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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

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[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.

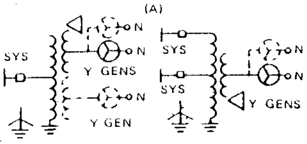
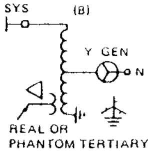
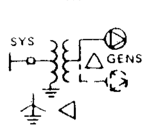
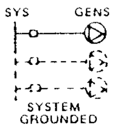
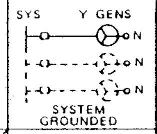
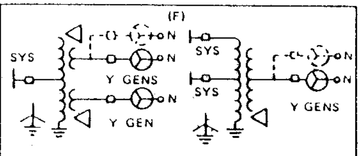
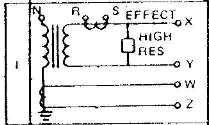
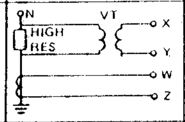
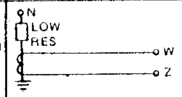
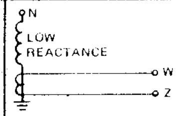
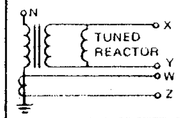
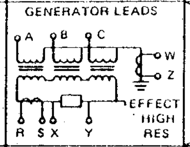
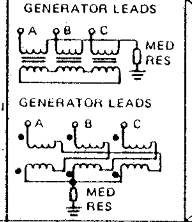
In connection A, if two units are paralleled on one transformer delta winding (as in the case of a cross-compound machine, or machines with two-stator windings per phase), the same kind of protective schemes could be used as if only one unit were connected to the transformer. In general, for these applications, 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

	GENERATOR CONNECTIONS → GROUNDING METHODS ↓	(A) 	(B) 	(C) 	(D) 	(E) 	(F) 
I		[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		[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			10, 11, 15, 16, 20			[14, 16] 10, 11, 15, 19, 20	
IV			10, 11, 15, 16, 20			10, 15, 16, 19	
V		[6]					6, 10, 11, 5S, 20
VI				[1, 9, 10] 2, 3, 4, 11 5S	[12, 17] 13 5S		
VII					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

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[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.

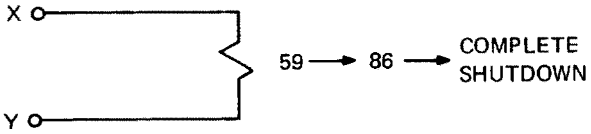


Figure 1—Scheme 1: Ground overvoltage—Complete shutdown

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.

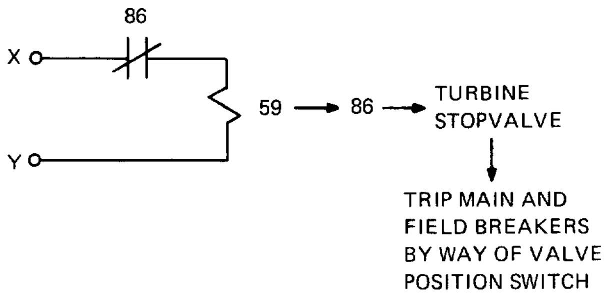


Figure 2—Scheme 2: Ground overvoltage—Permissive shutdown

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.

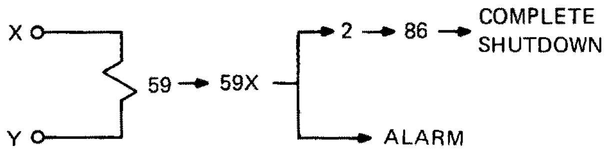


Figure 3—Scheme 3: Ground overvoltage—Alarm and time-delay shutdown

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.

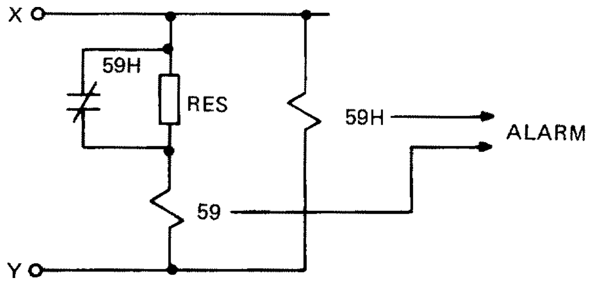


Figure 4—Scheme 4: Ground overvoltage—Alarm

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.

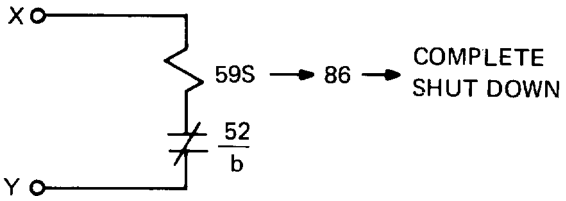


Figure 5—Scheme 5: Start-up ground overvoltage—Complete shutdown

6.6 Scheme 6: Ground-fault neutralizer overvoltage—Alarm and time-delay orderly shutdown

Scheme 6 is generally employed for the protection of units that are grounded by means of the ground-fault neutralizer (GFN) method. This is indicated as grounding method V in table 1.

The GFN 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 significantly 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 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. 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 that is not as sensitive as device 59 and can withstand higher voltages continuously. Device 59H is set to pick up at a voltage level somewhat below the continuous rating of device 59.

An increase in voltage readings across the neutralizing reactor 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 voltage can be recorded.

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 effect 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.

The addition of an undervoltage relay with an 180 Hz pass filter will provide protection for these faults at or near the generator neutral terminals. Used in conjunction with device 59H, complete protection of the generator winding results.

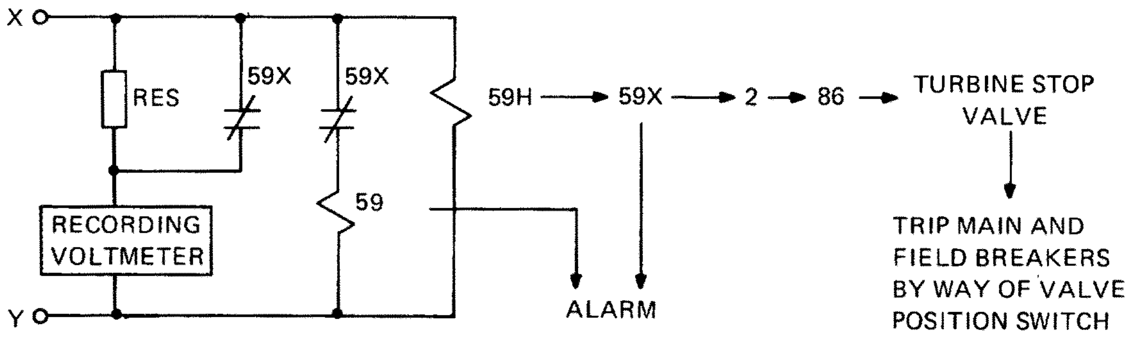


Figure 6—Scheme 6: Ground-fault neutralizer overvoltage—Alarm and time-delay orderly shutdown

Another advantage of this scheme is the ability to detect much higher resistance faults than scheme 1 with the same relay setting. This is because the zero-sequence network impedance of the ground fault neutralizer is 30 to 50 times greater than the resistance used in high-resistance grounding. This arises from the parallel tuned circuit comprising the neutral reactor and the capacitance of the generator system whereby the resulting impedance is a high pure resistance that can be estimated [B33] from the relationship:

$$R_0 = \frac{3KX_L}{2}\Omega$$

where

X_L	is the inductive reactance of the neutral reactor
K	is the reactor coil X/R ratio = X_L/R_L
R_L	is the resistance of the neutral reactor

The example in the annex of reference [B32] demonstrates how effective the resonant grounding system is in reducing the magnitude of generator phase-to-ground fault current to values for which stator iron damage is not expected to occur. Also illustrated in [B32] is how the resonant grounding system can detect much higher resistance faults than can the neutral resistor grounding system.

The results are summarized in the following table:

	Resistor grounded	**Resonant neutral grounded**
	Scheme 1	**Scheme 6**
Maximum fault current	7.95 A	0.45 A
Maximum value of fault resistance detected with 59 device set for 5.4 V	66.9 KΩ	3574 KΩ

Additional examples for calculating high-resistance grounding and resonant grounding can be found in annexes A and C.1 of IEEE Std C62.92.2-1989.

Along with these desirable features are several that may be considered undesirable listed in the following:

a) If automatic tripping is used, coordination with generator voltage transformer (vt) fuses may not be possible. Vt secondary wiring faults may cause ground indications where wye/wye connected generator vt's are used. Coordination can be achieved by various methods (see [B36]).
b) For GFN grounding, the primary neutrals of the three wye-wye connected voltage transformers are tied together and to the generator neutral using an insulated conductor. Grounding at the voltage transformer cubicle is not used since the resulting phase-to-ground inductive reactance comprising the magnetizing branch of the voltage transformer would detune the resonant circuit consisting of the generator system capacitance-to-ground and the neutral reactor.
c) High zero-sequence voltages on the generator system are possible if too high a reactor coil constant is selected for the neutralizer.

Also, if surge protective equipment is used on the generator, it must be selected on the basis of possible higher temporary overvoltages during ground faults. Voltages can be kept to within reasonable limits by selecting a value of reactor coil constant in a range from 10 to 50 without excessively reducing the sensitivity of the fault detection system [B33] .

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 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 phasor sum 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 annex A.

As figure 7 indicates, 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. See IEEE Std C37.102-1987 for further discussions on ferroresonance problems concerning voltage transformers.

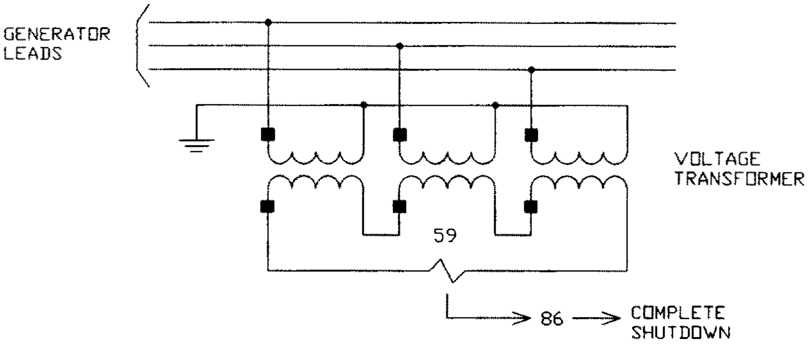


Figure 7—Scheme 7: Wye-broken-delta vt, ground overvoltage—Complete shutdown

6.8 Scheme 8S: Start-up wye-broken-delta vt, ground overvoltage—Complete shutdown

Scheme 8S 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 intended for stator ground-fault detection during the time that the protected machine is disconnected from the system and running with field excitation applied.

6.9 Scheme 9: Secondary-connected current transformer (ct), time-delay ground overcurrent—Complete shutdown

Scheme 9 may be used for single-phase-to-ground fault detection on generators that are connected to the transmission system through delta-wye connected transformers. They may be wye-connected generators that are high-resistance grounded through distribution transformers (grounding method I) or delta-connected generators that use wye-delta grounding transformers (grounding method VI).

This scheme 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 act, which is connected in series with the resistor. A 5 kV or 15 kV ct with a C100 or higher relaying accuracy classification at the ratio used will provide a conservatively rated current source. The current transformer ratio is usually selected so that the current in the relay is approximately equal to the current in the neutral of the generator or in the neutral of the grounding transformer.

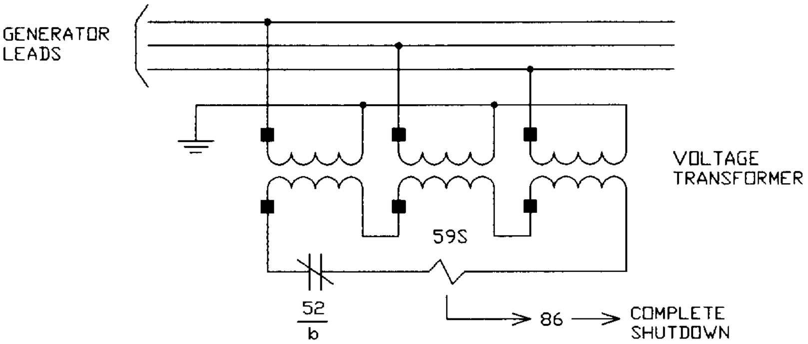


Figure 8—Scheme 8S: Start-up wye-broken-deltta vt, ground overvoltage—Complete shutdown

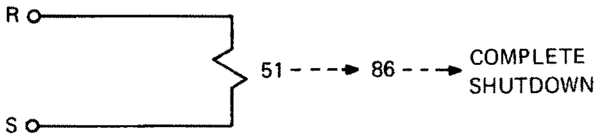


Figure 9—Scheme 9: Secondary connected ct, time-delay ground overcurrent—Complete shutdown

The overcurrent relay used in scheme 9 is, by design, very sensitive to harmonics, while the overvoltage relay of scheme is 1 is not. Therefore, the overcurrent relay must bee set somewhat less sensitively than the scheme 1 voltage relay. Refer to A.3.4 in annex A for scheme 9 relay settings. However, the disadvantage of a leeks sensitive relay 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. Annex A provides an example of relay setting calculations and voltage transformer fuse coordination for both schemes.

6.10 Scheme 10: Primary connected 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 the neutral of the generator or the neutral of the grounding transformer instead of being in series with the resistor in the secondary circuit. This scheme may be used with a wide variety of grounding methods such as high resistance (grounding methods, I, II and VI), low resistance (grounding method III), low reactance (grounding method IV), and tuned reactance (grounding method V).

If the generator being protected is isolated from the network by the delta winding of the generator step-up 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 current transformer with a 5/5 ratio should be used so that the current in the relay is approximately equal to the current in the neutral of the generator or in the neutral of the grounding transformer. A setting calculation example similar to that for scheme 9 of annex A 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 column E in table 1. 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.

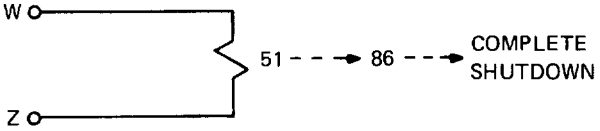


Figure 10—Scheme 10: Primary connected ct, time-delay ground overcurrent—Complete shutdown

These same comments apply generally to column B if the machine is grounded using 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 less sensitively. This prevents operations for system faults. Since the fault-current levels may be high, this results in considerable damage when a ground occurs near the high-voltage terminals of the unit being protected. This damage maybe 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 and/or complete shutdown

Scheme 11 includes an extended range 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 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. This may require an extended range relay. 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 detected and tripped high speed, ground-fault current will 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 front the system by means of the delta winding of a generator step-up transformer.

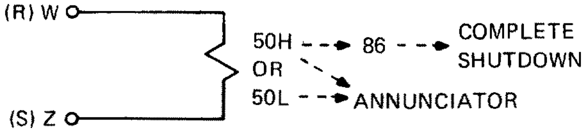


Figure 11—Scheme 11: Instantaneous ground overcurrent—Alarm and/or complete shutdown

6.12 Scheme 12: Generator leads ground overcurrent—Complete shutdown

Protective scheme 12 may be used for ground fault protection for high- or medium-resistance grounded generators that are connected at generator voltage to an otherwise grounded system. Table 1 indicates that this scheme is appropriate for wye-connected generators that are grounded using grounding methods I, II, VII, and VIII, and for delta-connected generators that use grounding methods VI, VII, and VIII. Scheme 12 may also be used for ground fault detection in ungrounded generators (grounding method VIII) that are connected to the system through an autotransformer with either a wound delta tertiary or a “phantom” tertiary.

Relaying scheme 12 consists of an instantaneous and an inverse time overcurrent relay. The relays are supplied with residual current from current transformers in each phase of the generator leads. The current transformers are sized to carry generator full-load current and are positioned on the generator side of the generator synchronizing breaker.

The fault current detected by this scheme is the system contribution to a generator fault and not the contribution from the generator itself. Since the generator will contribute very little to a ground fault, there will be considerable difference in the relay current for a ground fault on opposite sides of the current transformers. Therefore, a directional relay is not necessary. When the unit is operating while disconnected from the system, the ground-fault current is limited by the high-resistance grounding method. It is not feasible to attempt to recognize a ground fault in the zone under this condition with an overcurrent relay supplied from residually connected current transformers sized to carry generator full-load current. Also the relay may not see the fault at all because of the ct location in the circuit. Consequently, some other type of fault detection for use during start-up and shutdown must be provided. Relay scheme numbers with The S suffix shown in table 1 can be used for this application.

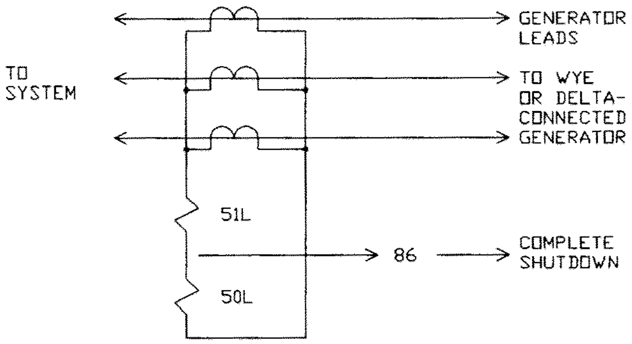


Figure 12—Scheme 12: Generator leads ground overcurrent—Complete shutdown

Two conditions must be satisfied when determining the settings for these relays. First, with the three individual current transformers summed, some lack of symmetry is inevitable. This false residual current should be considered when selecting and setting the overcurrent relays. The relays should coordinate for the maximum expected value of residual current during an external system phase fault with maximum infeed from the generator. Second, the relays should coordinate for ground-current contribution due to the generator zone capacitance during an external system ground fault.

The pickup of the instantaneous relay 50L must 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 time-delay characteristics. The instantaneous relay will be set less sensitively and will operate faster than the time overcurrent relay.

The advantage of scheme 12 is that the three separate current transformers may also be used for other relays, either in the phase or residual circuit.

6.13 Scheme 13: Three-wire generator leads window ct instantaneous ground overcurrent—Complete shutdown

This relay scheme is a variation of scheme 12 but makes use of a window-type ct that surrounds the phase leads to the generator. This limits the scheme to relatively small generators based on the availability of window ct sizes. The ct measures the ground (zero-sequence) current in the generator leads during a ground fault. Unbalanced current in the generator leads that 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 act 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.

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 A 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 that 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, the higher the available fault current, the greater will be the damage to the generator for ground faults near the generator terminals.

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, it would affect 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.

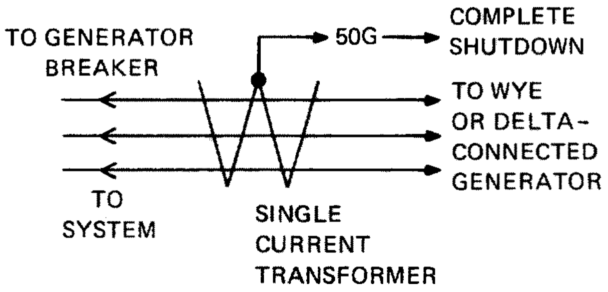


Figure 13—Scheme 13: Three-wire generator leads window ct ground overcurrent—Complete shutdown

It is important to note that window type ct's (sometimes called *doughnut* ct's) used ir 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 limitations in switchgear. As a result, such cts have a poor saturation characteristic. It is necessary to test such ct in combination with its associated relay 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 · 10/1 = 5 primary A.

It is very important to note that when a high burden time delay overcurrent relay is used, the published timecurrent characteristics of the relay are not valid for this application. Here again, device 51G and the current transformer 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 ct's that permit the published time-current characteristic curves to be followed.

6.14 Scheme 14: Four-wire generator leads window current transformer 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 that surrounds the generator phase leads and the generator neutral lead. This scheme is similar in principle to scheme 13 with its ct application restrictions, but is applicable to low-resistance as well as high-resistance grounded generators. The generator neutral lead passes through the current transformer, so that point N is 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, and the relay can safely be set to a low value.

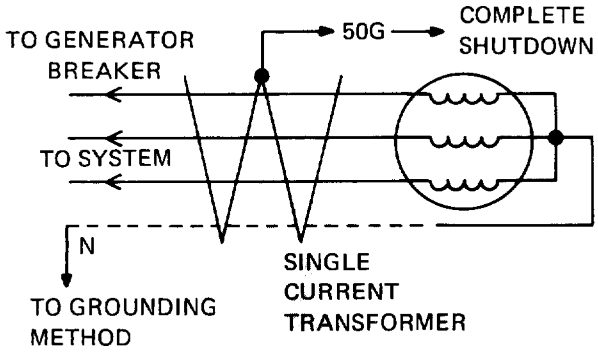


Figure 14—Scheme 14: Four-wire generator leads window current transformer, instantaneous ground overcurrent—Complete shutdown

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—these differential relays will generally detect phase-to-ground fault within 10% to 15% of the generator neutral. Either a fixed or variable percentage differential relay may be used.

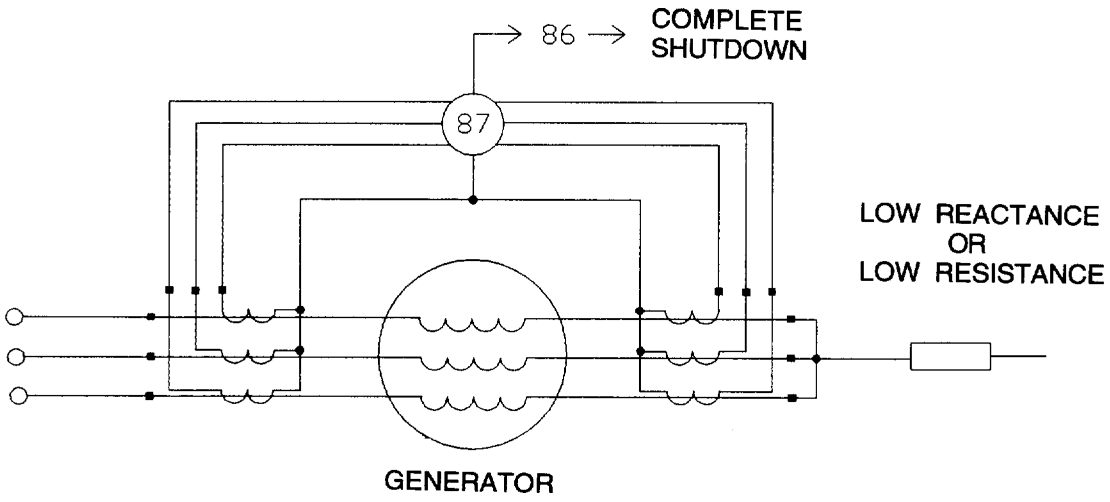


Figure 15—Scheme 15: Generator percentage differential—Complete shutdown

6.16 Scheme 16: Generator ground differential using product type relay

Protective scheme 16 utilizes a product type overcurrent relay in a ground differential arrangement. The relay is connected to receive differential current in its operating coil circuit, and generator neutral $3I_0$ current in its polarizing circuit.

The differential comparison is biased to assure that a positive restraint exists for an external fault even though the current transformers, R_{CN} and R_{CL} have substantially different performance characteristics. This scheme provides excellent security against misoperation for external faults and provides very sensitive detection of internal ground faults.

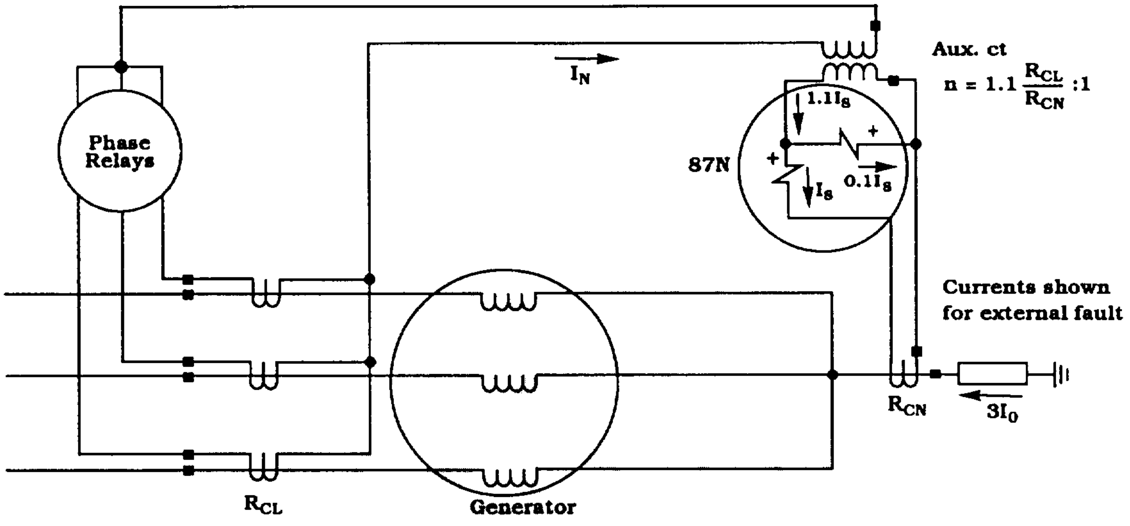


Figure 16—Scheme 16: Generator ground differential using product type relay

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 and isolated from the grounded system.

6.18 Scheme 18: Ground-fault relays for the complete protection of the generator stator winding

This subclause describes relaying schemes for the detection of ground faults in the generator stator that may go undetected using the schemes described previously. Some provide complete wincing coverage while others perform a complementary function to other schemes described.

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, severe damage may be sustained by the machine because this may result in a short-circuit current not limited by the grounding impedance. This condition is aggravated if the first ground fault occurs close to, or at, the neutral of the generator, because 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.

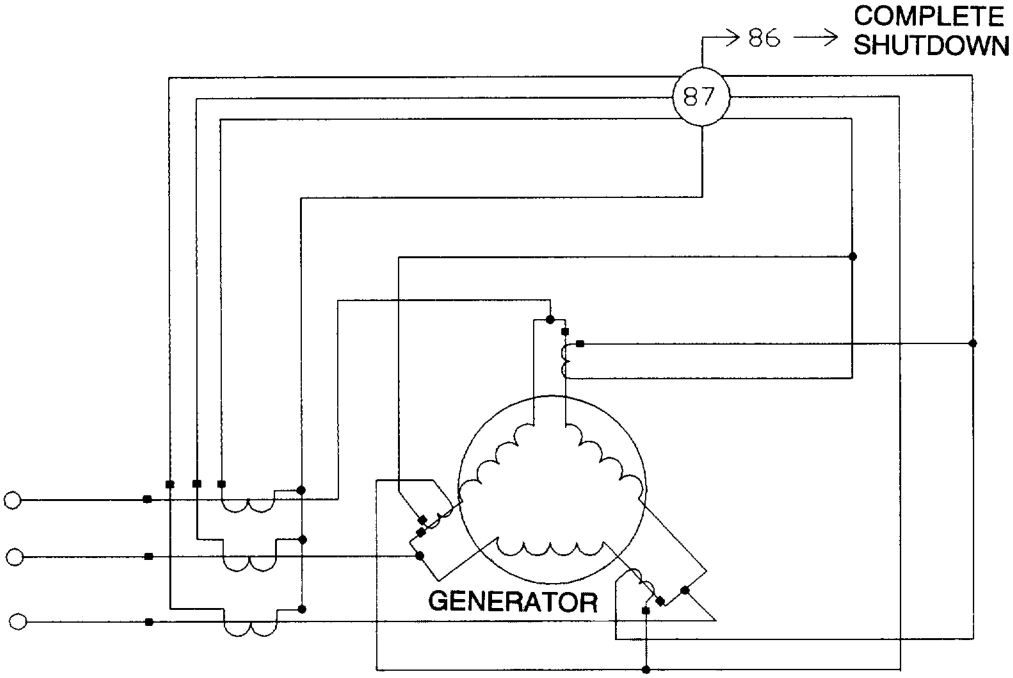


Figure 17—Scheme 18: Delta-connected generator, generator percentage differential—Complete shutdown

Though the negative sequence overcurrent or backup overcurrent relays will detect this fault, they are so slow that they will not prevent serious thermal damage. Even though a relay applied to detect this fault were to be instantaneous, mechanical deformation of the winding would still be expected.

The schemes now in use to assure the detection of all stator ground faults use the following:

a) Third harmonic neutral voltage
b) Third harmonic terminal residual voltage
c) Third harmonic comparator
d) Neutral or residual voltage injection

Some generators are designed to avoid the generation of triplen harmonics and. therefore, none of the third harmonic schemes described here may be applied to protect them.

There are often differences in the 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 alarm with the relay that detects faults in the neutral region, so as to permit inspection and possible repair during normal shutdown for maintenance. This election to “alarm only” for faults in the neutral region accepts the risk of much greater damage that would occur in the event that a second ground fault occurred, and is done in the interests of keeping an important machine in service. However, all ground-faults must be considered serious and it is recommended that immediate tripping be initiated.

a) *Third harmonic neutral voltage*. This scheme shown in figure 18a), uses an undervoltage relay 27 to supplement the overvoltage relay 59 of scheme 1. The undervoltage relay detects an absence of third harmonic voltage at the generator neutral resulting from a fault near the neutral or failure of the neutral transformer. The 27 and 59 relays must be filtered to prevent fundamental or third harmonic voltages respectively from affecting operation. The 27 relay should, if not self-protecting, include circuitry to protect its coil from sustained overvoltage. This scheme offers the advantage of not requiring any additional high voltage 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 third harmonic relay to monitor the voltage at the neutral of the ungrounded stator winding. The scheme provides protection when the main breaker is open, provided that the terminal voltage is above the pickup of the supervisory relay 59C. Supervision is required during start-up and shutdown. This absence of 100% coverage until relay 59C picks up is a disadvantage of this scheme.
   The settings of the 27 and 59 relays should be analyzed to assure overlap for all fault locations. Typically, not more than 1% of third harmonic voltage with reference to rated voltage is needed to provide adequate overlap. Third harmonic voltage is a function of load. Normally 10% to 30% of the stator winding from the neutral point towards the machine terminal can be protected by the 27 relay.
   Device 27 operates for opens or short circuits of primary or secondary windings of the neutral grounding transformer but will not detect an open grounding resistor.
b) *Third harmonic terminal residual voltage*. This scheme is similar to a) above in that it utilizes third harmonic voltage at the machine terminals. This is supplied by a wye-grounded broken-delta transformer. Upon the occurrence of a generator neutral ground, the third harmonic voltage available at the line terminals of the generator becomes elevated. The accompanying overvoltage is used to operate a relay used in this application and must be set in such a way as to be unresponsive to the maximum third harmonic voltage appearing at this point during normal system operation. An advantage of this scheme is that it will also detect ground faults on the bus or in the delta winding when the generator disconnect is open. However, the need for a three-phase vt on the machine terminals is a disadvantage.
c) *Third harmonic ratio comparator*. Like a), this scheme 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.

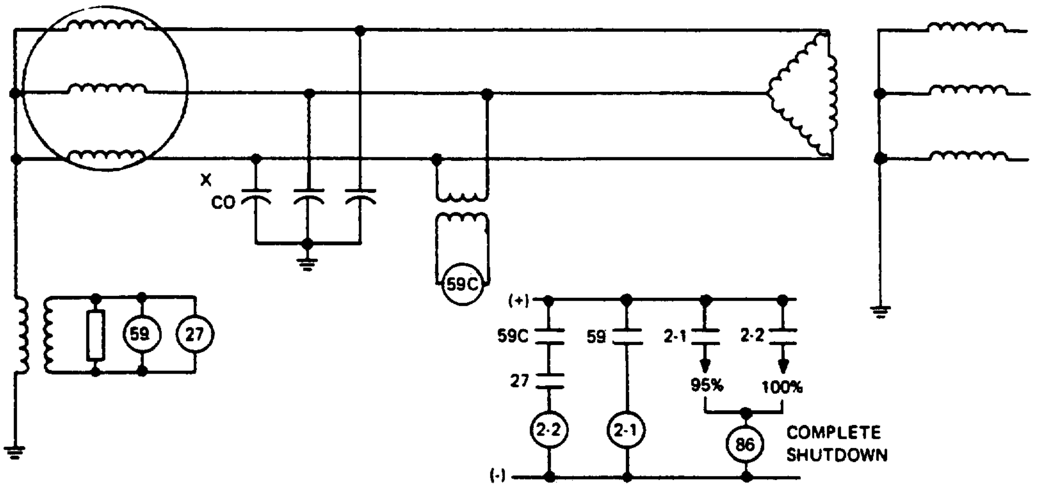
This scheme utilizes the fact that the third harmonic residual voltage at the terminals of a machine increases, while the third harmonic voltage at the neutral decreases, for a fault near the neutral. The ratio of the third harmonic residual voltage to the neutral third harmonic content is nearly constant for all load conditions on an unfaulted machine. The slight variation in this ratio may necessitate a reduced sensitivity setting. Overlap between the two relay functions 59 and 59D will exist. The settings for both relays should be determined during field testing in conjunction with commissioning. The third harmonic differential relay 59D detects ground faults near the neutral as well as at the terminal. Relay 59, which measures the fundamental frequency neutral voltage, detects a fault in the upper portion of the winding as well as overlapping much of the winding covered by 59D. The (comparator) relay sensitivity is least for a fault near the middle of the windings. At some point on the winding, the difference between the neutral and terminal third 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.

The need for multiple vt's and the requirement for field tests during commissioning to determine relay settings are among this scheme's disadvantages. However, this scheme has the advantage of providing the optimum 100% coverage for high-impedance grounded machines.

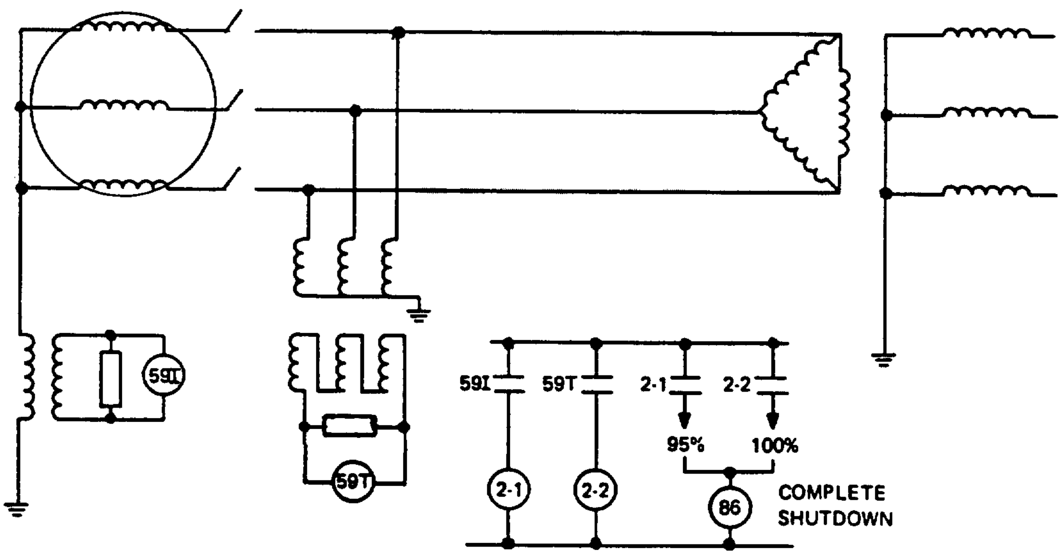
d) *Neutral or residual voltage injection*. Schemes using voltage injection at the neutral, or residually in the broken-delta voltage transformer (vt) secondary, can detect ground faults anywhere in the stator winding of the generator, including the neutral point. Full ground-fault protection is available when the generator is on turning gear and during start-up if the injected voltage source does not originate from the generator. Certain schemes inject a coded signal at a subharmonic frequency that can be synchronized with the system frequency (e.g., 1/4 rated frequency). When compared to other injection schemes, this coding improves the security of the relay system without sacrificing dependability. For proper relay performance, the scheme is dependent on a reliable subharmonic source. 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. The economic penalty associated with providing and maintaining a reliable subharmonic source and injection equipment is a disadvantage.

The major advantage of neutral injection schemes is that they provide 100% ground-fault protection independent of the 95% ground-fault protection schemes, including when the generator is on turning gear and during start-up. In addition, some of these injection schemes are self-monitoring and most have a sensitivity independent of load current, system voltage, and frequency.

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

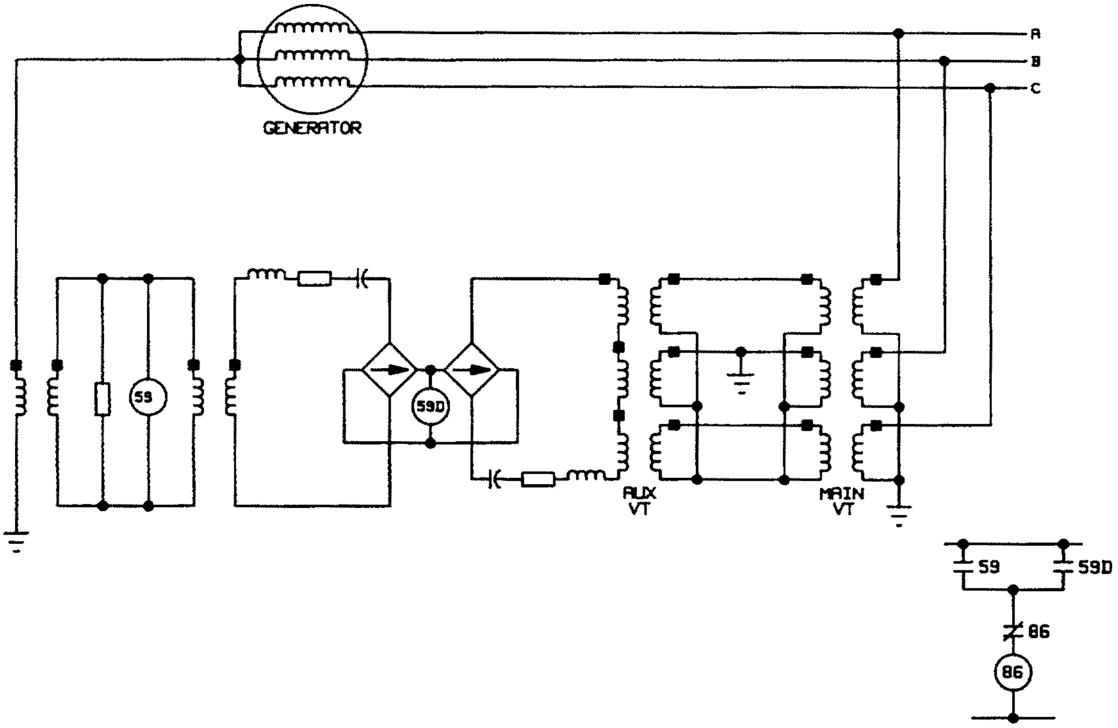


a) Scheme 18a: Third harmonic neutral voltage



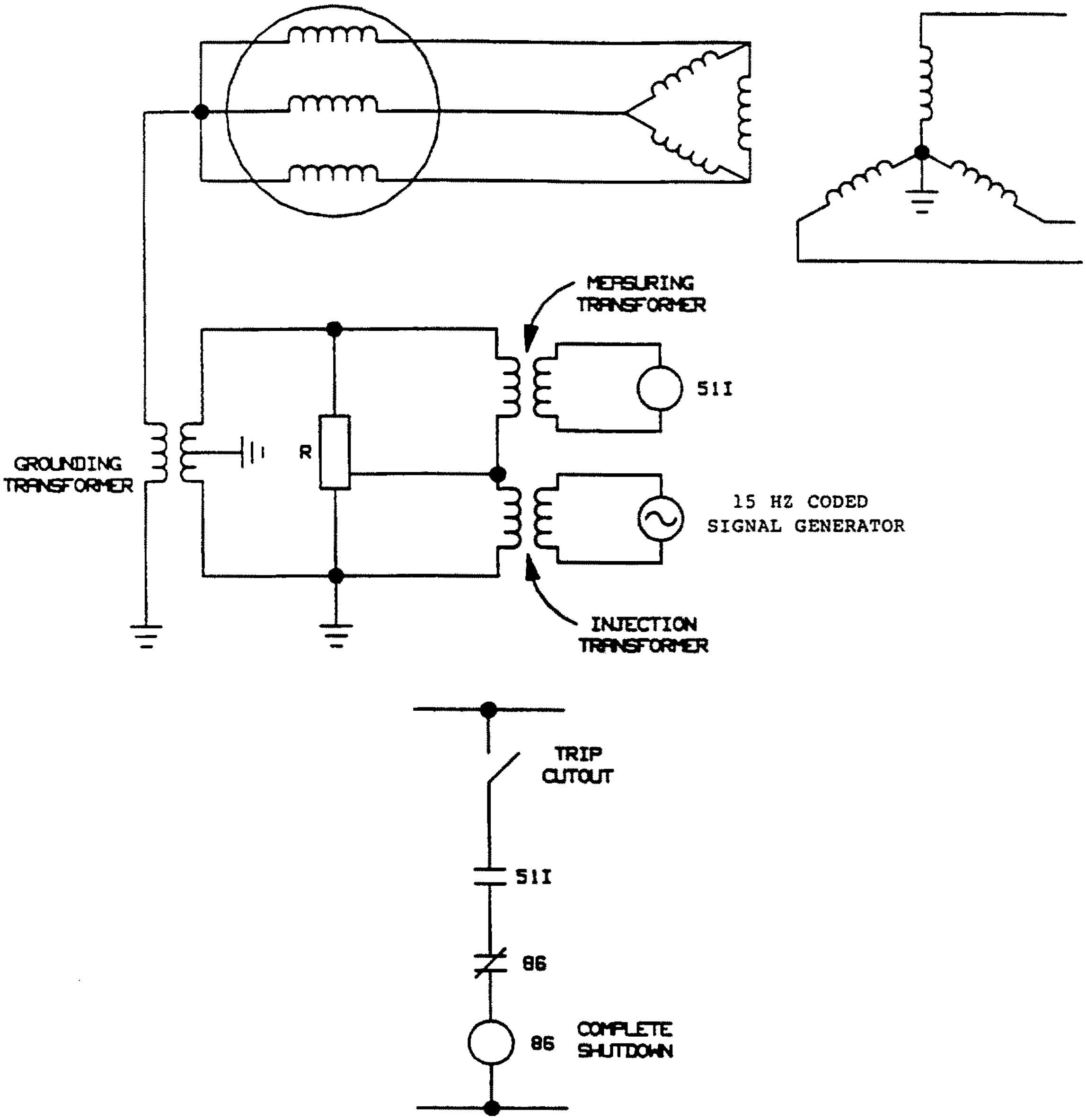
b) Scheme 18b: Third harmonic terminal-to-ground residual voltage

Figure 18—Ground-fault relays for the complete protection of the generator state winding



c) Scheme 18c: Third harmonic ratio comparator

Figure 18—Ground-fault relays for the complete protection of the generator stator winding (*Continued*)



d) Scheme 18d: Neutral or residual voltage injection

Figure 18—Ground-fault relays for the complete protection of the generator stator winding (Concluded)

6.19 Scheme 19: Alternate stator winding protection using high-impedance differential relays

Protection for single-phase-to-ground faults in the stator winding may be provided by utilizing high-impedance differential relays. While the high-impedance differential relay is normally associated with bus protection, synchronous generator applications, although limited in number, have been successfully implemented. Scheme 19a) shown in figure 18a) uses three high-impedance relays, device 87H, to provide protection for both multi-phase faults and single-phase-to-ground faults. Scheme 19b) shown in figure 18b) uses a single high-impedance relay to detect ground faults only. Two alternate connections are shown for scheme 19b). 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.

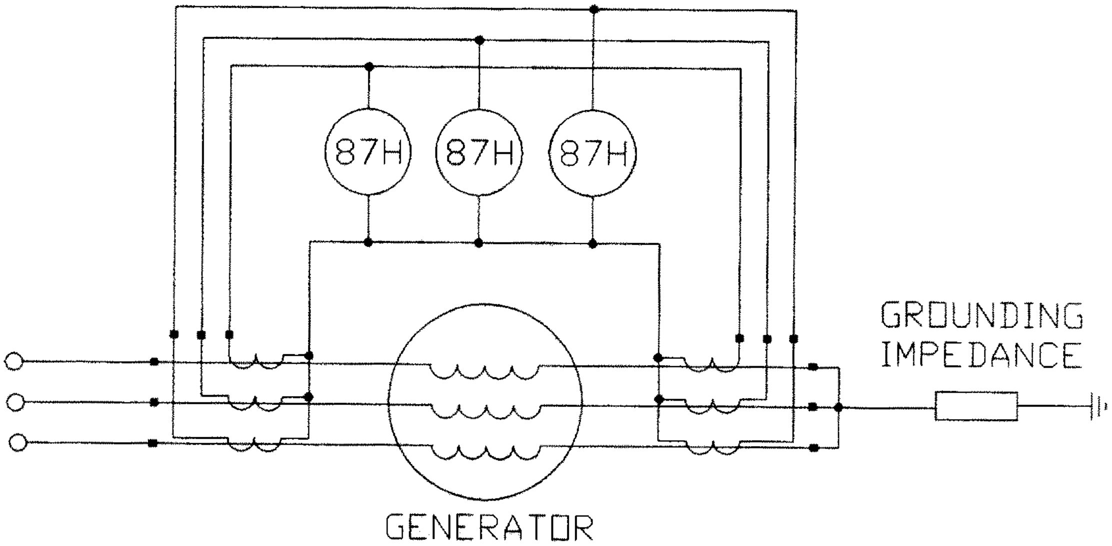
Since the voltage pickup level of a high-impedance differential relay is calculated to prevent operation for worst-case current transformer saturation conditions during an external fault, excellent security is provided. The minimum primary current required for operation on an internal fault is easily calculated, and from this value the percent coverage of the stator winding from output bushings to neutral point can be determined. The percent coverage for ground faults is dependent upon the grounding impedance. The example in annex B illustrates a procedure used to determine the percent coverage.

6.20 Scheme 20: Generator neutral overcurrent protection for the case of accidental solid neutral grounding

A variation of scheme 11 may be used in those installations where the neutral grounding equipment is located at some distance from the generator neutral. Here, the possibility exists that the neutral could accidentally become solidly grounded before it reaches the grounding equipment. If a phase-to-ground fault then occurs in the generator or associated bus duct, the current-limiting benefits of the neutral grounding equipment will be lost, and a high magnitude of fault current will be present.

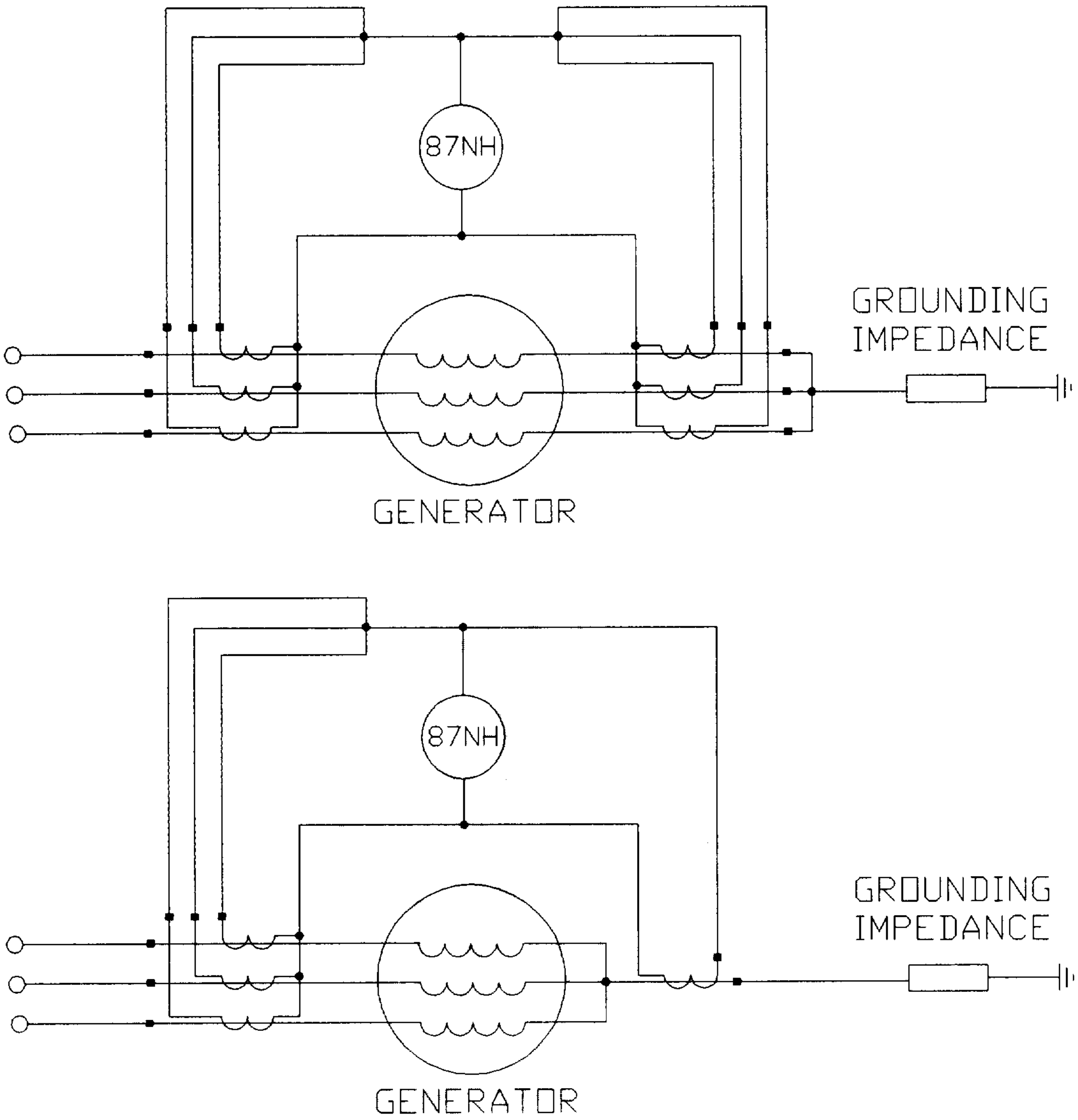
In such a situation, an overcurrent relay connected to a relatively high-ratio current transformer, located close to the generator neutral connection as shown in figure 20, will provide detection. This relay will also provide protection in the event that the secondary of the neutral grounding transformer becomes short circuited, thus bypassing the neutral voltage relay.

An instantaneous relay, or one with a few cycles of time delay, would be appropriate for this application. A time overcurrent relay may be considered if selective tripping is required for a generator connected to a bus feeding several loads. The sensitivity of the relay is not critical due to the magnitude of fault current present. Although differential protection will detect this type of fault, there could be certain portions of the bus duct associated with a unit-connected generator that are covered by only a single differential scheme. In such an instance, the overcurrent relay will provide excellent backup protection.



a) Scheme 19a: High-impedance generator differential for phase or ground faults

Figure 19—Alternate stator winding protection using high-impedance differential relays



b) Scheme 19b: Residual high-impedance generator differential

Figure 19—Alternate stator winding protection using high-impedance differential relays (*Concluded*)

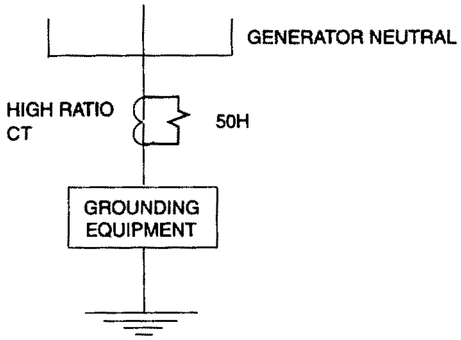


Figure 20—Scheme 20: Generator neutral overcurrent protection for the case of accidental solid neutral grounding

7. Protective device function numbers

All of the different protection schemes, illustrated in figures 1 through 20 and described in clause 6, utilize protective relays that are represented or designated by device function numbers It is the purpose of this clause to define, in broad terms, the following required characteristics of the relays designated by these numbers. Specific definitions for device numbers are found in IEEE Std C37.2-1991.

a) *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.
b) *Device* 27. This is an instantaneous third harmonic undervoltage relay.
c) *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.
d) *Device 50H*. This is an instantaneous overcurrent relay. There is no need to desensitize this device to third harmonic current because of its relatively high pickup setting.
e) *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.
f) *Device 51*. This is a sensitive time overcurrent relay. The time delay is inversely related to the magnitude of the input current. The sensitivity of this relay and its current transformer to fundamental current 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 third harmonic current should be such that the maximum third 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 annex A.
g) *Device 51I*. This is a time delayed overcurrent device that is only sensitive to lower than fundamental frequencies.
h) *Device 51L*. This is a standard time overcurrent relay. The time delay 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.
i) *Device 59*. This is a time delay overvoltage relay that is designed to be very sensitive to fundamental frequency voltage but insensitive to third 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.

j) *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.
k) *Device 59D*. This is an instantaneous third harmonic voltage differential relay.
l) *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.
m) *Device 59I*. This is an instantaneous overvoltage relay, very sensitive to the fundamental frequency voltage and to somewhat lower frequencies, but insensitive to the third and higher harmonics. See device 59 for additional information.
n) *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.
o) *Device 59T*. This is an instantaneous overvoltage relay sensitive to the third harmonic component.
p) *Device 59X*. This is an ac-operated, self-reset multicontact auxiliary relay.
q) *Device 86*. This is a hand reset, multicontact, dc-operated auxiliary relay.
r) *Device 87*. This is a conventional generator percentage differential relay.
s) *Device 87H*. This is a high-impedance phase or ground differential relay: whose sensitivity is independent of the load current and requires no coordination with external relays and devices.
t) *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.
u) *Device 87NH*. This is a 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.

Annex A Ground protection example for a high-resistance grounded generator

(Informative)

The example below illustrates two methods of calculating the resulting fault voltages and currents in a resistance type grounded generator. The two methods are

a) Symmetrical components analysis
b) Phasor diagram analysis

Sample calculations for a ground fault neutralizer application, including a comparison of performance (ability to limit fault current and sensitivity to fault resistance) against resistance type grounding are illustrated in the annex of [B32] . Additional examples for calculating high-resistance grounding and resonant grounding can be found in annexes A and C.1 of IEEE Std C62.92.2-1989.

A 974 MVA, 22 kV generator is unit-connected to a 345 kV transmission bus and grounded through a distribution transformer as shown in figure A.1. 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)^2.

$$R_n = 0.738 \cdot (13280/240)^2 = 2260\ \Omega$$

A.1 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 a) of figure A.2 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 zero-sequence capacitance, and therefore can be neglected. For a unit-connected generator, the zero-sequence network is open at the delta 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 b) of figure A.2.

$$I_0 = I_{0n} + I_{0c}$$

where

I_0	is the total zero-sequence fault current
I_{0n}	is the zero-sequence current flowing in the neutral resistor
I_{0c}	is the zero-sequence current flowing in the distributed capacitance

The total fault current I_f is equal to $3I_0$, which is equal to $I_n + I_c$.

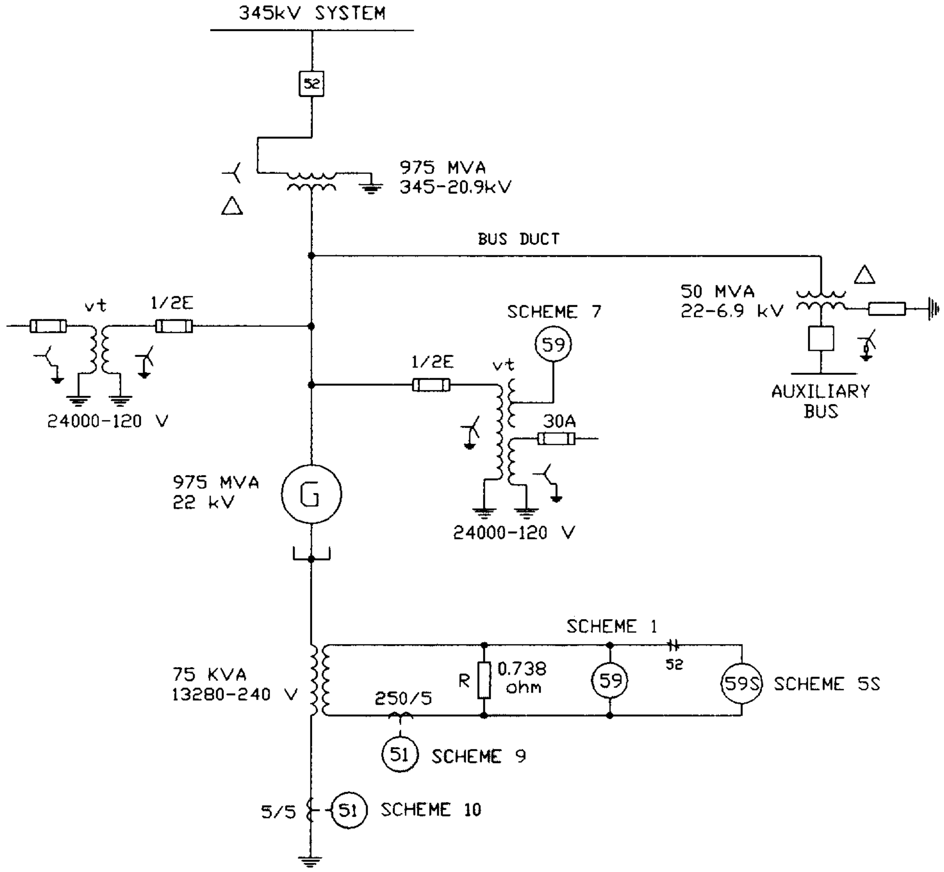


Figure A.1—Typical generator ground protection one-line diagram

The current through the generator neutral for a single phase-to-ground fault at the generator terminals is

$$I_n = 3I_{0n} = \frac{3E_{lg}}{3R_n} = \frac{E_{lg}}{R_n}$$

The fault-current contribution from the capacitance is

$$I_c = 3I_{0c} = \frac{3E_{lg}}{-jX_c} = \frac{j3E_{lg}}{X_c}$$

where

E_{lg} is the generator phase-to-neutral voltage

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

R_n equals 2260 Ω

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

$$I_c = j\frac{12\,700 \cdot 3}{6780} = J5.62 \text{ A}$$

$$I_f = 5.62 + j5.62 = 7.95\angle 45°\text{A}$$

I_s is the generator neutral current multiplied by the turns ratio of the distribution transformer. This current flows in the distribution transformer secondary wiring and through the resistor.

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

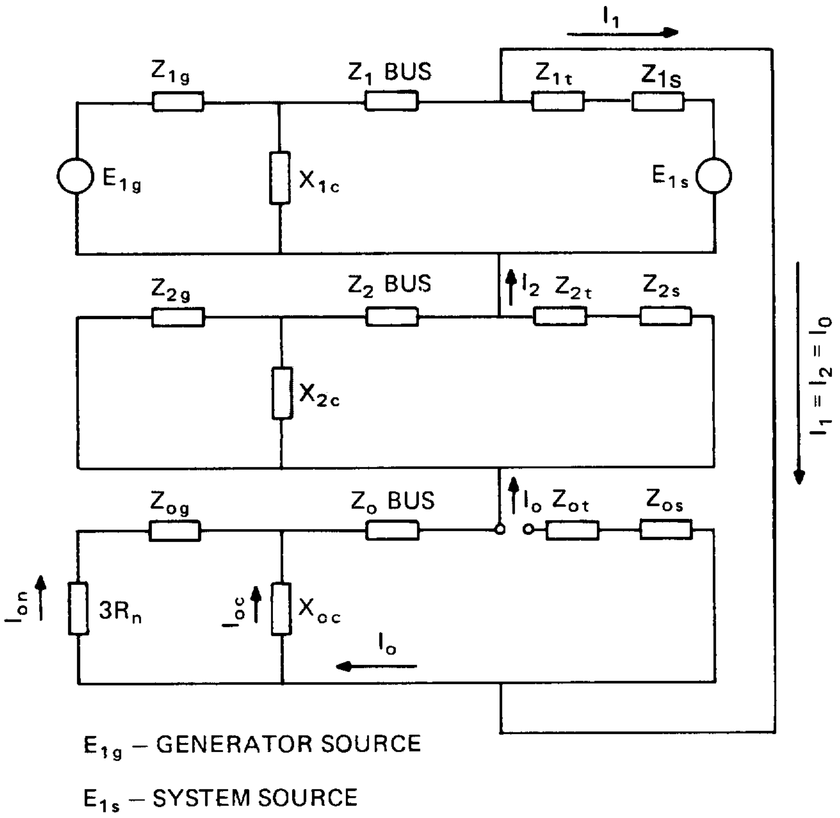
The voltage across the secondary resistor is

$$V_R = I_s R = 311 \cdot 0.738 = 229.5\ \text{V}$$

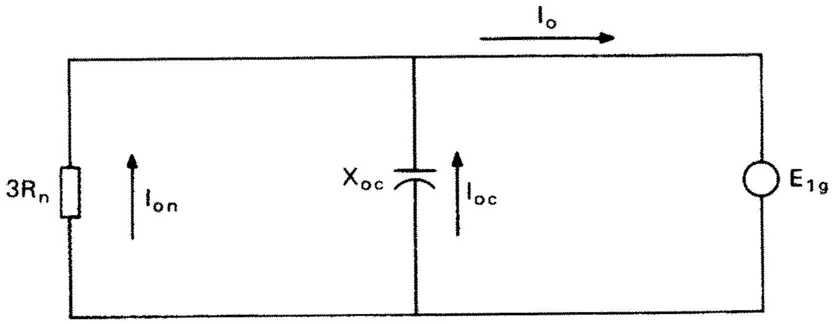
The KVA rating of the grounding transformer is

$$\text{KVA} = I_s \cdot \text{transformer secondary voltage rating (kV)} = 311 \cdot 0.240 = 74.65$$

Therefore, select a 75 KVA transformer.



a) Symmetrical component equivalent circuit



b) Reduced symmetrical component equivalent circuit

Figure A.2—Phase-to-ground-fault symmetrical component equivalent circuit

A.2 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 a) of figure A.3. In a balanced three-phase system, the neutral current will be zero, as illustrated in b) of figure A.3. The capacitive current in each phase is

$$I_{cx} = \frac{E_x}{-jX_c} = \frac{12700\angle 0°}{6780\angle -90°} = 1.87\angle 90°\ \text{A}$$

$$I_{cy} = \frac{E_y}{-jX_c} = \frac{12700\angle 240°}{6780\angle 90°} = 1.87\angle 330°\ \text{A}$$

$$I_{cz} = \frac{E_z}{-jX_c} = \frac{12700\angle 120°}{6780\angle 90°} = 1.87\angle 210°\ \text{A}$$

The sum of the current is

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

$$I_c = 1.87\angle 90° + 1.87\angle 330° + 1.87\angle 210°$$

$$= 0$$

If we place a line-to-ground fault on phase X between the generator stator terminal and the bushing of the generator step-up transformer, the equivalent circuit will be shown in c) and d) of figure A.3.

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

$$E_x - l_1(-jX_c) + I_2(-jX_c) - E_y = 0 \tag{A1}$$

$$E_x - E_y - l_1(-jX_c) + I_2(-jX_c) = 0 \tag{A2}$$

$$E_y + l_1(-jX_c) - I_2(-jX_c) - I_2(-jX_c) - E_z = 0 \tag{B1}$$

$$E_y - E_z + l_1(-jX_c) - 2\mathrm{I}_2(-jX_c) = 0 \tag{B2}$$

$$-I_3R_n - E_x = 0 \tag{C1}$$

$$I_3 = \frac{-E_x}{R_n} \tag{C2}$$

Adding equations 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 equation A2

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

From c and d of figure A.3

$$I_f = I_1 - I_3$$

$$I_{cy} = I_2 - I_1$$

$$I_{cz} = -I_2$$

$$E_x = 12\ 700\angle 0°\ \mathrm{V}$$

$$E_y = 12\ 700\angle 240°\ \mathrm{V}$$

$$E_z = 12\ 700\angle 120°\ \mathrm{V}$$

$$R_n = 2\ 260\ \Omega$$

$$X_c = 6\ 780\ \Omega$$

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

$$I_{cy} = \frac{12700\angle 240° - 12700\angle 0°}{6780\angle -90°} = 3.24300\angle°\ \mathrm{A}$$

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

$$I_{cz} = \frac{12\ 700 < 120° - 12\ 700 < 0°}{6780 < -90°} = 3.24 < 240° A$$

$$I_c = I_{cy} + I_{cz} = 3.24\angle 300° + 3.24\angle 240°$$

$$I_c = 5.62\angle 270°\ \mathrm{A}$$

The current in generator neutral is

$$I_n = -I_3 = \frac{E_x}{R_n} = \frac{12\ 000\angle 0°}{2260\angle 0°}$$

$$I_n = 5.62\angle 0°\ \mathrm{A}$$

From d) of figure A.3 the total fault current is the sum of the capacitive and neutral current.

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

$$I_f = 3 \cdot \frac{12\ 700\angle 0°}{6780\angle -90°} + \frac{12\ 700\angle 0°}{2260\angle 0°}$$

$$I_f = 5.62\angle 90° + 5.62\angle 0°$$

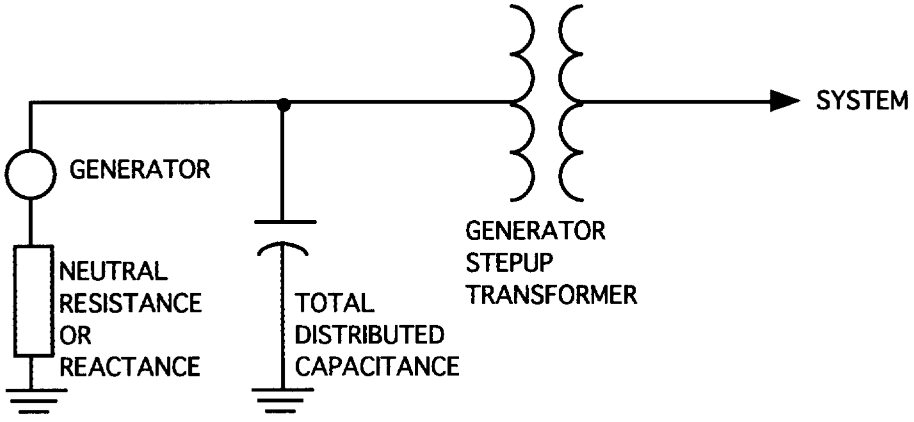
$$I_f = 7.95\angle 45°\ \mathrm{A}$$

Also from c of figure A.3:

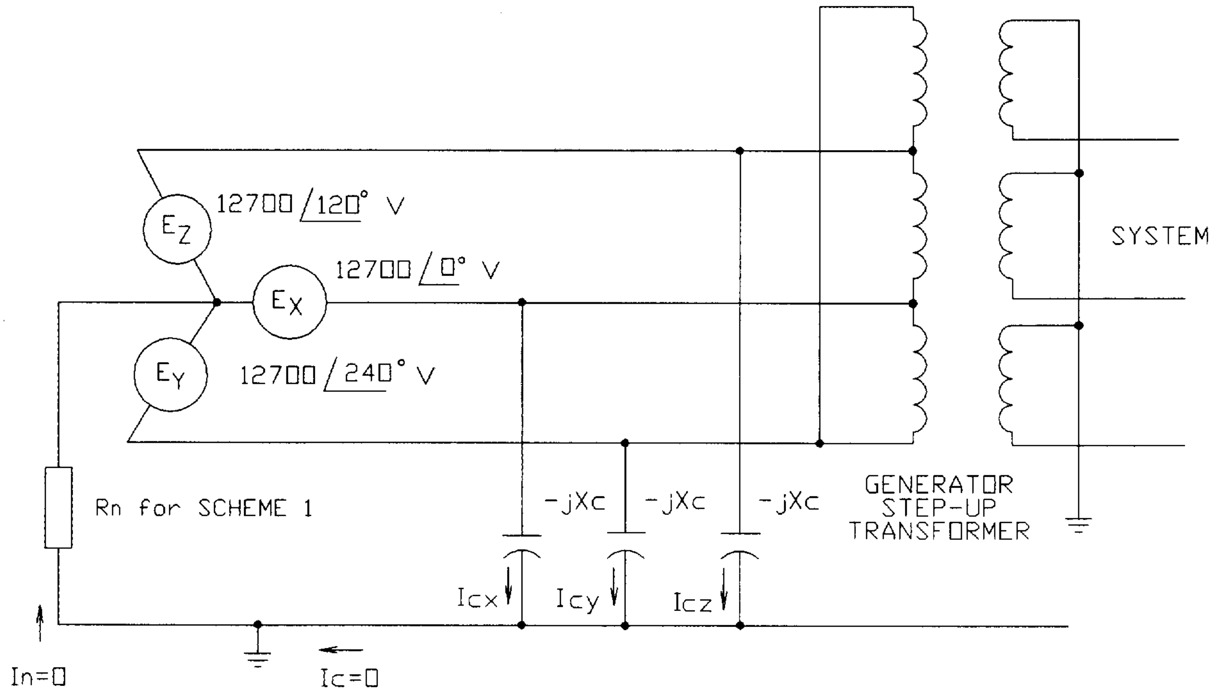
$$I_f = I_n - I_c = 5.62\angle 0° - 5.62\angle 270°$$

$$I_f = 7.95\angle 45°\ \mathrm{A}$$

Figure A.3e) 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.

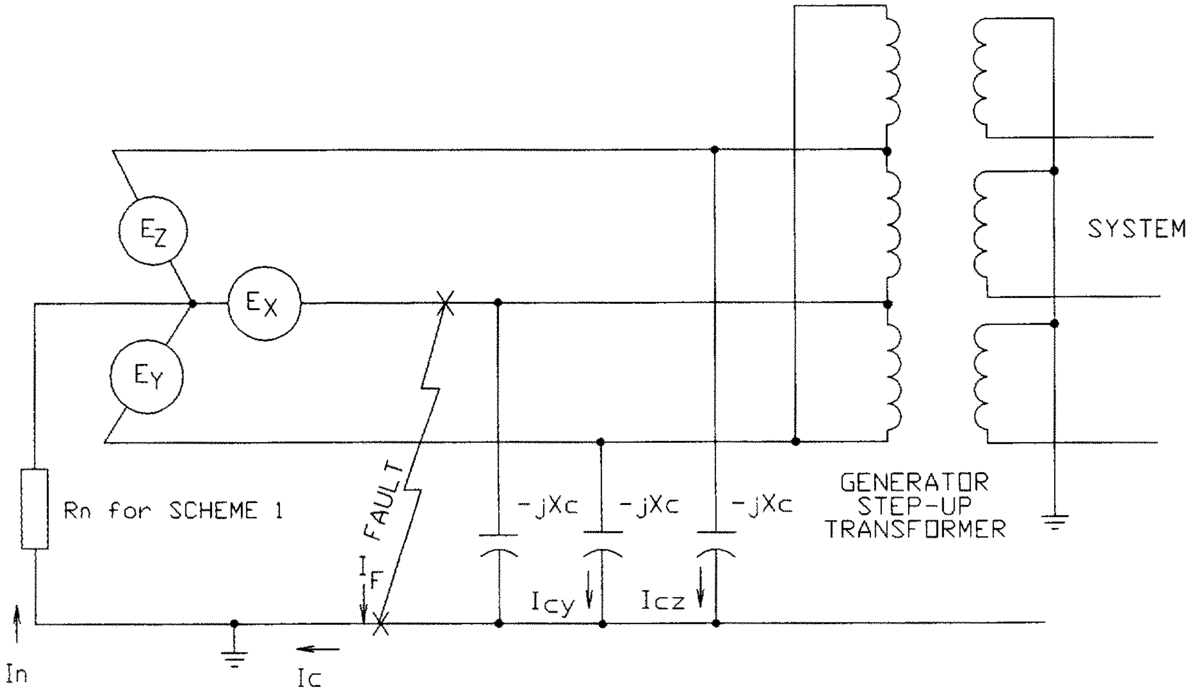


a) Equivalent single-line diagram

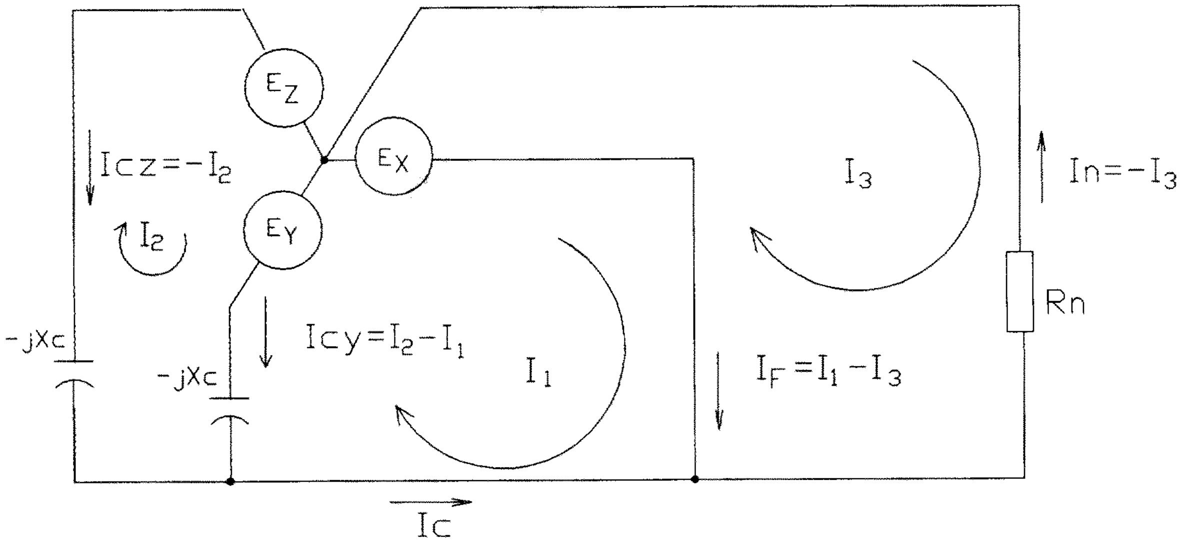


b) Normal currents during balanced load conditions

Figure A.3—Phase-to-ground-fault capacitive reactance equivalent circuits and phasor diagrams

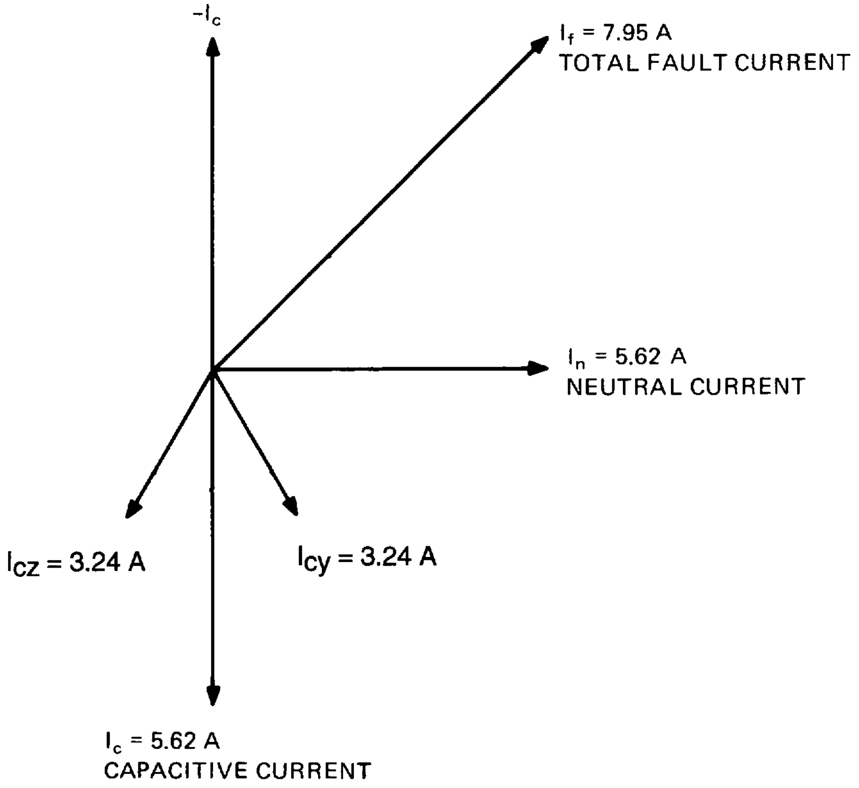


c) Equivalent network during line-ground fault



d) Loop current network for line-ground fault high-reactance grounding

Figure A.3—Phase-to-ground-fault capacitive reactance equivalent circuits and phasor diagrams (*Continued*)



e) Current relationships during fault

Figure A.3—Phase-to-ground-fault capacitive reactance equivalent circuits and phasor diagrams (*Concluded*)

A.3 Relay applications

A.3.1 Scheme 1 relay settings

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

$$\frac{5.4}{29.5} \cdot 100 = 2.35\%$$

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.

A.3.2 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.

A.3.3 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 $3E_0/N = 3 \cdot 12\,700/200 = 191$ V. This application will require that the relay has a continuous rating of 199 V. If the relay is set at 24 V pickup and 10 time dial, this relay will coordinate closely with the primary-voltage transformer fuses and will detect single-phase-to-ground faults to within $(24/191) \cdot 100 = 12.6\%$ of the neutral. The primary current at relay pickup will be 1.0 A ($12.6\% \cdot 7.95 = 1.0$). This is satisfactory for a backup relay to scheme 1.

A.3.4 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 the third. 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 at or near full load.

This value should not exceed 75% of the ground relay setting. Assuming a maximum operating current of 0.3 A, the generator ground overcurrent relay may be set at 0.5 A pickup. This setting will provide protection for all but $0.5 \cdot 100/6.2 = 8.1\%$ 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 step-up 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 to be adequate if a very inverse relay is used.

A.3.5 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 wye-wye with both neutrals grounded. Figure A.1 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 transformer fuses may be used to limit multiphase fault current to within the interrupting rating of the fuse.

Figure A.4 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 figure A.4, 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 voltage is 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 figure A.4. For problems associated with voltage transformer grounding on GFNs scheme 6, see [B36] .

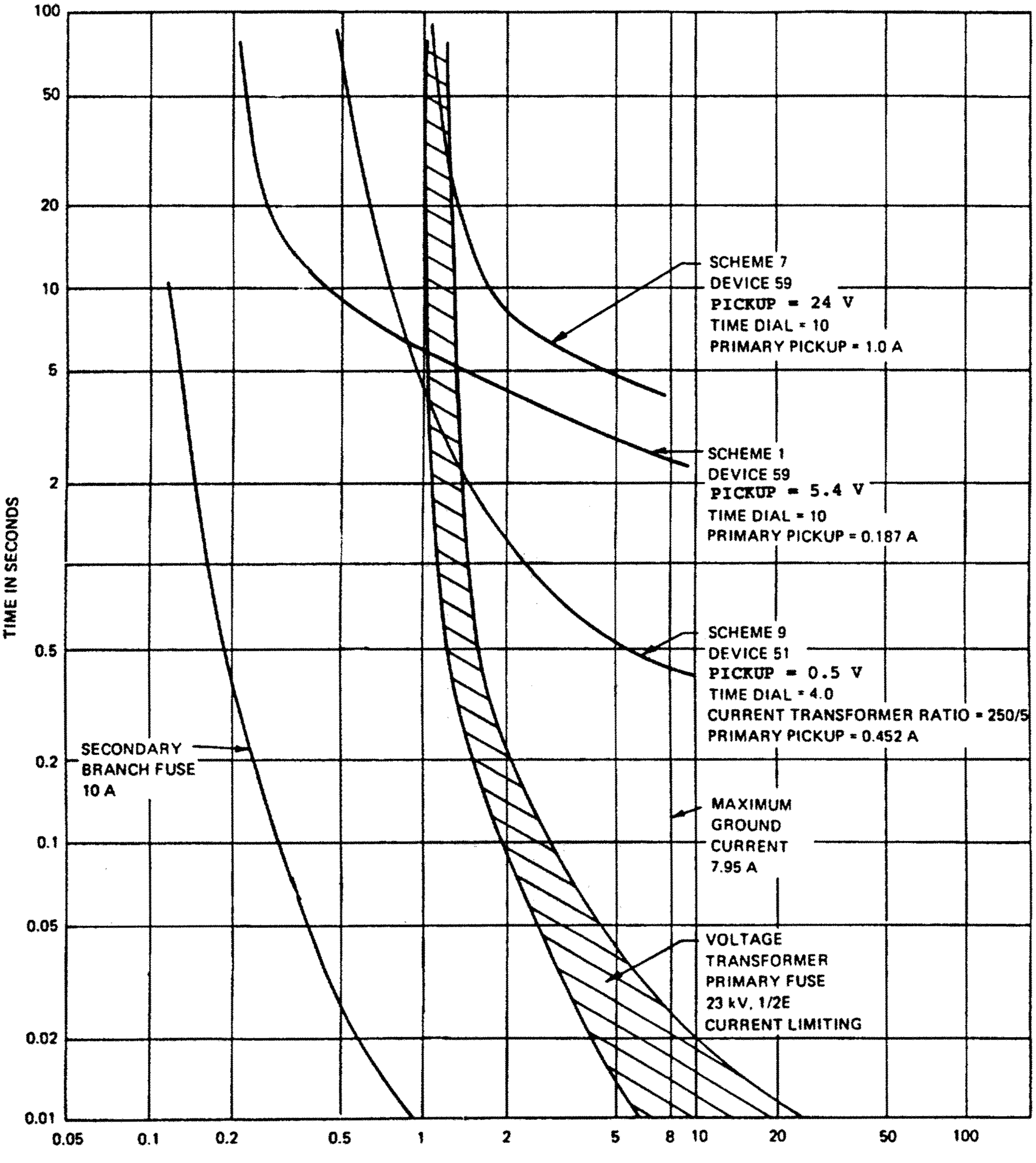


Figure A.4—Relay and fuse coordination curves

Annex B Ground protection example to determine the percent coverage of a high-impedance differential relay

(Informative)

The example below illustrates a procedure used to determine the percent coverage of a high-impedance differential relay.

A diesel generator with a terminal voltage of 4.16 kV and rated at 4.085 MVA is protected using high-impedance differential relays connected per figure 18a. The one-line diagram is shown in figure B.1 together with the pertinent impedance values.

The generator neutral is grounded through a 6 Ω resistor that limits ground-fault current to approximately 400 A. The bushing current transformers have a ratio of 1200/5, and their secondary excitation curve is shown in figure B.2. The high-impedance relay setting is based on assuring that the relay will not operate for the maximum external fault at the generator terminals assuming that the terminal cts saturate completely and that the neutral cts do not saturate at all. The voltage that appears across the junction point of the paralleled cts for this worst case condition is equal to the loop resistance times the secondary fault current.

$$V_J = (R_S + P \cdot R_L)\frac{I_F}{N} \tag{1}$$

where

V_J is the junction voltage
R_S is the dc resistance of fault ct secondary windings and leads = 0.66 Ω
R_L is the single conductor dc resistance of ct cable from junction point to fault ct = 0.397 Ω
P is 1 (3ϕ fault); 2 (ϕG fault)
I_F is the primary RMS fault current (phase value)
N is the ct ratio = 240

Since the differential relays are connected to provide both phase fault and ground fault protection, and the ground fault current is limited to approximately 400 A, the maximum fault that must be considered is a three-phase fault at the terminals of the generator.

$$I_F(3\phi) = \frac{1}{X_d''}$$

= 1/0.04995 = 20.02 pu

The primary RMS fault current in amperes is

$$I_F = \frac{KVA_{base}}{\sqrt{3}KV_{base}}(20.02)\ A = \frac{(4\,085)(20.02)}{\sqrt{3}(4.16)} = 11\,350\ \text{A}$$

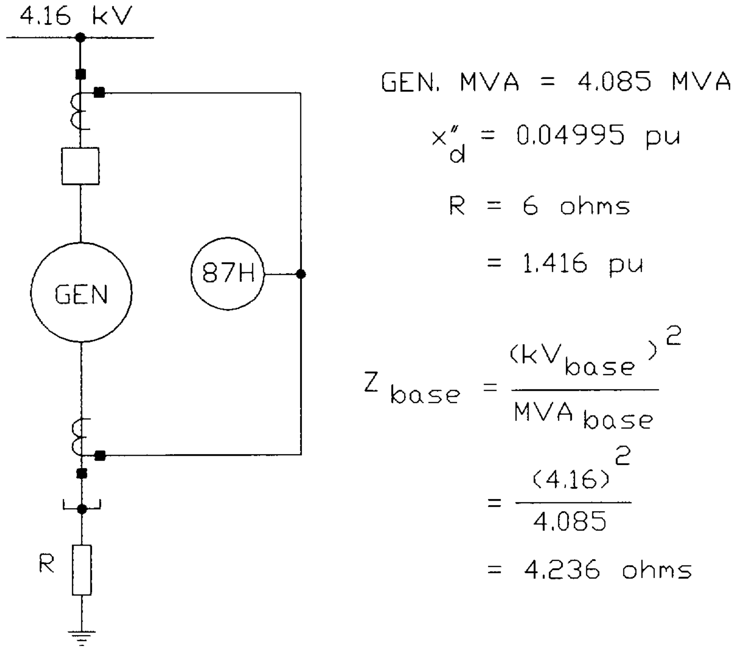


Figure B.1—One-line diagram for the example for scheme 19

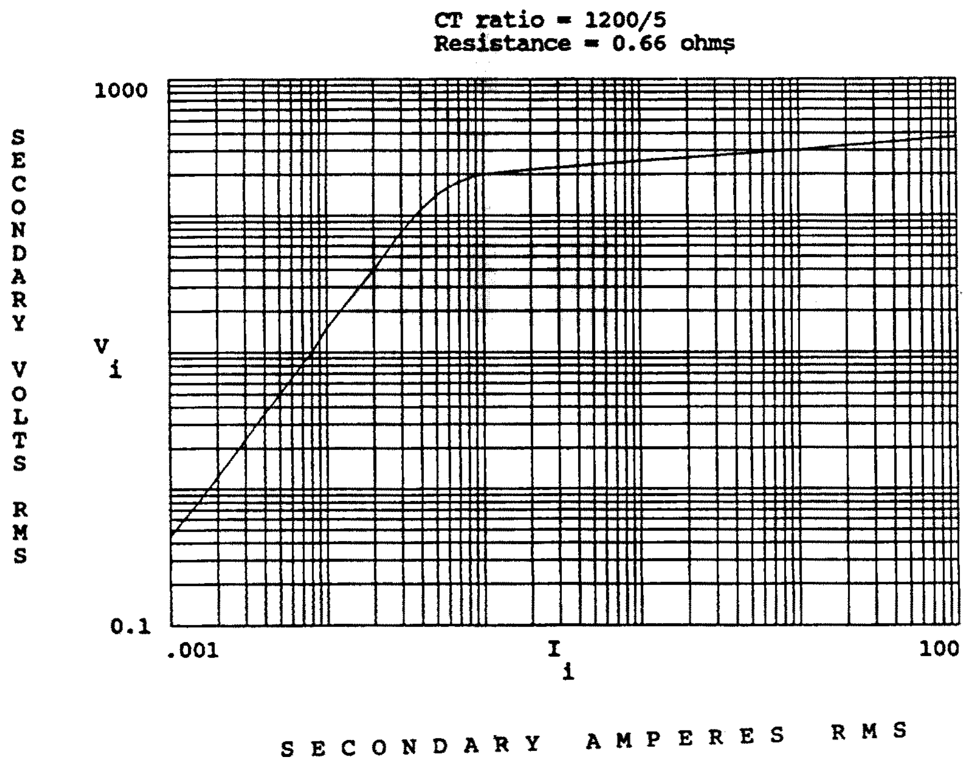


Figure B.2—Secondary excitation curve for the example for scheme 19

Evaluating equation (1) yields

V_J = (0.66+ 1 (0.397)) (11 350/240) = 50 V

Assuming a 50% safety margin, the relay voltage setting is

V_R = 1.5(50) = 75 V

Now that a secure pickup setting has been determined, the minimum internal fault current required to trip the high-impedance differential relay must be calculated. The following equation (2) below is used:

$$I_{MIN} = N\left[\sum_{x=1}^{n}(I_e)_x + I_r + I_l\right] \tag{2}$$

where

I_{MIN}	is the minimum internal fault current
n	is the number of parallel cts = 2
I_e	is the secondary excitation current of each ct at 75 V
I_r	is the current in relay at 75 volts
I_1	is the current in voltage limiting non-linear resistor at 75 V
N	is the ct ratio = 240

From the secondary excitation curve of figure B.2, I_e = 0.03 A at 75 V. Given that lite impedance of the relay operating circuit is 1700 Ω, then

I_r = 75/(1700) = 0.044 A

This example assumes that the relay used has a voltage limiting non-linear resistor connected across the relay operating coil. I_1 is determined from curves provided by the manufacturer. Evaluating equation (2) yields

I_{MIN} = 240(2(0.03) + 0.044 + 0.01) = 27.4 A

The percentage of the stator winding covered is determined by

$(1 - 27.4/400) \cdot 100\% \approx 93\%$

where I_{MIN} = 27.4 A and the maximum ground fault current at the terminals of the generator = 400 A. Therefore, ground faults in 93% of the stator windings can be detected.

With the generator breaker closed, fault contribution from the system to the generator ground fault will increase the percentage coverage. The fault contribution from the system creates additional relay operating voltage.

Annex C Bibliography

(Informative)

C.1 Analysis of ground fault transients

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