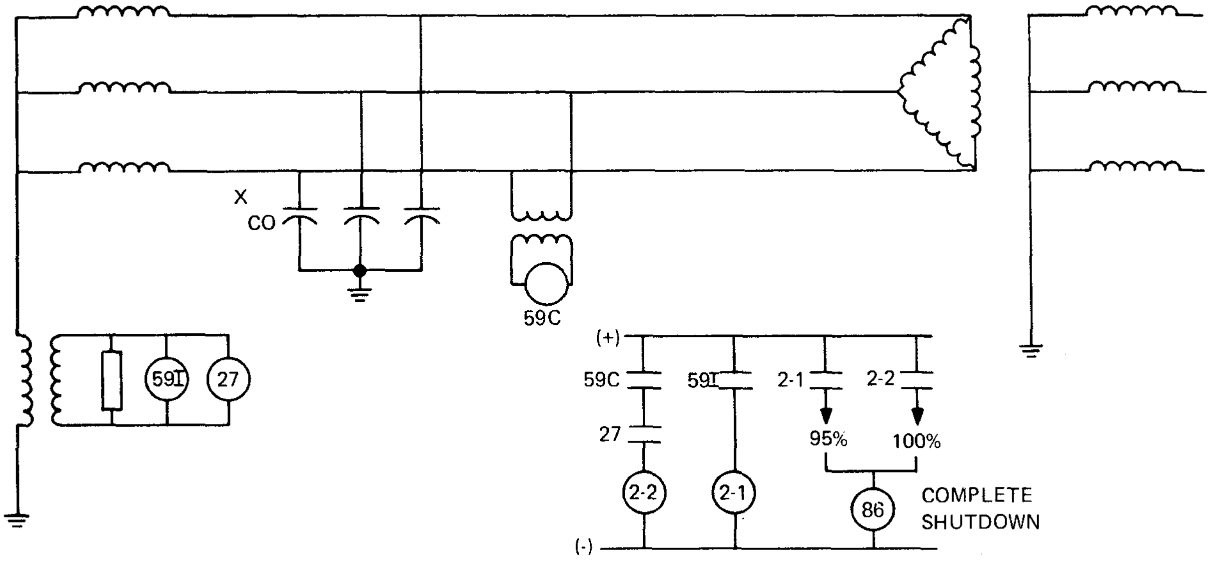


Fig A1
Scheme A, 3rd Harmonic Neutral Voltage

A1.1 Scheme A, 3rd Harmonic Neutral Voltage. This scheme uses relay element 27 to detect the lack of 3rd harmonic voltage at the neutral point in addition to the fundamental neutral overvoltage element 59I. It offers the advantage of not requiring any additional HV equipment other than that needed for conventional ground-fault detection schemes for single-stator generators. The scheme can also be used for cross compound and split winding machines by adding a second voltage transformer and 3rd harmonic relay to monitor the 3rd harmonic voltage at the neutral of the ungrounded stator winding. The scheme also provides protection when the main breaker is open, provided that the terminal voltage is above the set level on relay 59C. Typically, not more than 1% of 3rd harmonic voltage with reference to rated voltage is needed, and normally 10%—30% of the stator winding from the neutral point towards the machine terminal can be protected. This offers excellent overlap with the conventional 95% overvoltage relay 59I, which is a required part of the scheme to provide full protection.

A1.2 Scheme B, 3rd Harmonic Terminal to Ground Residual Voltage. Like scheme A, scheme B supplements the conventional 95% relay 59I, to provide 100% protection for ground faults in the generator stator winding. This scheme is also intended primarily for high-impedance grounded machines, provided that approximately 1% of 3rd harmonic voltage is generated by the machine. This 3rd harmonic voltage is distributed between the terminal capacitance and the grounding impedance of the machine.

A broken-delta-connected secondary-voltage transformer winding provides the input to the 3rd harmonic overvoltage relay 59T, which measures the residual 3rd harmonic to ground zero-sequence voltage at the machine terminals. The relay is set above the maximum machine or system 3rd harmonic voltage possible at the machine terminal during normal generator operation.

The 3rd harmonic terminal overvoltage relay will operate for a ground fault in the vicinity of the neutral of the stator winding. Upon occurrence of a fault, the major impedance for the 3rd harmonic current will be the terminal capacitance of the machine, since the grounding impedance is short circuited to ground by the fault. The 3rd harmonic voltage generated by the machine will be redistributed, with the major portion appearing at the machine terminal.

Since the 3rd harmonic component increases with the machine output current and during external faults on the power system, time coordination with other system relays is often necessary. Full generator stator winding ground-fault protection is only ensured when the generator output current is above a certain value.

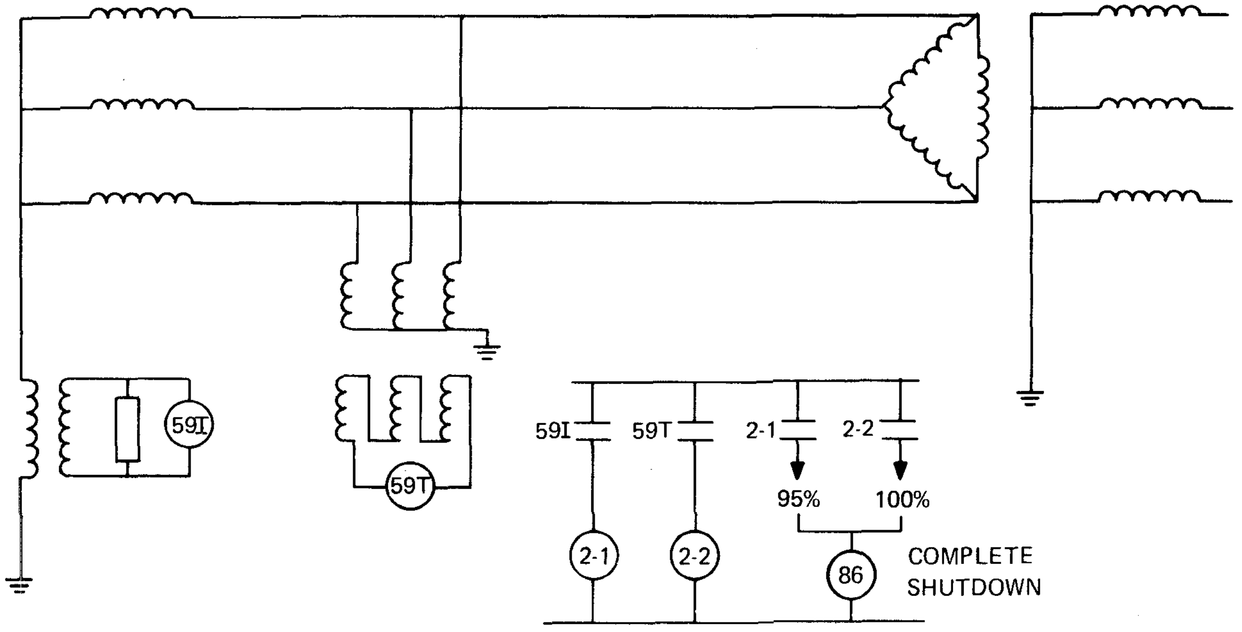


Fig A2
Scheme B, 3rd Harmonic Terminal to Ground Residual Voltage

To ensure full stator coverage, two relays are required in scheme B. The relay settings have to be determined during commissioning, after tests have been completed. Normally, good overlapping protection can be expected only when the machine is heavily loaded.

A1.3 Scheme C, 3rd Harmonic Ratio Differential Quantities. Like schemes A and B, this scheme also supplements the conventional 95% relay to provide 100% coverage for ground faults in the generator stator winding. This scheme was also designed primarily for high-impedance grounded machines.

Scheme C utilizes the fact that the 3rd harmonic residual voltage at the terminals of a machine increases, while the 3rd harmonic voltage at the neutral decreases, for a fault near the neutral. It was formerly believed that the ratio of the 3rd harmonic residual voltage to the neutral 3rd harmonic content is nearly constant for all load conditions on an unfaulted machine. However, experience has recently proven that the ratio of 3rd harmonic current is not constant over the load range of the machine. This complicates the application of this type of relay and may necessitate a reduced sensitivity setting and overlap between the two relay functions 59I and 59D. The settings for both relays should be determined during field testing in conjunction with commissioning. The 3rd harmonic differential relay 59D detects ground faults near the neutral, while relay 59I, which measures the fundamental neutral voltage, protects the upper portion of the winding. The differential relay sensitivity is maximum for a fault at the neutral point and decreases proportionally as the fault location moves toward the line terminals. At some point on the winding, the difference between the neutral and terminal 3rd harmonic voltages is equal to the relay setting. Double ground faults tend to reduce the sensitivity for the differential relay, and multiwinding machines offer application difficulties that require careful consideration.

A1.4 Scheme D, Neutral or Residual Voltage Injection. Schemes using voltage injection at the neutral, or residually in the broken-delta voltage transformer (vt) secondary, can detect ground faults anywhere in the stator winding of the generator, including the neutral point. Full ground-fault protection is available when the generator is on turning gear and during startup, if the injected voltage souce does not originate from the generator. Certain schemes inject a coded signal at a subharmonic frequency which can be synchronized with the system frequency (for example, $\frac{1}{4}$ rated frequency). This coding improves the security of the relay

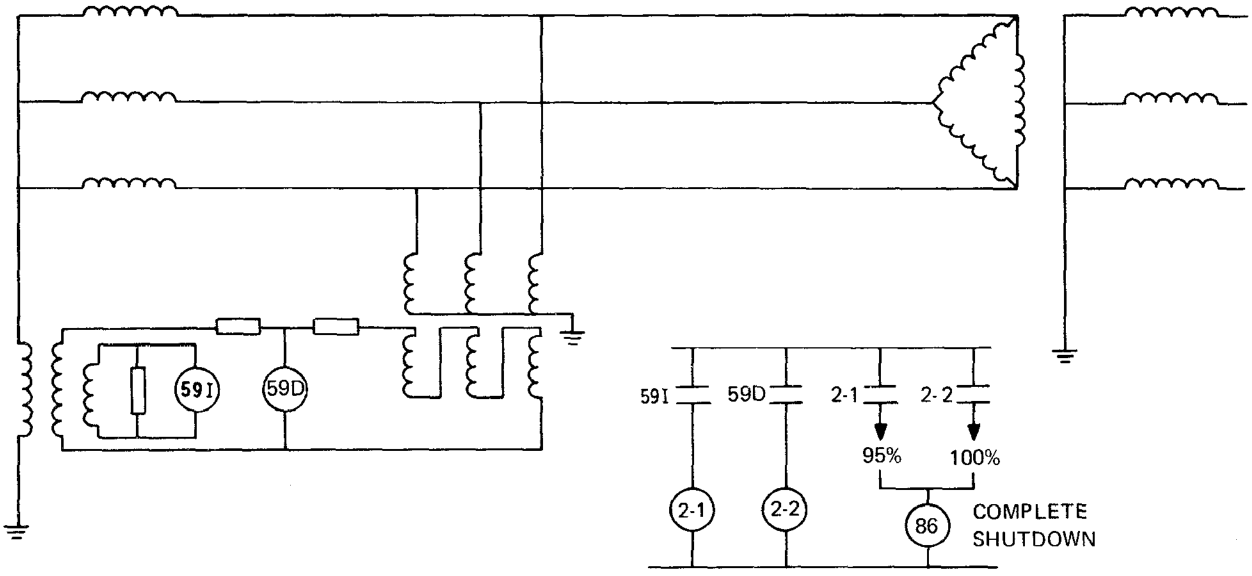


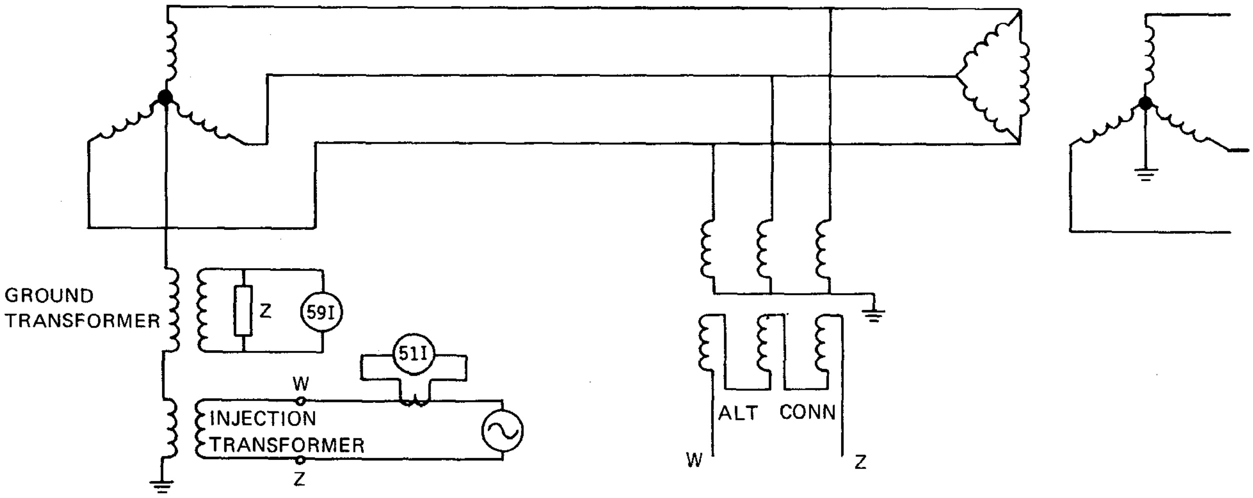
Fig A3
Scheme C, 3rd Harmonic Ratio Differential Quantities

system, without sacrificing dependability, when compared to other injection schemes. For proper relay performance, the scheme is dependent on a reliable subharmonic source, usually derived from the station battery. The use of subharmonic frequencies may offer improved sensitivities due to the higher-impedance path of the generator capacitances at these frequencies. Such frequencies are not normally present at the generator neutral.

Schemes injecting fundamental frequency voltage require relatively large signal power due to the lower impedance involved. System disturbances at the fundamental frequency can cause false operation unless precautions are taken to provide additional security. However, these schemes may still provide 100% protection.

A feature of neutral injection schemes is that they provide 100% ground-fault protection

Fig A4
Scheme D, Neutral or Residual Voltage Injection



independently of the 95% ground-fault protection schemes. In addition, some of these injection schemes are self-monitoring. The majority of these injection schemes are independent of load current, system voltage, and frequency.

In applying neutral injection schemes, consideration should be given to the additional neutral transformer required. This transformer should be designed so as not to interfere with the insulation coordination of the generator system.

A2. Restricted Ground-Fault Relays

A2.1 Scheme E, High-Impedance Generator Differential for Phase or Ground Faults. Scheme E uses a high-impedance differntial relay, device 87H, for phase- and ground-fault protection. The use of high-impedance differential relays for phase faults in generators provides additional security against malfunction due to current transformer (ct) saturation during external faults. These relays also provide high-speed tripping and, in many cases, provide excellent ground-fault coverage of the stator winding.

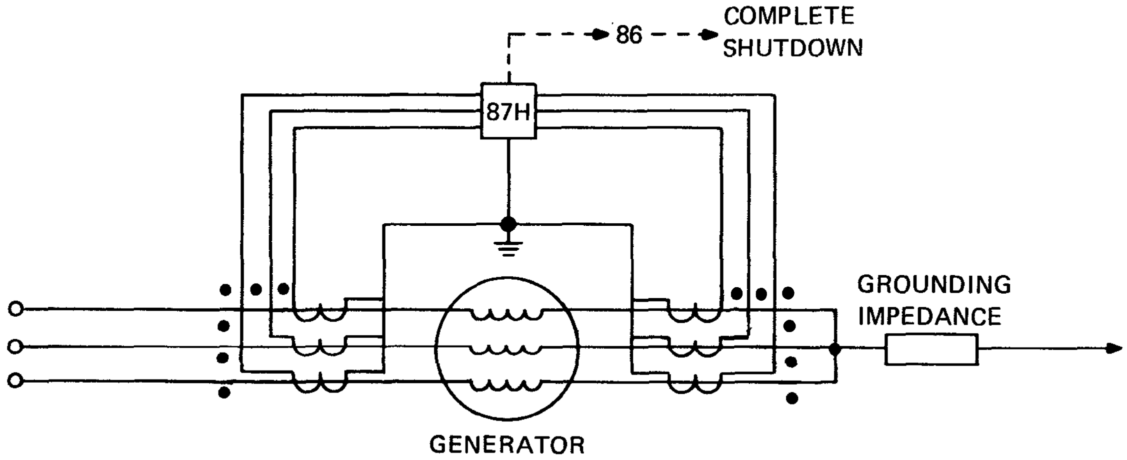
Normally, a sensitivity of approximately 1% of rated current can be obtained, which means that the coverage for ground faults is dependent upon the grounding impedance. Relays which operate for current between 1 mA and 200 mA are available. Since the relay does not restrain on the load current, the same sensitivity is maintained for all load conditions.

These relays are usually set with a voltage value equal to the calculated maximum secondary through fault current times the maximum ct loop impedance in parallel with the relay, plus a margin. The margin is determined by the relay engineer, based on the manufacturer's recommendations for the relay involved. Also note that the calculated setting shall not exceed 50% of the saturation voltage of the current transformers to which relays are connected. The high-impedance relay is normally provided with overvoltage protection in the form of nonlinear resistors in parallel with the relay. Depending on the resistor size, short circuiting of the differential circuit following relay operation may be required to prevent damage.

A2.2 Scheme F, Residual High-Impedance Generator Differential. Scheme F is a variation of scheme E, which uses a separate single high-impedance element to detect ground faults only in the machine. Two alternate connections are shown. The first uses all phase-current transformers on both sides of the machine, the second uses a neutral-current transformer on the neutral side of the machine. The same setting procedures are used as described under scheme E.

A2.3 Scheme G, Residual High-Impedance Generator Differential and Generator Percentage Differential. Scheme G is a variation of schemes E and F for the detection of both phase and ground faults. Ground-fault protection is provided by a single high-impedance element connected in the neutral of the conventional percentage restraint phase differential relays. The same setting procedures are used as described under scheme E.

Fig A5
Scheme E, High-Impedance Generator Differential for Phase or Ground Faults



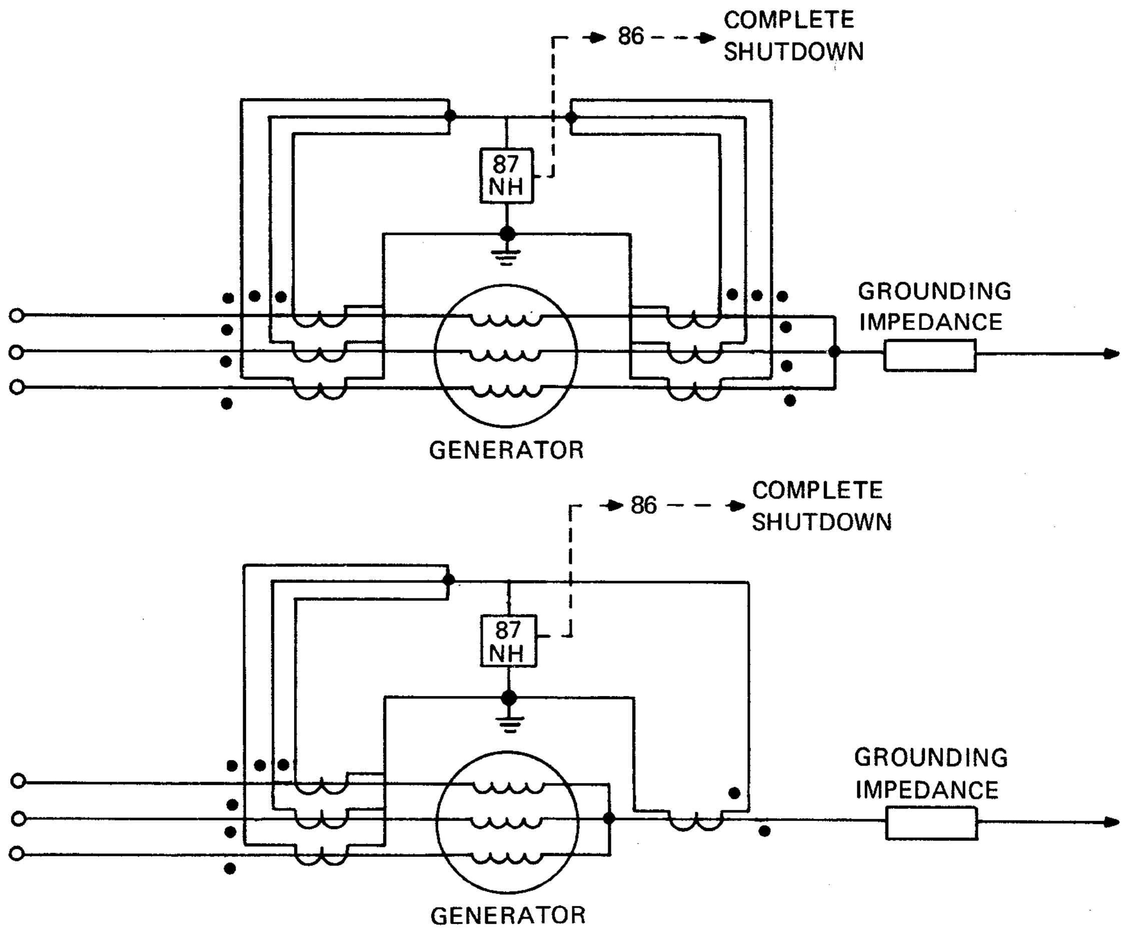


Fig A6
Scheme F, Residual High-Impedance
Generator Differential

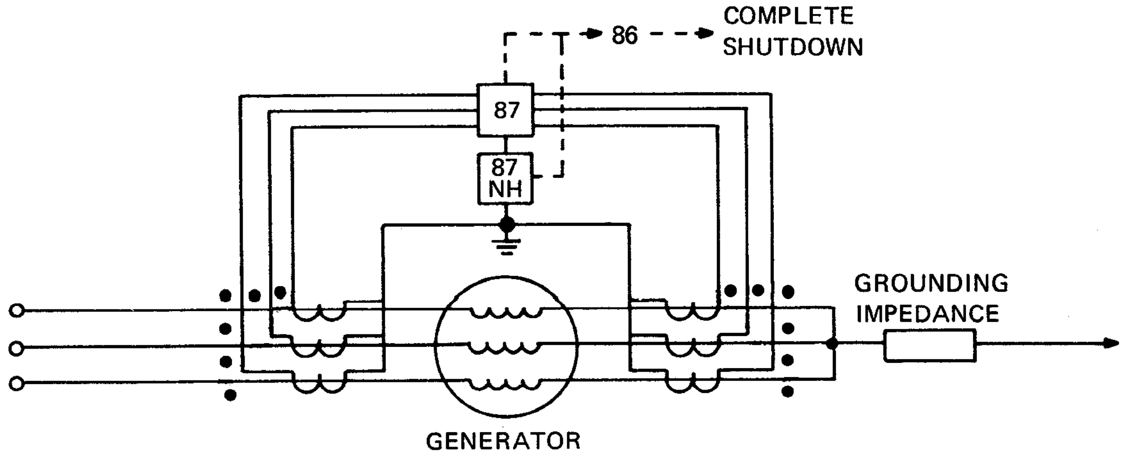


Fig A7
Scheme G, Residual High-Impedance Generator Differential and
Generator Percentage Differential

Appendix B
Generator Ground Protection Examples

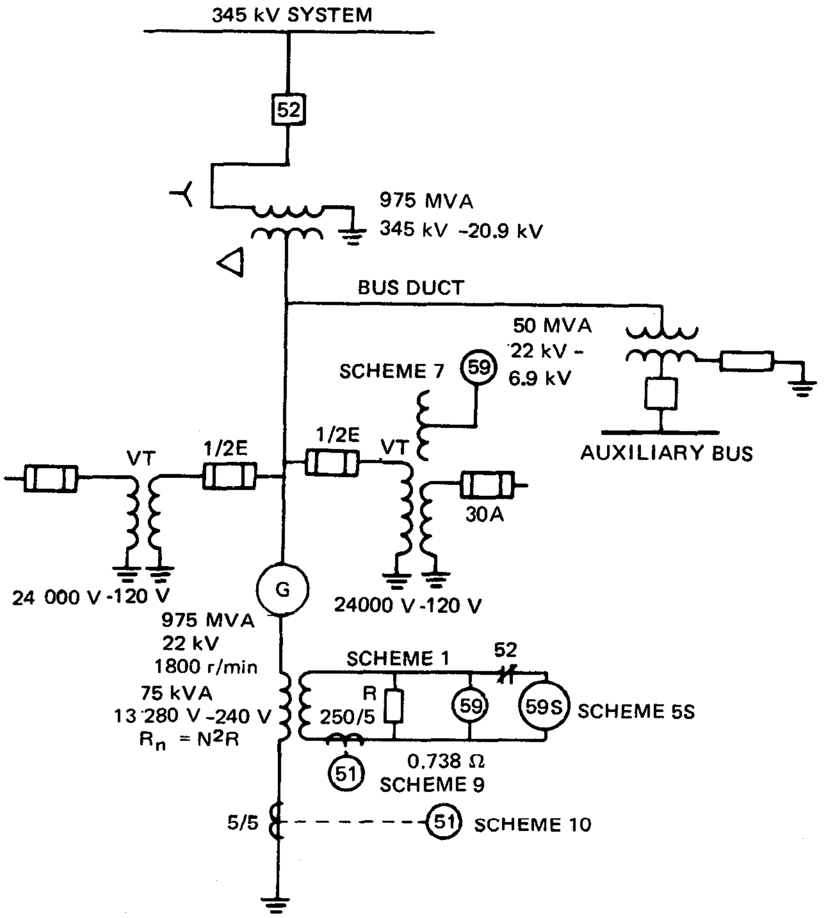
A 974 MVA, 22 kV generator is unit-connected to a 345 kV transmission bus and grounded through a distribution transformer as shwon in Fig B1. The phase-to-ground capacitive reactance of the generator, transformers, leads, and associated equipment is 6780 Ω per phase. The distribution transformer is rated 13 280 V – 240 V. The secondary resistor is 0.738 Ω. The secondary resistance reflected to the primary circuit is (R secondary) • (turns – ratio squared).

$$R_n = 0.738 \left(\frac{13\,280}{240}\right)^2 = 2260\ \Omega$$

Fault current and voltages are calculated by two methods: symmetrical component analysis, and with the aid of phasor diagrams.

B1. Symmetrical Components Solution. With symmetrical components, phase-to-ground faults are calculated by connecting the positive, negative, and zero-sequence networks in series as shown in Fig B2(a) and solving for I_0. Thus, the equivalent positive and negative sequence impedances of the system and the zero-sequence impedance of the generator are extremely small, as compared to the neutral resistor equivalent circuit and the distributed

Fig B1
Typical Generator Ground Protection
One Line Diagram



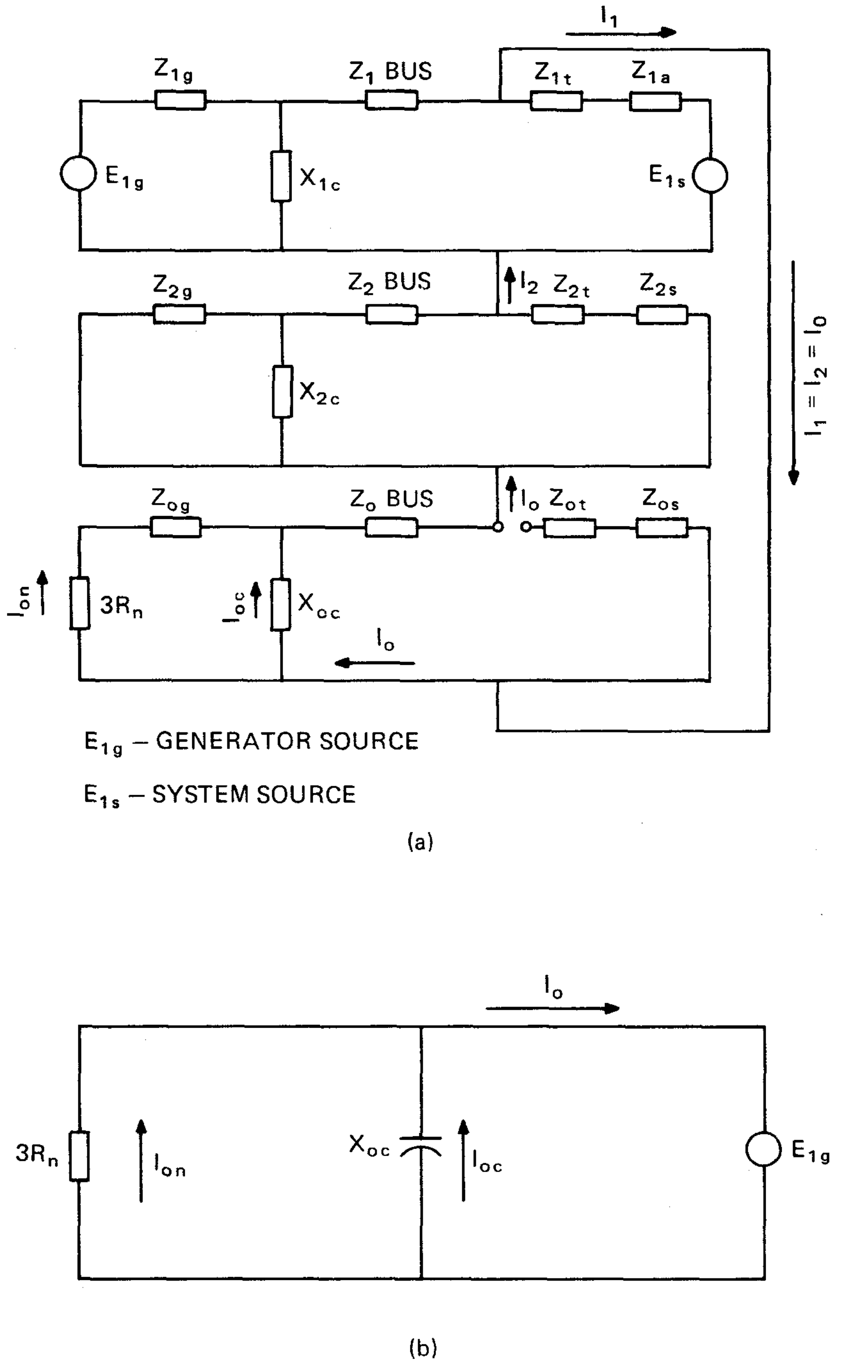


Fig B2
Phase to Ground-Fault Symmetrical Component Equivalent Circuits
(a) Symmetrical Component Equivalent Circuit
(b) Reduced Symmetrical Component Equivalent Circuit

zero-sequence capacitance, and therefore can be neglected. For a unit-connected generator, the zero-sequence network is open at the Δ winding of the power transformers and consists of the generator neutral resistor and the phase-to-ground capacitance of the generator windings and associated equipment. The equivalent circuit will then be that shown in Fig B2(b).

$I_o = I_{on} + I_{oc}$

I_o = total zero-sequence fault current

I_{on} = zero-sequence current flowing in the neutral resistor

I_{oc} = zero-sequence current flowing in the distributed capacitance

The total fault current I_f is equal to $3I_o$, which is equal to $I_n + I_c$.

The current through the generator neutral is

$$I_n = 3I_{on} = \frac{3E_{lg}}{3R_n} = \frac{E_{lg}}{R_n}$$

The fault-current contribution from the capacitance is

$$I_c = 3I_{oc} = \frac{3E_{lg}}{-jX_c} = \frac{j3E_{lg}}{X_c}$$

E_{lg} = generator phase-to-neutral voltage

$E_{lg} = 22\,000/\sqrt{3} = 12\,700$ V

$R_n = 2260\ \Omega$

$I_n = 12\,700/2260 = 5.62$ A

$$I_c = j\frac{12\,700 \cdot 3}{6780} = j5.62 \text{ A}$$

$I_f = 5.62 + j5.62 = 7.95\angle 45^\circ$ A

I_n is the current flowing in the generator neutral for a single phase-to-ground fault at the generator terminals. The current I_s flowing in the distribution transformer secondary wiring and through the resistor is the generator neutral current multiplied by the turns ratio of the distribution transformer.

$$I_s = 5.62 \cdot \frac{13\,280}{240} = 311 \text{ A}$$

The voltage across the secondary resistor is

$$\begin{aligned} V_R &= I_s R = 311 \cdot 0.738 \\ &= 229.5 \text{ V} \end{aligned}$$

B2. Phasor Diagram Analysis. The single line diagram for the equivalent phase-to-ground capacitance of the generator windings, bus duct, and generator step-up transformers is shown in Fig B3(a). In a balanced three-phase system, the neutral current will be zero, as illustrated in Fig B3(b). The capacitive current in each phase is

$$\begin{aligned} I_{cx} &= \frac{E_x}{-jX_c} = \frac{12\,700\angle 0^\circ}{6780\angle -90^\circ} \\ &= 1.87\angle 90^\circ \text{ A} \end{aligned}$$

$$\begin{aligned} I_{cy} &= \frac{E_y}{-jX_c} = \frac{12\,700\angle 240^\circ}{6780\angle -90^\circ} \\ &= 1.87\angle 330^\circ \text{ A} \end{aligned}$$

$$\begin{aligned} I_{cz} &= \frac{E_z}{-jX_c} = \frac{12\,700\angle 120^\circ}{6780\angle -90^\circ} \\ &= 1.87\angle 210^\circ \text{ A} \end{aligned}$$

The sum of the current is

$I_c = I_{cx} + I_{cy} + I_{cz}$

$$\begin{aligned} I_c &= 1.87\angle 90^\circ + 1.87\angle 330^\circ + 1.87\angle 210^\circ \\ &= 0 \end{aligned}$$

If we place a line-to-ground fault on phase x between the generator stator terminals and the bushings of the generator stepup transformer, the equivalent circuit will be shown in Fig B3(c) and B3(d).

To obtain the fault current I_f, the following loop equations may be written

A1: $E_x - I_1(-jX_c) + I_2(-jX_c) - E_y = 0$

A2: $E_x - E_y - I_1(-jX_c) + I_2(-jX_c) = 0$

B1: $E_y + I_1(-jX_c) - I_2(-jX_c) - I_2(-jX_c) - E_z = 0$

B2: $E_y - E_z + I_1(-jX_c) - 2I_2(-jX_c) = 0$

C1: $-I_3R_n - E_x = 0$

C2: $I_3 = \dfrac{-E_x}{R_n}$

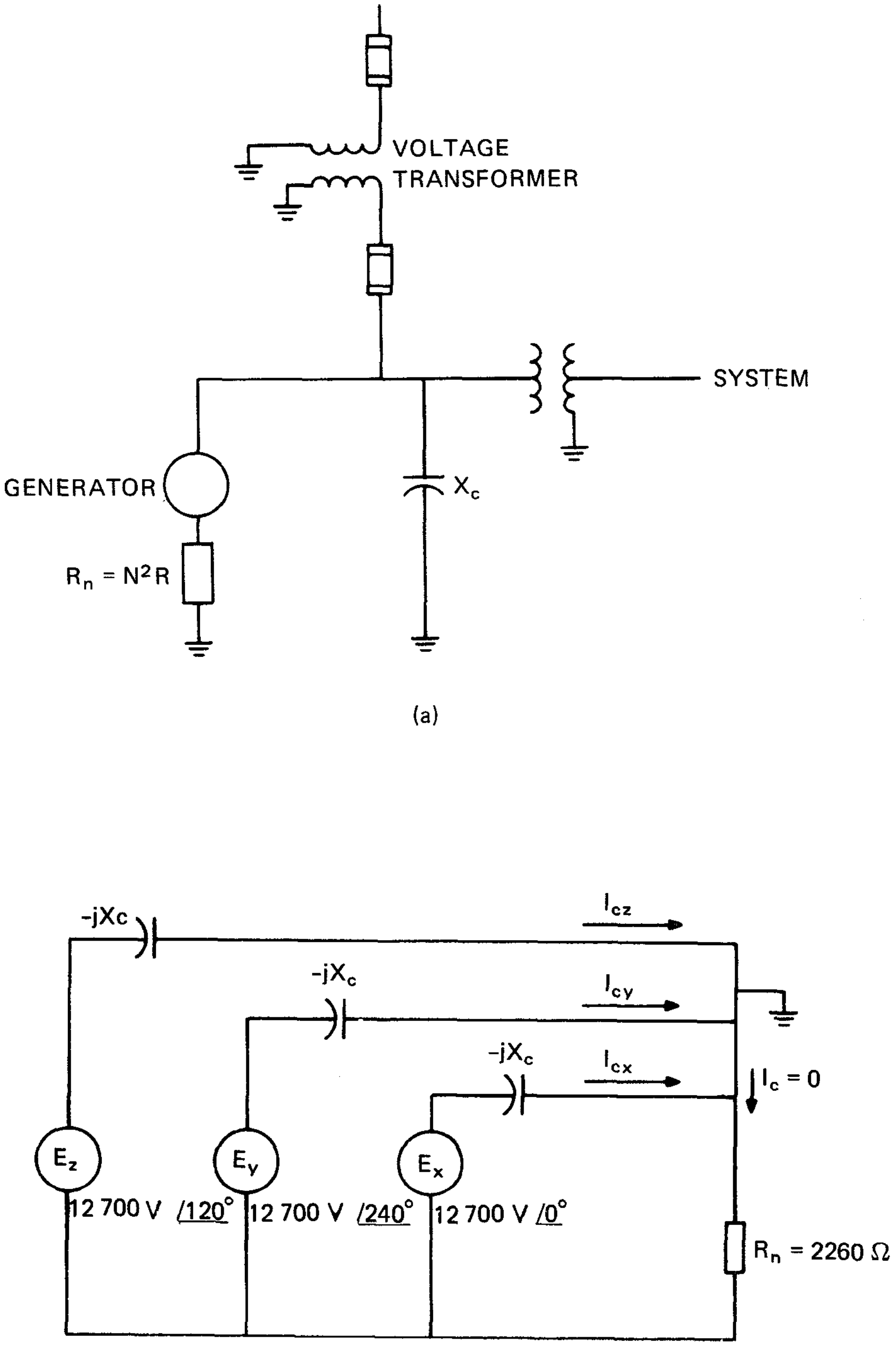
Adding Eqs A2 and B2

$E_x - E_z - I_2(-jX_c) = 0$

$$I_2 = \frac{E_x - E_z}{-jX_c}$$

Substituting for I_2 in Eq A2

$$I_1 = \frac{2E_x - E_y - E_z}{-jX_c} = \frac{3E_x}{-jX_c}$$



(a)

(b)

Fig B3
Phase to Ground-Fault Capacitive Reactance Equivalent Circuits and Phasor Diagrams
(a) Equivalent Single Line Diagram
(b) Normal Resistor Current During Balanced Load Conditions

From Figs B3(c) and B3(d):

$I_f = I_1 - I_3$

$I_{cy} = I_2 - I_1$

$I_{cz} = -I_2$

$E_x = 12\,700\underline{/0}° \text{ V}$

$E_y = 12\,700\underline{/240}° \text{ V}$

$E_z = 12\,700\underline{/120}° \text{V}$

$R_n = 2260\ \Omega$

$X_c = 6780\ \Omega$

$$I_{cy} = I_2 - I_1 = \frac{E_x - E_z}{-jX_c} + \frac{E_y + E_z - 2E_x}{-jX_c}$$

$$= \frac{E_y - E_x}{-jX_c}$$

$$I_{cy} = \frac{12\,700\underline{/240}° - 12\,700\underline{/0}°}{6780\underline{/-90}°}$$

$$= 3.24\underline{/300}° \text{ A}$$

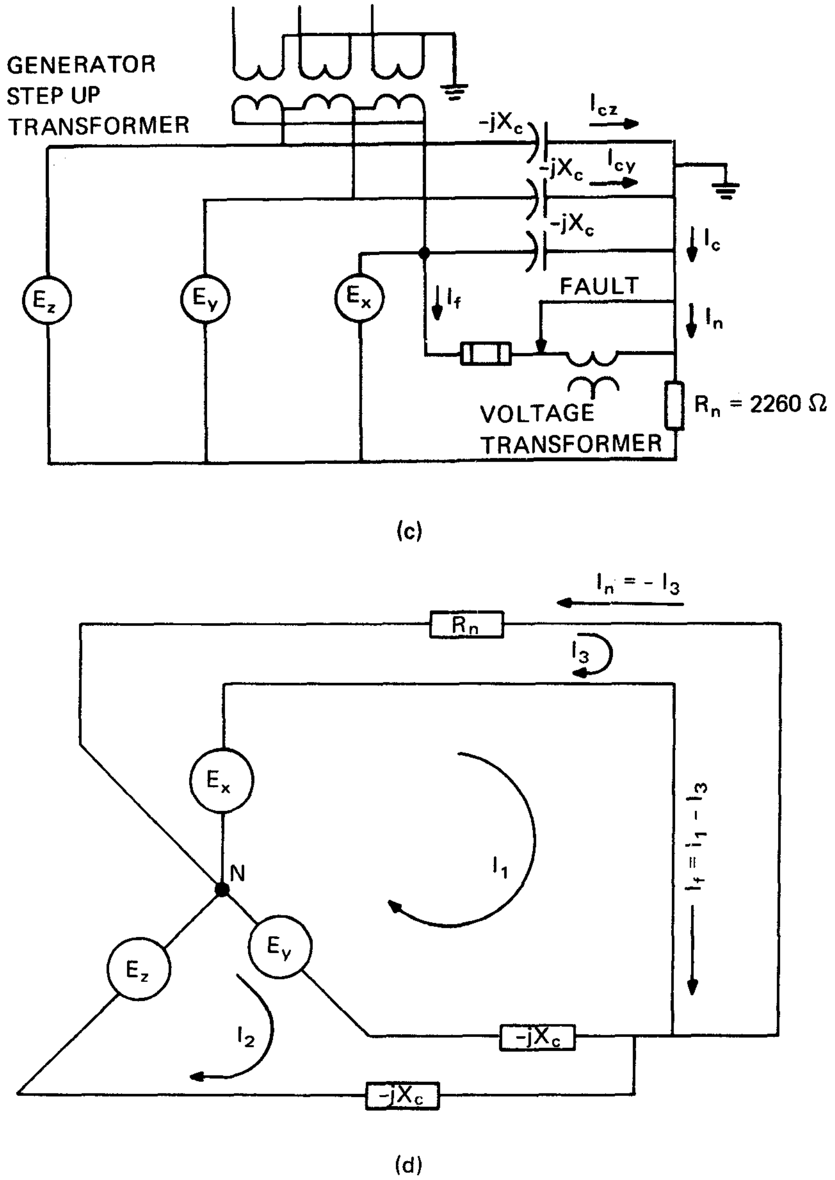


Fig B3 (*Continued*)
Phase to Ground-Fault Capacitive Reactance Equivalent Circuits and Phasor Diagrams
(c) Equivalent Network During Fault
(d) Loop Current Network for the System During Fault

$$I_{cz} = -I_2 = \frac{E_z - E_x}{-jX_c}$$

$$I_{cz} = \frac{12\ 700\underline{/120^\circ} - 12\ 700\underline{/0^\circ}}{6780\underline{/-90^\circ}}$$
$$= 3.24\underline{/240^\circ}$$

$$I_c = I_{cy} + I_{cz}$$
$$= 3.24\underline{/300^\circ} + 3.24\underline{/240^\circ}$$

$$I_c = 5.62\underline{/270^\circ}\text{ A}$$

The current in the generator neutral is

$$I_n = -I_3 = \frac{E_x}{R_n} = \frac{12\ 700\underline{/0^\circ}}{6780\underline{/0^\circ}}$$

$$I_n = 5.62\underline{/0^\circ}\text{ A}$$

From Fig B3(d) the total fault current is the sum of the capacitive and neutral current.

$$I_f = I_1 - I_3 = \frac{3E_x}{-jX_c} + \frac{E_x}{R_n}$$

$$I_f = 3 \cdot \left(\frac{12\ 700\underline{/0^\circ}}{6780\underline{/-90^\circ}}\right) + \frac{12\ 700\underline{/0^\circ}}{2260\underline{/0^\circ}}$$

$$I_f = 5.62\underline{/90^\circ} + 5.62\underline{/0^\circ}$$

$$I_f = 7.95\underline{/45^\circ}\text{ A}$$

Also from Fig B3(c):

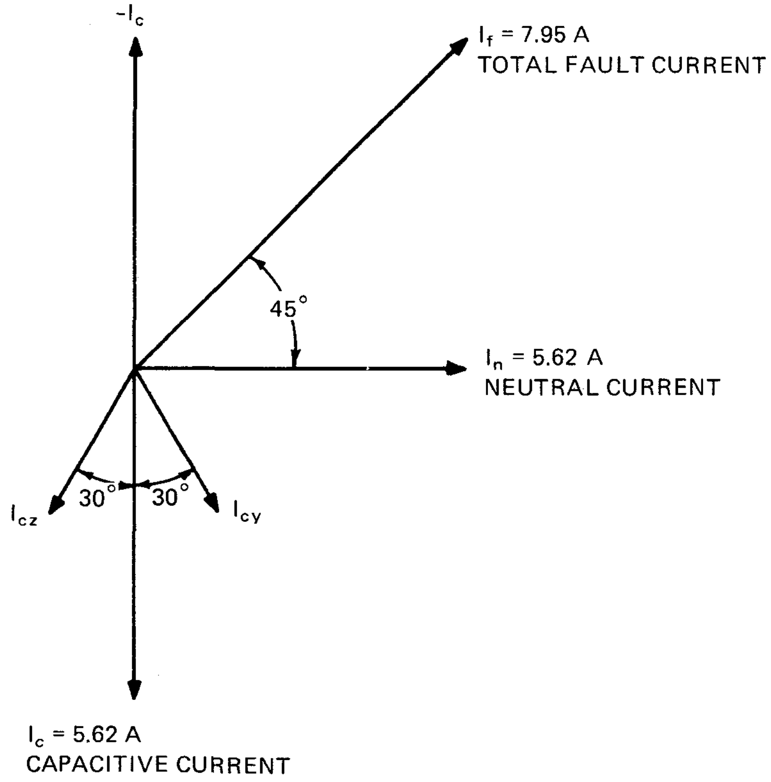
$$I_f = I_n - I_c = 5.62\underline{/0^\circ} - 5.62\underline{/270^\circ}$$

$$I_f = 7.95\underline{/45^\circ}\text{ A}$$

Figure B3(e) illustrates the phase relationships of the current. The current through the primary of the grounding transformer is 5.62 A. The secondary voltage is 229.5 V, and the resistor current is 311 A.

B3. Relay Applications

B3.1 Scheme 1 Relay Settings. The relay (device 59) is a low pickup time-delayed voltage relay designed to be insensitive to 3rd harmonic voltages. The relay is rated 67 V continuously and 140 V for 2 min and should be set at 5.4 V



(e)

Fig B3 (*Continued*)
Phase to Ground-Fault Capacitive Reactance Equivalent Circuits and Phasor Diagrams
(e) Current Relationships During Fault

pickup and 10 time dial. Since the generator voltage is uniformly distributed along its stator winding (0 V at the neutral and 12 700 V to ground at its terminals), the voltage across the relay will be proportional to the percentile of the winding that is faulted. The 59 relay with a 5.4 V setting will detect single-phase-to-ground faults to within

$$\frac{5.4}{229.5} \cdot 100 = 2.35\%$$

of the generator neutral, or 97.65% of the stator winding measured from the terminals will be protected. The fault current for single-phase-to-ground faults on the unprotected 2.35% of the winding will be 0.0235 • 7.95 = 0.187 A and will decrease to zero at the neutral.

B3.2 Scheme 5S Relay Settings. If scheme 5S is applied to provide protection during warm-up, the relay selected should be a plunger type relay with a 7 V—16 V pickup range. The relay is set at 7 V. At 60 Hz and rated generator voltage, this setting protects 97% of the winding. During warm-up, the machine is operating at reduced frequency and voltage. The amount of the winding protected will vary with generator voltage; however, because a plunger type relay has essentially a constant volts per hertz characteristic, maximum stator protection will be obtained.

B3.3 Scheme 7 Relay Settings. In this scheme, voltage transformers with two secondary windings rated 24 000 – 120/120 V are connected grounded wye-grounded wye-broken delta. For a fault at the generator terminals, $E_0 = 12\,700$ V. The voltage across the overvoltage relay connected in the broken delta will be $3E_0/N$ = 3 • 12 700/200 = 191 V. This application will require that the relay has a continuous rating of 199 V. If the 24 V tap and 10 time dial are used, this relay will coordinate closely with the primary-voltage transformer fuses and will detect single-phase-to-ground faults to within (24/191) • 100 = 12.6% of the neutral. The primary current at relay pickup will be 1.0 A (12.6% • 7.95 = 1.0). This is satisfactory for a backup relay to scheme 1.

B3.4 Scheme 9 Relay Settings. Scheme 9, using an overcurrent relay scheme, may be used instead of scheme 1. The grounding transformer has a ratio of 13 280 to 240, or 55.3 to 1. A 250-to-5 current transformer will provide relay current approximately equal to generator neutral current.

As calculated earlier, the maximum generator neutral fault current is 5.62 A. This will produce 311 A in the secondary resistor and 311/50 = 6.2 A in the ground overcurrent relay.

The overcurrent relay should be set as sensitively as possible without introducing the possibility of false tripping. When the unit is on line, there will be a small neutral current due to system unbalance and generated harmonics, principally in the 3rd. This neutral current will vary directly with generator load so the maximum relay current will flow when the machine is operating at full load. This current can be expected to be less than 0.5 A. Actual field measurements on 29 hydro and 59 thermal units ranging in size from 15 MW to 950 MW, showed relay current from 0.1 A — 0.6 A with a mean value of 0.3 A.

It is important that the current in the ground relay operating coil be measured with the unit running as near full load as possible.

This value should not exceed 75% of the ground relay tap setting. Assuming a maximum operating current of 0.3 A, the generator ground overcurrent relay may be set on the 0.5 A tap. This setting will provide protection for all but 0.5 • 100/6.2 = 8.1% of the generator winding, or 91.9% of the winding will be protected.

Since a voltage may exist at the generator neutral when a fault occurs on the high-voltage side of the generator stepup transformer, some time delay should be provided for the time overcurrent unit. Otherwise, the machine will be incorrectly tripped for a transmission system fault. A time dial setting of 3.5 to 4.0 will usually prove adequate if a very inverse relay is used.

B3.5 Relay — VT Fuse Coordination. The sensitive relaying used to detect phase-to-ground faults on the generator stator winding will also detect phase-to-ground faults on the secondary leads of the voltage transformers, if the voltage transformers are connected Y — Y with both neutrals grounded. Figure B1 shows the voltage transformers protected with 0.5 A current limiting fuses. Current limiting fuses are not required for the maximum phase-to-ground fault current of 7.95 A calculated in this example; however, phase-to-phase fault current exceeds the interrupting rating of an ordinary voltage transformer fuse of this size by far. Resistors in series with ordinary 0.5 A voltage

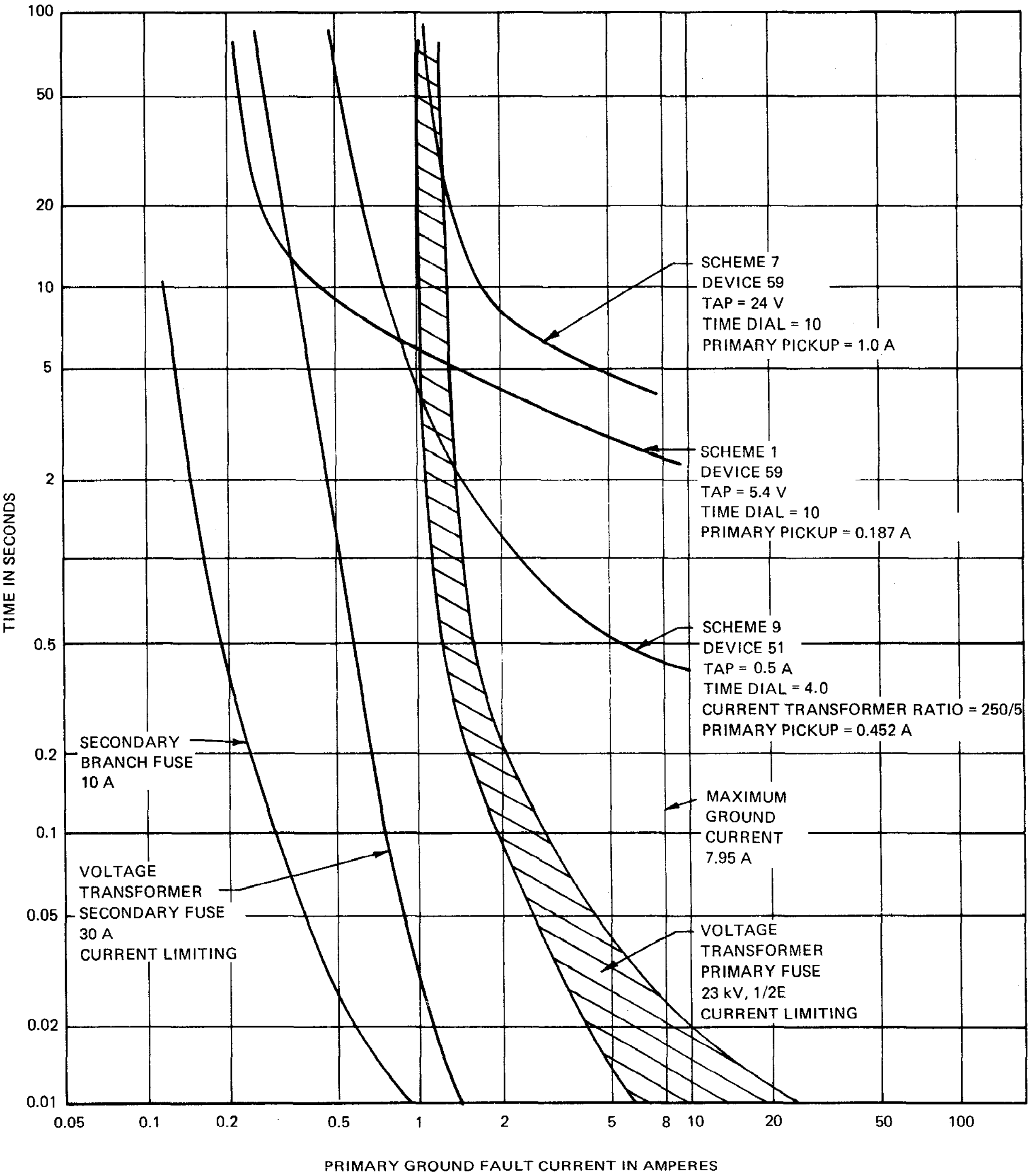


Fig B4
Relay and Fuse Coordination Curves

transformer fuses may be used to limit multiphase fault current to within the interrupting rating of the fuse.

Figure B4 shows both relay and fuse time-current characteristics plotted in terms of total phase-to-ground fault current at the generator terminals or the primary terminals of the voltage transformer. Since the voltage transformer ratio in this example is 24 000 V–120 V, secondary fuse characteristics are plotted on the basis that 200 A secondary current is equal to 1 A primary.

The voltage relays of protection schemes 1, 5S, and 7 have volt-time characteristics. In order to plot these characteristics in Fig B4, volts shall be converted to equivalent primary ground-fault amperes. In this example, the fault at the generator terminals was 7.95 A and relay volts 229.5 for schemes 1 and 5S. The ratio of relay volts to primary ground-fault current is 28.9 to 1. This same ratio holds for fault current less than maximum. In scheme 7, the relay volts are 191 for the maximum ground-fault current of 7.95 A. The ratio for this relay is 24 to 1.

In scheme 9, the relay current is 6.2 A for a maximum ground-fault current of 7.95 A. The ratio of relay current to total ground current is 0.78 to 1.

Using the aforementioned ratios, the relay and fuse characteristics are plotted on a common current base in Fig B4. For problems associated with voltage transformer grounding on ground-fault neutralizers scheme 6, see [5].

Appendix C

Bibliography

C1. Analysis of Ground Fault Transients

[B1] ALACCHI, J. Zero-Sequence Versus Residual Ground-Fault Protection. *Power*, vol 115, no 10, Oct 1971, p 97.

[B2] JOHNSON, A.A. Grounding Principles and Practices. *Electrical Engineer*, vol 64, Mar 1945, pp 92–99.

[B3] PETERSON, H.A. *Transients in Power Systems*. New York: Wiley, 1951.

[B4] PETERSON, H.A. Critical Analysis of Rotating Machine Grounding Practice. *General Electric Review*, Apr 1942.

[B5] WATERS, M., and WILLHEIM, R. *Neutral Grounding in High-Voltage Transmission, Part 2.* New York: Elsevier Publishing Co, 1956, pp 266–649.

[B6] WISZNIEWSKI, A. *Effect of Grounding Method of Star Connection in Unit Generator Transformer on Values of Grounded Short Circuit Overvoltages, Przeglad Electrotechniczny.*

C2. Generator Protection

[B7] GANTNER, J. *New Developments in the Protection of Large Turbo-Generators.* IEE Mar 1975, pp 64–70. (England)

[B8] GANTNER, J., and WANNER, R. The Protection ov Very High Power Turbo-Generators in Relation to the Protection of the System and Back-Up Protection. *CIGRE*, vol 34–08, Aug/Sep 1972, pp 1–8.

[B9] MASON, C.R. *The Art and Science of Protective Relaying.* New York: Wiley, 1956, pp 209–214.

[B10] STADLER, H. *New Developments on Generator Protection.* Brown Boveri Review, vol 53, no 11/12, 1966, pp 791–794.

[B11] VAN C. and WARRINGTON, A.R. *Protective Relays, Their Theory and Practice*, vol 1. London: Chapman & Hall, Ltd 1968, p 181.

[B12] WANNER, R. *Protection of Large Generators.* Brown Boveri Review, vol 58, no 7, 1971, pp 257–264.

[B13] ZUROWSKI, E. *The Protection of Large Power Station Generating Units.* Siemens Review, Feb 1965.

C3. Generator Ground Fault Protection

[B14] AIEE COMMITTEE REPORT. Present Day Grounding Practices on Power Systems. *AIEE Transactions on Power Apparatus and Systems*, vol 66, 1947, pp 1525–1548.

[B15] BERMAN, J., KRIPSKY, A., and SKALKA, M. Protection of Large Alternators Connected to Step-Up Transformers Against the Consequences of Earth Faults in the Stator Winding. *CIGRE*, 34–02, 1972.

[B16] *Electrical Transmission and Distribution Reference Book.* Westinghouse Electric Corporation, East Pittsburgh, PA, 1950, pp 655–665.

[B17] GROSS, E.T.B. Ground Relaying of Generators in Unit Connection. *Electrical Engineering*, vol 72, Feb 1973, p 115.

[B18] PAZMANDI, L. Stator Earth Leakage Protection for Large Generators, *CIGRE*, 34–01, 1972.

[B19] RAJK, M.N. Ground Fault Protection of Unit Connected Generators. *AIEE Transactions on Power Apparatus and Systems.* vol 77, pt III, 1958, pp 1082–1094.

[B20] STADLER, H. *Earth Leakage Protection of Alternator.* Brown Boveri Review, vol 31, 1944, pp 392–400.

C4. Neutral Grounding

[B21] IEEE Std 32–1972. IEEE Standard Requirements, Terminology, and Test Procedure for Neutral Grounding Devices.

[B22] AIEE COMMITTEE REPORT. Application Guide for the Grounding of Synchronous Generators. *AIEE Transactions on Power Apparatus and Systems,* vol 72, Jun 1953, pp 517–530.

[B23] BERGER, I.B., and JOHNSON, A.A. Y-Connected Potential Transformers as Generator Neutral Grounding Devices. *IEEE Transactions on Power Apparatus and Systems,* vol 73, Jan/Feb 1954, pp 341–345.

[B24] BROWN, P.G., JOHNSON, I.B., and STEVENSON, J.R. Generator Neutral Grounding. Some Aspects of Application for Distribution Transformer with Secondary Resistor and Resonant Types. *IEEE Transaction on Power Apparatus and Systems,* vol 97, no 3, May/Jun 1978, pp 683–694.

[B25] JOHNSON, A.A. Generator Grounding. *Electric Light and Power,* Mar 1952.

[B26] JOHNSON, I.B., and STEVENSON, J.R. Neutral Grounding and Prevention of Neutral Instability. *IEEE Transactions on Power Apparatus and Systems,* vol 92, Jan/Feb 1973, p 341.

[B27] Teichmann, H.T. Improved Maintenance Approach for Large Generator Armature Windings Subject to Insulation Migration, IEEE Transactions on Power Apparatus and Systems, vol 91, Jul/Aug 1973, pp 1234–1238.

[B28] WEBB, C.E. Determining the Rating of a Generator Neutral Grounding Reactor, Industrial Power Systems, General Electric Co., Dec 1970.

C5. Resonant Grounding

[B29] AIEE COMMITTEE REPORT. Guide for Application of Ground-Fault Neutralizers. *AIEE Transactions on Power Apparatus and Systems,* vol 72, Apr 1953, pp 183–190.

[B30] HADDAD, M.V., KHUNKHUN, K.J.S., and KOEPFINGER, J.L. Resonant Grounding (Ground Fault Neutralizer) of a Unit Connected Generator. *IEEE Transactions on Power Apparatus and Systems,* vol 96, no 2, Mar/Apr 1977, pp 550–559.

[B31] TOMLINSON, H.R. Ground-Fault Neutralizer Grounding of Unit Connected Generators. *AIEE Transactions on Power Apparatus and Systems,* vol 72, pt III, Oct 1953, pp 953–966.

C6. Synchronous Generators

[B32] ANSI C50.10-1977, American National Standard General Requirements for Synchronous Machines.

C7. Voltage Transformers

[B33] MASON, C.R. *Preventing Generator Relay Operations when a Potential Transformer Fuse Blows.* General Electric Co, vol 19, Oct 1957.