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IEEE Guide for Generator Ground Protection

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Abstract: Guidance in the application of relays and relaying schemes for protection against stator ground faults on high-impedance grounded generators is provided.
Keywords: synchronous generator, stator fault, ground-fault protection

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Introduction

(This introduction is not a part of IEEE Std C37.101-1993, IEEE Guide for Generator Ground Protection.)

IEEE Std C37.101, IEEE Guide for Generator Ground Protection, was initially published in 1985. It was subsequently reaffirmed in 1990.

In this revision of IEEE C37.101-1985, there is no longer a distinction between schemes commonly used in the North American continent and those considered nonstandard, special, unique, or not extensively used in that region. Any scheme that is judged to be a good alternative practice for generator ground protection is contained in the main body of the guide. Some such schemes, 100% coverage and high-impedance differential, that were previously described in the annexes of the prior version, have since been incorporated into the main body of this guide. These schemes have also gained acceptance and increased usage since their publication in the original guide (an application example for the high-impedance differential relay has been included in the annex).

Data for the ground-fault neutralizer overvoltage scheme used with resonant neutral grounded unit-connected generators is updated and includes comparisons of sensitivity with the resistor grounded scheme.

The discussion of grounding methods in clause 5 has been revised to align with the grounding categories described in IEEE Std C62.92.2-1989, IEEE Guide for the Application of Neutral (Grounding in Electrical Utility Systems, Part II—Grounding of Synchronous Generator Systems. This standard supersedes IEEE Std 143-1954, which was referenced in IEEE C37.101-1985.

A scheme for the generator neutral overcurrent protection is added for the case of accidental solid neutral grounding.

The references and bibliography have been updated. Table 1 has been similarly revised to reflect the addition of new schemes. Text and figures have been generally revised for improved readability and technical enhancement.

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CLAUSE PAGE

IEEE Guide for Generator Ground Protection

1. Overview

1.1 Scope

This guide has been prepared to aid in the application of relays and relaying schemes for protection against stator ground faults on high-impedance grounded generators. The guide is not intended for the selection of generator or ground connection schemes.

Differential relaying will not detect stator ground faults on high-impedance grounded generators. The high impedance normally limits the fault current to levels considerably below the best practical sensitivity of the differential relaying. Separate ground fault protection is then provided.

1.2 Description of the guide

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

Annex A 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.

Annex B provides an example of a procedure used to determine the percent coverage of a high-impedance differential relay.

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

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 in table 1 and various schemes. However, all current and voltage transformer secondary circuits shall be grounded in a way that is consistent with accepted practices for personnel safety.

2. References

This standard shall be used in conjunction with the following publication. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std C37.2-1991, IEEE Standard Electrical Power System Device Function Numbers (ANSI).[1]

IEEE Std C37.102-1987 (Reaff 1991), IEEE Guide for AC Generator Protection.

IEEE Std C62.92.2-1989, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part II—Grounding of Synchronous Generator Systems (ANSI).

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 that 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 clause 4 of this guide. Vertically, along the left 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 C62.92.21-1989 [2] as explained in clause 5. 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, 16, 19, and 20 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 that 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 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 clause 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 start-up 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 start-up 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

[1]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

[2]Information on references can be found in clause 2

scheme 17 is intended for protection during the time that the main breaker is closed and the machine is running normally. In general, start-up and shutdown protection 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 start-up cycle or is removed late in the shutdown cycle. This start-up 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 start-up protective schemes, where they apply, listed last. Within each box, the schemes within the brackets are the most widely used. 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 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 speed. Under these conditions, the need for start-up or shutdown protection is minimized.

Clause 5 describes grounding methods I through 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 through 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 through 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 that 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 through 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 clause 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. 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 commonly used 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 neither 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 step-up 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 runing 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 type of common grounding equipment is employed regardless of the number of generator units that are connected to a given transformer winding.

Table 1—Generator connections, generator grounding methods, and protective scheme numbers

Grounding methods ↓ / Generator connections →	(A)	(B) REAL OR PHANTOM TERTIARY	(C)	(D) SYSTEM GROUNDED	(E) SYSTEM GROUNDED	(F)
I — EFFECT HIGH RES	[1, 7, 10, 18] 2, 3, 4, 9, 11, 20 5S, 8S				[12, 15] 13, 19 5S, 8S	[1, 7, 10, 18] 2, 3, 4, 9, 11, 20, 5S, 8S
II — HIGH RES, VT	[1, 7, 10, 18] 2, 3, 4, 11, 20 5S, 8S				[12, 15] 13, 19 5S, 8S	[1, 7, 10, 18] 2, 3, 4, 9, 11, 20, 5S, 8S
III — LOW RES		10, 11, 15, 16, 20			[14, 16] 10, 11, 15, 19, 20	
IV — LOW REACTANCE		10, 11, 15, 16, 20			10, 15, 16, 19	
V — TUNED REACTOR	[6]					6, 10, 11, 5S, 20
VI — GENERATOR LEADS, EFFECT HIGH RES			[1, 9, 10] 2, 3, 4, 11 5S	[12, 17] 13 5S		
VII — GENERATOR LEADS, MED RES				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

The circuit arrangements of connection D and E indicate generators connected directly to the system bus without any interposing step-up transformers. In general, these will be relatively small generators and they will be connected to a solid or low impedance grounded 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 five of the six grounding categories described in IEEE Std C62.92.2- 1989. The following are the six categories:

a) Effectively grounded
b) Low-inductance grounded
c) Low-resistance grounded
d) Resonant grounded
e) High-resistance grounded
f) Ungrounded

Effectively grounded is a form of low-inductance grounded and is not considered in this guide. The standard considers distribution transformer and high-resistance grounding as a single category. This guide lists them as separate grounding methods since each requires a different type of protective scheme. The protection for two additional methods of grounding, high- and medium-resistance grounding-transformer grounded, are explained in this guide. Thus, the eight grounding methods considered in this guide are the following:

a) High-resistance grounded (distribution-transformer grounded)
b) High-resistance grounded (neutral-resistor grounded)
c) Low-resistance grounded (neutral-resistor grounded)
d) Low-inductance grounded (neutral-reactor grounded)
e) Resonant grounded (GFN grounded)
f) High-resistance grounded (grounding-transformer grounded)
g) Medium-resistance grounded (grounding-transformer grounded)
h) Ungrounded

5.1 Method I: High-resistance grounded (distribution-transformer grounded)

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 volt-amperes in the zero-sequence capacitive reactance 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 to 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.

A generator system grounded through a distribution transformer with a secondary resistor has certain characteristics that may have the following desirable features:

a) Mechanical stresses and fault damage are limited during phase-to-ground faults by restricting fault current.
b) Transient overvoltages are limited to safe levels.
c) The grounding device is more economical than direct insertion of a neutral resistor.

A disadvantage of this grounding scheme is that surge protective equipment must be selected on the basis of higher temporary overvoltages during ground faults.

5.2 Method II: High-resistance grounded (neutral-resistor grounded)

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: Low-resistance grounded (neutral-resistor grounded)

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 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. The main advantage of low-resistance grounding is the ability of the neutral resistance to limit ground-fault current to a moderate value while limiting the transient overvoltages to 2.5 times the phase-to-ground voltage or less. However, arresters with maximum continuous overvoltage (MCOV) capability that will tolerate full line-to-line voltage until the generator is tripped are required.

The current through a neutral resistor can be limited to any value; but usually it ranges from about several hundred amperes to about 1.5 times the normal rated generator current. The lower limit may be based on the sensitivity of the generator ground differential relays. The upper limit of 1.5 times normal rated current is related to the loss in the resistor during single phase-to-ground faults. A value of 1.5 times normal current through a neutral resistor gives a power loss of 50% of the kVA rating of the generator. The main disadvantages of low-resistance grounding is the cost of the grounding resistor and the possibility of iron lamination burning from the higher ground fault current.

5.4 Method IV: Low-inductance grounded (neutral-reactor grounded)

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 some generator differential relays for faults in the stator, except for those near the neutral end of the machine.

5.5 Method V: Resonant grounded (ground-fault neutralizer grounded [GFN])

Method V illustrates the ground-fault neutralizer (GFN) 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 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 capacitive reactance of the circuit does not change significantly for different system conditions. Thus, it may not be readily applied to units arranged as in column F of table 1, such as when low-side breakers are applied.

5.6 Method VI: High-resistance grounded (grounding-transformer grounded)

Grounding method VI uses three distribution transformers whose primary windings are connected to the generator leads in a wye configuration, while the secondaries are connected in broken delta configuration with a resistor. These transformers must have their primary voltage rating equal to the line-to-line voltage of the generator. Secondary voltage is commonly 120 V or 240 V. 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 three-phase zero-sequence reactive volt-amperes in the zero-sequence capacitance of the generator windings, its leads, and the windings of the transformers connected to the generator terminals. The total capacity of the three transformers must be 1.732 times the watt dissipation of the resistor, and the voltage applied to the resistor is 1.732 times the transformer rated secondary voltage. This grounding method is used on ungrounded systems such as those having delta-connected generators and power transformers.

5.7 Method VII: Medium-resistance grounded (grounding-transformer grounded)

Grounding method VII uses either a zig-zag transformer or a wye-delta 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.

The advantages of this class are essentially the same as for high-resistance grounding except that the maximum fault current is somewhat less. A disadvantage is that excessive transient overvoltages may result from switching operations or intermittent faults.

In grounding methods I through 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 clause 7.

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 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 [B36] [3], rather than at the neutral point, and if the neutral

[3]The numbers in brackets correspond to those of the bibliography sources in annex C.

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.

For ground fault neutralizer (GFN) grounding, the primary neutral connections of the two sets of wye-wye connected generator voltage transformers (vt's) are tied together and to the generator neutral using an insulated conductor. The secondary neutrals are grounded at the voltage transformer cubicle. Grounding of the primary neutral connections at the cubicle is not used since the resulting phase-to-ground inductive reactance comprising the magnetizing branch of the voltage transformers would detune the resonant circuit consisting of the generator system capacitance to ground and the neutral reactor.

A complete discussion of voltage-transformer fusing is given in [B36] and A.3 of annex A.

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 574 unit-years with generators (since 1951) has shown no cases 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 [B32]).

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 preferred 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 affect 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 significantly 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, 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 be used for single-phase-to-ground fault detection on high-resistance grounded generators that are connected to the system through delta-wye connected transformers. Table 1 indicates that this includes grounding methods I and II for wye-connected generators and grounding method VI for delta-connected generators.

All three of these grounding methods limit the available fault current to extremely low levels for single-phase-to-ground faults in the generator stator windings, the generator leads, and the delta windings of the associated transformers. 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 over-voltage 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.

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.

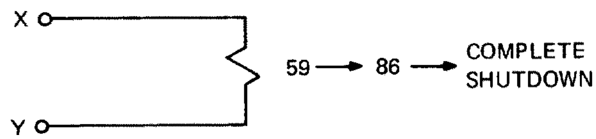

Figure 1—Scheme 1: Ground overvoltage—Complete shutdown

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 third harmonic voltages generated by the machine under full-load conditions.

Harmonic generation in a generator is dependent on many factors, such as slot spacing, variation in reluctance that occurs at various pole positions, and pole pitch. Manufacturing difficulties and their associated costs generally prohibit the design of machines whose waveform contains no third harmonic. The nature of third harmonic voltage that is generated equally in each of the three phases is such that these harmonic voltages are in phase. The machine neutral-to-ground voltage will then contain a third harmonic voltage.

Relays that are intended to detect fundamental frequency voltage between machine neutral and ground cannot be allowed to respond to this third harmonic voltage. They must then be desensitized to it or be set above it. Other relays use this third harmonic voltage for neutral-to-ground fault detection. These must be set so that they remain picked up on the minimum third harmonic voltage.

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-wye-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 wye-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 low-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 (vt's) or their secondary leads. Annex A 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, which is 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 either two separate generators or a cross-compound unit 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 parallel connected 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, each having its own low-side circuit breaker, are connected to the same transformer primary delta 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 delta winding. This relay should trip the transformer high side and all the generator breakers. In such applications, a fault in any machine, or the delta winding of the transformer will be detected by all the relays so that complete selectively 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 delta 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. 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 units.

A third approach is to supervise the tripping of the relay in the broken delta 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-delta 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 disadvantages 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 annex A.

6.2 Scheme 2: Ground overvoltage—Permissive shutdown

Scheme 2, the variation of schemes 1 and 7, utilizes the same 59 and 86 devises 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 with its accompanying overspeed condition. Its disadvantages are that it permits a longer fault duration and the additional complexity of its tripping circuits. 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.

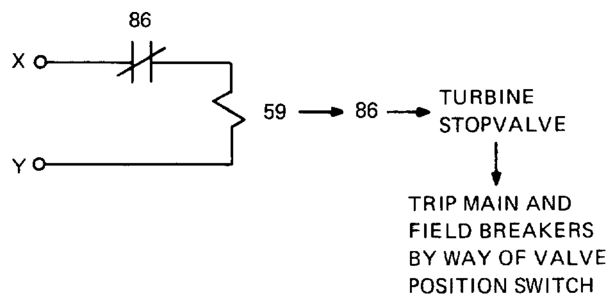

Figure 2—Scheme 2: Ground overvoltage—Permissive shutdown

6.3 Scheme 3: Ground overvoltage—Alarm and time-delay shutdown

Scheme 3, the variation of schemes 1 and 7, utilizes the same overvoltage relay but provides for an immediate alarm with 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 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.

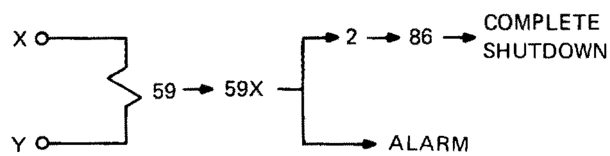

Figure 3—Scheme 3: Ground overvoltage—Alarm and time-delay shutdown

6.4 Scheme 4: Ground overvoltage—Alarm

Scheme 4, the 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 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 to which it will be subjected 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.

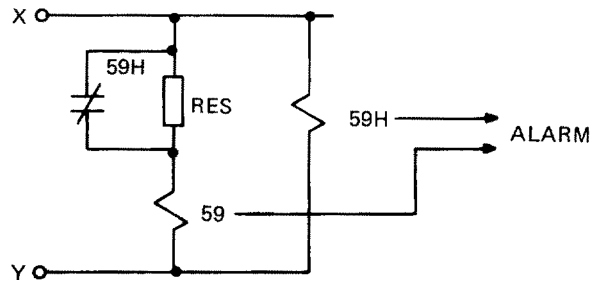

Figure 4—Scheme 4: Ground overvoltage—Alarm

6.5 Scheme 5S: Start-up ground overvoltage—Complete shutdown

As indicated by the suffix S, scheme 5S 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 wye or delta-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 shutdown while maintaining an essentially constant volts per hertz.

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. In ring bus and breaker-and-a-half arrangements, auxiliary switches from the two associated high voltage breakers and the motor-operated disconnect switch shall be configured in such a way that the relay is armed when the unit is disconnected from the high voltage system even if the unit breakers have been closed to reestablish the bus arrangement.

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 third harmonic voltages that might be present during start-up and 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 annex A.

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 start-up 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.

