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GROUNDING AND GROUND FAULT PROTECTION OF MULTIPLE GENERATOR INSTALLATIONS ON MEDIUM-VOLTAGE INDUSTRIAL AND COMMERCIAL POWER SYSTEMS

PART 1 – THE PROBLEM DEFINED

An IEEE/IAS Working Group Report

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Abstract - **The paper discusses typical grounding practices and ground fault protection methods for medium voltage generator stators, highlighting their merits and drawbacks. Particular attention is given to applications of multiple generators connected to a single bus. The paper also provides an overview of the generator damage mechanism during stator ground faults. Problem areas associated with each type of grounding are identified and solutions are discussed. The paper also provides a list of references on the topic. The paper is intended as a guide to aid engineers in selecting adequate grounding and ground fault protection schemes for medium voltage industrial and commercial generators for new installations, for evaluating existing systems, and for future expansion of facilities, to minimize generator damage from stator ground faults. These topics are presented in four separate papers, Part 1 through Part 4. Part 1 covers scope, introduction, user examples of stator ground failure, and theoretical basis for the problem. Part 2 discusses various grounding methods used in industrial applications. Part 3 describes protection methods for the various types of grounding and Part 4 provides a conclusion and bibliography of additional resource material.**

I. SCOPE OF PAPER

In recent years severe damage to bus-connected generators from stator ground faults has been observed in numerous industrial plants. Such generator failures may require extensive stator lamination repairs at the manufacturer's premises with the associated down time. The primary objective of this paper is to present methods of protecting medium-voltage industrial generators against extensive and expensive stator iron damage from internal ground faults. The paper will review the issues associated with various grounding practices and ground fault protection methods to minimize iron damage.

The paper summarizes some basic considerations in selecting grounding and ground fault protection of generators installed on medium voltage power systems with multiple ground sources and serving load directly at generator terminal voltage. The discussions also apply to generators installed in parallel with utility transformers. However, the paper excludes installations with special grounding requirements such as Independent Power Producer (IPP) connections and mining applications. Also, rotor ground faults are outside the scope of this paper.

The paper will:

a) Discuss factors requiring consideration in selecting grounding and ground fault protection schemes for medium-voltage industrial generators

b) Identify problem areas associated with grounding and ground fault protection of generators, especially for multiple units operating in parallel on medium-voltage industrial power systems

c) Provide alternate solutions to the identified problems

d) Identify items to be addressed in detail in future working group papers

The paper is organized into four parts. Part 1 covers scope, introduction, user examples of stator ground failure, and theoretical basis for the problem; Part 2 discusses various grounding methods used in industrial applications; Part 3 describes protection methods for the various types of grounding; and Part 4 provides a conclusion and bibliography.

II. INTRODUCTION

Many existing and new industrial facilities include multiple generators operating on plant distribution buses at the medium-voltage level (see Fig. 1). The trend of in-plant generation on a common bus is increasing due to low cost and simplicity. Also, the average size of bus-connected industrial generators is larger in recent years than in the past. While the economics of bus-connected in-plant generation is attractive, it imposes on the power system engineer concerns and added tasks of careful consideration regarding generator protection and equipment capabilities.

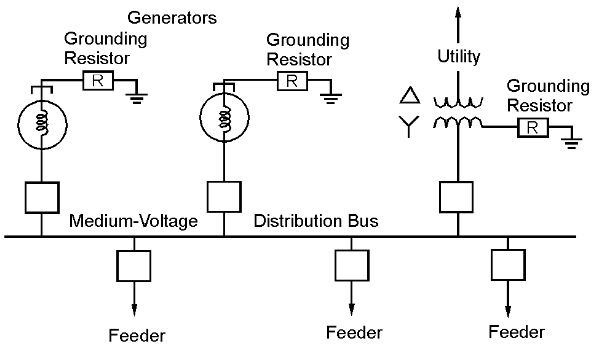

Fig. 1. Medium-Voltage Industrial Distribution System with Multiple Sources

The fault type to which stator windings are most often subjected is a short circuit to ground. Many incidents of severe damage to bus-connected generators from stator ground faults have been reported in recent years. It has been recognized by recent studies that the generator damage is caused more by the ground fault current contribution from the generator itself than from the system. During a stator ground fault in a generator, the fault current persists even after opening the generator breaker, thereby causing more extensive iron damage (see Fig. 2). The damage can be substantial even with high-resistance grounded generators when connected directly to a grounded distribution system bus. The significant increase in such incidents has alerted users and insurers. Also, multiple grounding of sources will result in very high fault currents causing severe damage and coordination problems. Therefore, special attention must be given to generator grounding and ground fault protection.

It should be noted that the method of ground fault protection is directly related to the method of system grounding used. There are many decisions, considerations and alternatives that should be carefully examined while designing an adequate and reliable grounding system for increasing personnel safety, minimizing equipment damage and avoiding unwanted interruptions in plant operation. Standards and other publications which cover generator grounding and ground fault protection are available, but they do not address specific problems associated with bus-connected multiple generator installations on medium voltage industrial systems. Therefore, concern and confusion exists among engineers regarding the appropriate application of grounding and ground fault protection for such installations.

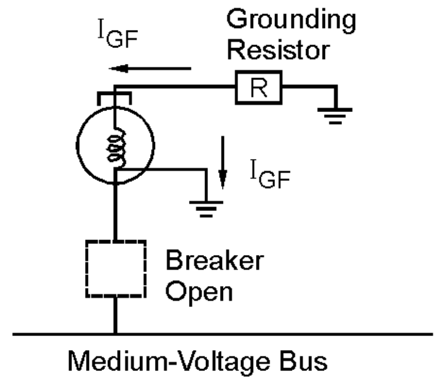

Fig. 2. Generator Internal Ground Fault – Current Flow after Opening Generator Breaker

III. EXAMPLES OF STATOR GROUND FAILURES

A large paper mill had the experience of having two generator failures approximately one year apart. Each of the two air cooled units, installed in 1971, was rated 15,625 kVA, 13,800 V. Each generator was wye-connected and grounded through its own 400 A grounding resistor. See Fig. 3 for simplified single-line diagram of the generator protection system. The protective scheme included the standard electromechanical relay protection as listed in Table 1. The total system ground current available was 2,000 A from three generators and two utility tie transformers.

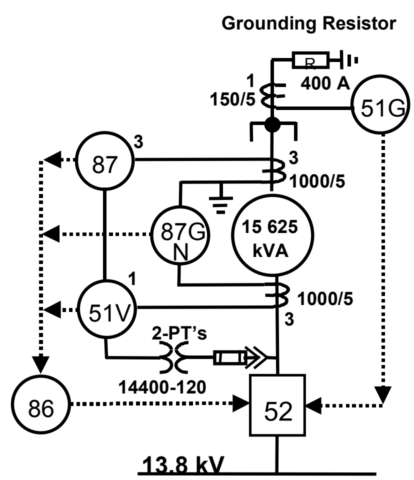

Fig. 3. Simplified Single-line Diagram of Example System

Table 1

Protective relays					
No.		CT	Tap	TD	Type
51G	Ground overcurrent	150:5	2.5	9.5	CO-9
51V	Overcurrent with voltage controlled	1000:5	4.0	10	COV-9
87	Phase differential	1000:5	Factory set at 0.14 A		SA-1
87GN	Ground differential	1000:5	1A M=1	1	ICC51A

The first unit to fail tripped off line as the result of a winding failure at a position approximately 25% electrically from the line terminals of Phase 3 winding. The stator winding was burned over an area of approximately 8 inches in length. The core steel was also burned approximately 8 inches, thus requiring its replacement. The restacking of the core steel could only be accomplished by removing the stator and shipping it to the manufacturer's plant.

The generator field was shipped to a service shop and the retaining rings were removed. There was splattered copper and steel with burned insulation from the stator winding imbedded in the field winding end turns. Copper contamination was also located in the field's cooling passages.

The total cost to rebuild the stator core, rewind the stator, rewind the field, and upgrade the generator protection was approximate $1,500,000. The incremental cost to remove, ship, replace the core steel, and reinstall the stator contributed approximately $500,000 of this total cost.

Subsequent investigation revealed that the 400 A grounding resistor was installed in such a manner that the ground lead could possibly short out 25% of the resistor grid. As a result, the actual ground fault current could have been as much as 20% greater than the design value. The second unit was tripped off line due to phase differential relay (device 87) operation. The winding failed in the middle of the Phase 1 coil, in a similar manner to the previous unit. The coil burning was approximately 10 inches long. The field winding also had splattered copper from the stator failure on the end turns. The stator core of this unit also had to be restacked due to the damage.

Investigation of the second unit revealed that the operating times of the phase differential (device 87) and ground differential (device 87GN) relays allowed the 87 device to pickup prior to the 87GN device. Both units utilized field breakers that were opened when the fault was detected. It was felt that both of these units failed initially due to an internal turn-to-turn short in the coil which quickly escalated to a phase-to-ground fault.

Figures 4 and 5 below show photographs of the generator parts that failed as described above. Fig. 4 shows the generator winding failure as viewed from inside the unit. Fig. 5 shows the burning of a stator lamination resulting from winding failure. Fig. 5 photograph was taken after removal of the laminations from the stator up to the area of the failure.

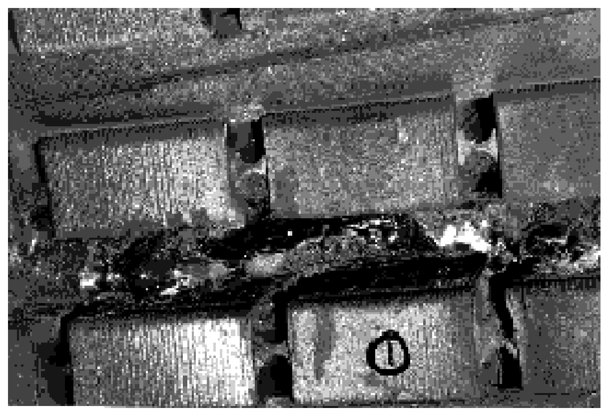

Fig. 4. Generator Winding Failure

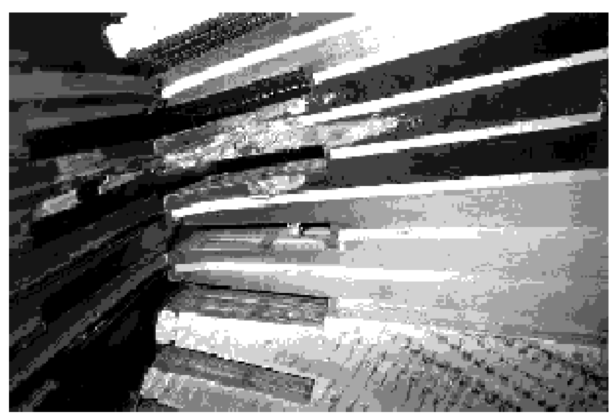

Fig. 5. Core Damage

IV. THEORETICAL BASIS FOR THE PROBLEM

The one-line diagram, shown in Fig. 6, depicts a simplified industrial system of a medium voltage bus with one generator and one utility step-down transformer. While any resistor rating could be chosen for this example, to make it as general as possible, both resistors will be assumed to be rated 400 A, for a maximum system ground fault level of 800 A.

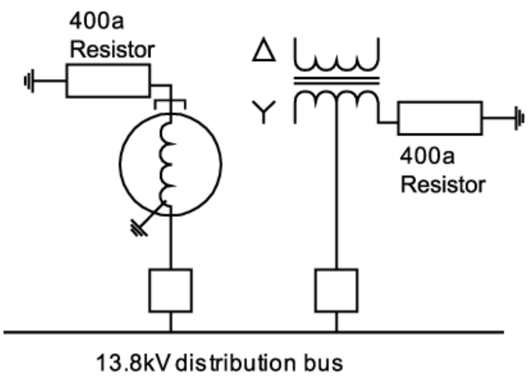

Fig. 6. Typical One-Line Diagram

Faults inside generators and transformers will be limited by the impedance of the generator or transformer winding and therefore will be lower in magnitude than faults on the bus. Therefore, the most severe fault condition for a generator (or motor) is a fault directly at the terminals on the first turn of the stator winding. For the system illustrated in Fig. 6, this fault will have a magnitude equal to the system maximum of 800 A, with 400 A flowing into the generator from external sources ("system sources") and 400 A generated within the generator itself. The potential damage associated with each of these currents can be considered separately and the total damage determined by superposition.

An intuitive expectation is that the damage caused by a fault inside a generator is proportional to the energy released in the arc at the fault point. A general expression for the energy released in a fault is

$$Energy = \int i^k \, dt \qquad (1)$$

Therefore, the damage associated with a fault is a function of two variables, the magnitude of current, i, and the duration of the fault, t.

The value of k in (1) is also a factor. A value of 2 would apply in the case of purely resistive heating. Various researchers have predicted values for k for an arc in the range of 1 to 2 [2, 3]. The purpose of this paper is to address the system design implications of stator fault point damage, not to suggest an exact value of k. Therefore, it is sufficient for this analysis to arbitrarily pick a value (k=1.5) for the purpose of illustration.

a) Stator Damage Due to Current Through the Transformer Neutral (System Current)

The technology of stator ground fault detection ranges from the conventional stator differential relay to modern detection modalities that can detect faults very close to the neutral end of the winding. For this hypothetical worst case scenario, therefore, it is reasonable to assume that the fault will be detected and tripping will be triggered with no intentional time delay. Allowing for one cycle of relay time with a five-cycle breaker, the 400 A current from the resistor on the utility step-down transformer will persist for six cycles (0.1 seconds on 60Hz systems). Therefore, a damage parameter associated with the externally-sourced ground fault can be determined by evaluating this integral expression of (1) over the six-cycle period during which this current will flow.

The curves shown in Fig. 7 depict the damage indices viewed in two ways. Fig. 7a shows that the potential damage increases as the current rating of the neutral grounding resistor on the transformer becomes larger. Fig. 7b shows how the damage accumulates with time for the singular case of a 400 A resistor on the transformer neutral. This curve is plotted on semi-logarithmic axes in order to depict more clearly the way that the damage accumulated during the six-cycle period of time prior to opening the generator breaker. Note that all of the damage associated with current from the resistor on the step-down transformer takes place during this short period.

Tripping the generator breaker does not interrupt the current that rises through the generator neutral. This current will flow as long as the generator field remains excited as a forcing function. Tripping the generator breaker should also trigger tripping the field, but the excitation will decay gradually under the control of the generator single-line-to-ground short-circuit time constant, τ. While this parameter does vary from one generator to the next, it falls in the range of 0.8-1.1 sec. Thus, the damage index associated with current produced by the faulted generator itself can be calculated using an expression similar to (1) in which the current is a decaying exponential. This integral must be evaluated over the entire period of time required for the current to decay to zero.

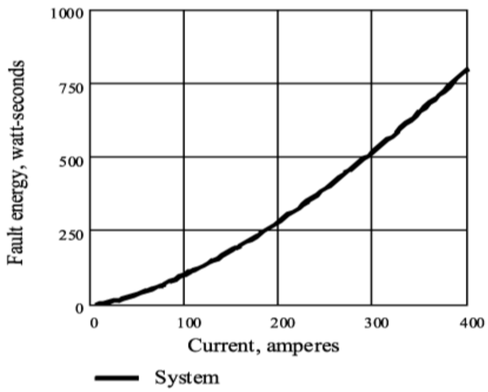

Fig. 7a. Energy due to "System Current – for Various Magnitudes of Current

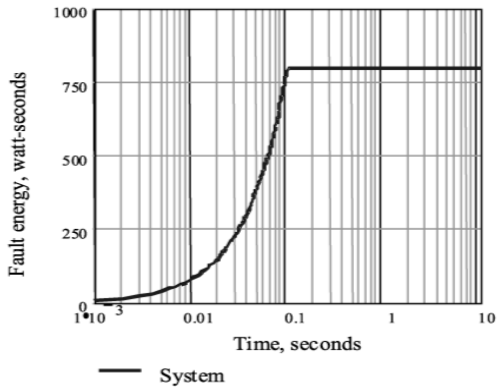

Fig. 7b. Arc Energy due to 400 A "System Current" Over Time

b) Current From the Faulted Generator

$$Energy = \int \left[I\varepsilon^{\frac{-t}{\tau}} \right]^k dt \qquad (2)$$

Fig. 8a shows the damage associated with the generator current for various ratings of the generator resistor up to a maximum of 400 A. Again, it is apparent that higher resistor ratings will result in greater damage. But note that in this instance, the maximum value of this damage parameter is about 5,200 watt-seconds compared with about 800 watt-seconds in Fig. 7a.

The reason for this difference is apparent in examining Fig. 8b. Note that the fault energy associated with current through the generator neutral resistor accumulates for several seconds of time, not just the 0.1 seconds depicted in Fig. 7b. This is because the fault current continues to flow until the generator field de-magnetizes; there is no breaker to interrupt fault current through the generator neutral itself.

Comparing Figs. 7 and 8 yields two very important observations.

1) In this simple case with one generator and one transformer, each of which is low-resistance grounded, most of the damage in the faulted generator is attributable to current from the generator itself. That is, most of the generator damage is self-inflicted. Therefore, changing generator grounding practices would have far more impact on reducing stator ground fault damage than changing system (transformer) grounding practices. Obviously, increasing the number of "system sources" will result in increased damage, and with enough external sources, the damage due to system current could exceed the damage due to current through the neutral of the faulted generator.

2) Most of the "self-inflicted" damage takes place after the generator breaker trips. Thus, while the importance of fast generator protection cannot be overemphasized, faster protection does not necessarily mean less damage because tripping the generator breaker does not interrupt the flow of current through the generator neutral.

Large generators are rarely bus-connected. Instead, the generator is associated with a dedicated step-up transformer, and other than perhaps station auxiliaries, no load is served at generator terminal voltage. This is known as a "unit-connected" generator (see Part 2 of the paper for details). Because there is no distribution system selectivity requirement, these generators are almost always grounded through distribution transformers equipped with secondary loading resistors. In these applications, the worst case ground fault current is typically limited to 10 A. Fig. 9 shows how potential fault damage increases through time, assuming that the initial magnitude of ground fault current is limited to 10 A.

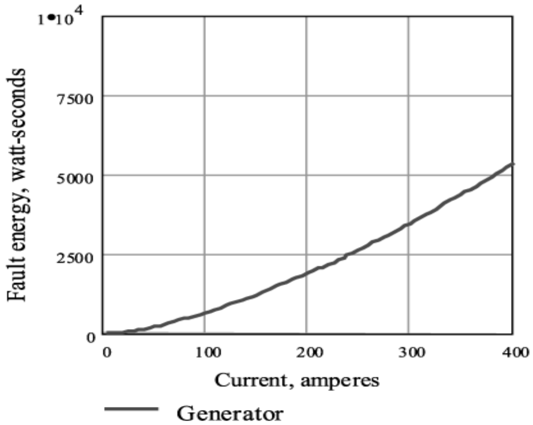

Fig. 8a. Fault Energy due to “Generator Current” – for Various Magnitudes of Current

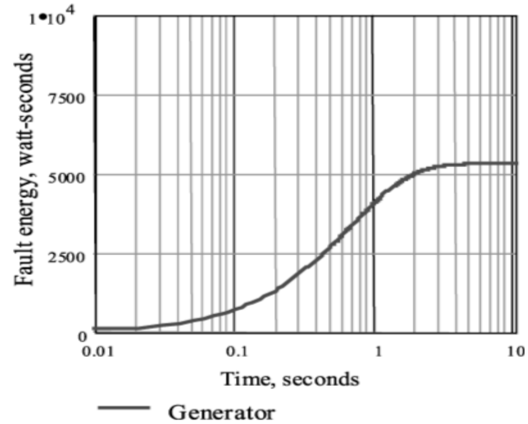

Fig. 8b. Arc Energy due to 400 A “Generator Current” Over Time

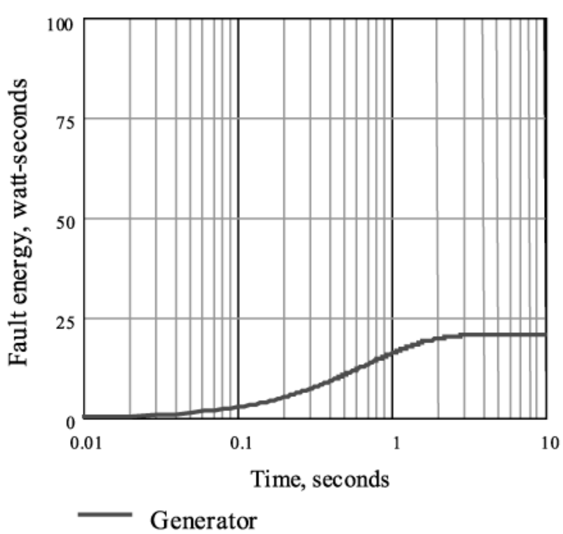

Fig. 9. Fault Energy Versus Time with 10A Grounding

It is interesting to observe that while the frequency of iron burning on bus-connected industrial generators is increasing, there are no anecdotal reports of iron burning on unit-connected generators with stator ground faults. One researcher demonstrated that a generator can withstand fault currents up to 10 A in magnitude indefinitely without iron burning [4].

An example was given earlier of an actual system that included three generators, each rated 15,625 kVA and grounded through 400 A resistors. In addition, the system included two wye-connected utility transformers with 400 A resistors, for a total available ground fault current of 2,000 A. The analytical techniques presented here can be applied to that instance to retrospectively predict the fault energy levels that may have occurred.

The faulted generator experienced a stator ground fault at a point that would have resulted in a current in the affected stator winding of about 75% of the theoretical current that would have been allowed by the nominal rating of its neutral resistor. But because that resistor was partially shorted, the actual available current was about 20% higher than rated. Therefore, the actual fault from the generator was probably close to the theoretical 400 A available for a terminal fault.

Because the fault occurred within the winding of the generator, the sources on the system would have contributed less than their nominal currents. With a fault 25% of the way between the terminals and the neutral, those sources would have contributed a maximum of 75% of their nominal currents. Taking these factors into consideration, the curves in the Fig. 10 show the accumulation of fault energy versus time. Note that because of the large number of sources, the energy from “system sources” is significant. However, the energy from the faulted generator still exceeds the energy from “system sources” because of the time required for the stator fault current to decay.

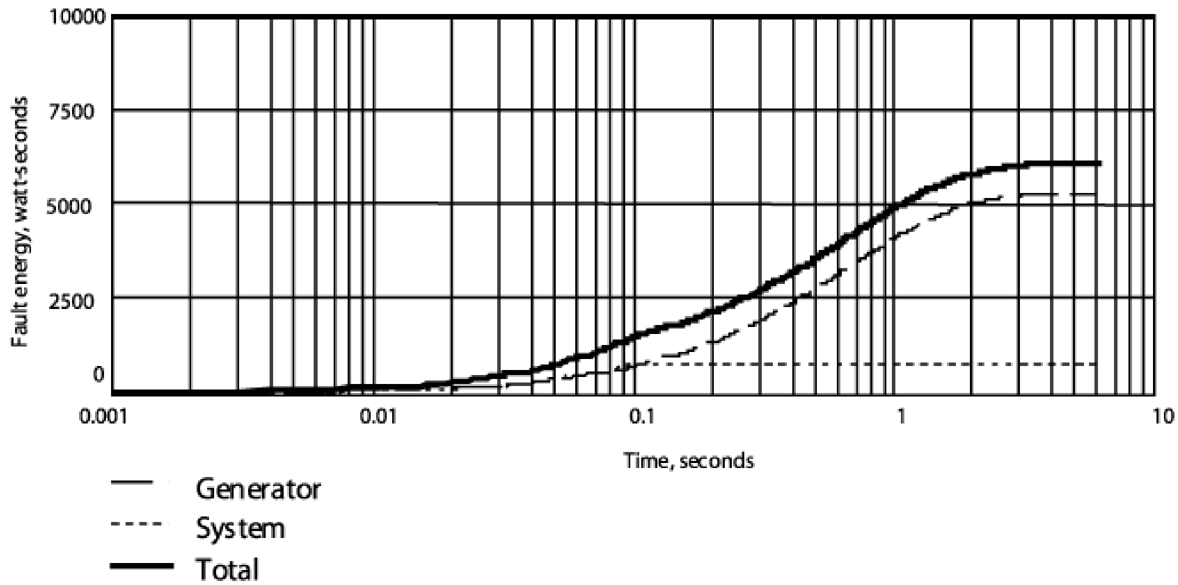

Fig. 10. Fault Energy Accumulation

V. SUMMARY

This paper presented Part 1 of a four-part Working Group Report on generator grounding and ground fault protection. Part 1 has introduced the mechanism of generator damage during stator ground faults. Actual examples are given where extensive damage occurred even after opening of the generator circuit breaker. This damage is due to the extended time required for the field to decay; thereby, maintaining the flow of current to the fault.

Part 2 of this Working Group Report discusses various grounding methods used in industrial applications, highlighting their advantages and limitations. Part 3 describes the protection methods for the various types of grounding. Part 4 of the report provides a conclusion and a bibliography of additional resource material on the subject of generator grounding and ground fault protection.

VI. REFERENCES

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GROUNDING AND GROUND FAULT PROTECTION OF MULTIPLE GENERATOR INSTALLATIONS ON MEDIUM-VOLTAGE INDUSTRIAL AND COMMERCIAL POWER SYSTEMS

PART 2: GROUNDING METHODS

An IEEE/IAS Working Group Report

[Working Group Members] - Prafulla Pillai (Chair), Alan Pierce, Bruce Bailey, Bruce Douglas, Charles Mozina, Clifford Normand, Daniel Love, David Shipp, Gerald Dalke, James R. Jones, Jay Fischer, Jim Bowen, Lorraine Padden, Louie Powell, Neil Nichols, Ralph Young, Norman T. Stringer

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Abstract - **The paper discusses typical grounding practices and ground fault protection methods for medium voltage generator stators, highlighting their merits and drawbacks. Particular attention is given to applications of multiple generators connected to a single bus. The paper also provides an overview of the generator damage mechanism during stator ground faults. Problem areas associated with each method of grounding are identified and solutions are discussed. The paper also provides a list of references on the topic. The paper is intended as a guide to aid engineers in selecting adequate grounding and ground fault protection schemes for medium voltage industrial and commercial generators for new installations, for evaluating existing systems, and for future expansion of facilities, to minimize generator damage from stator ground faults. These topics are presented in four separate parts, Part 1 through Part 4. Part 1 covers scope, introduction, user examples of stator ground failure, and theoretical basis for the problem. Part 2 discusses various grounding methods used in industrial applications. Part 3 describes protection methods for the various types of grounding and Part 4 provides a conclusion and bibliography of additional resource material.**

I. GENERAL

There are several methods of power system grounding. These include low-resistance grounded (LRG), effectively grounded, reactance grounded, high-resistance grounded (HRG), and ungrounded. Source grounding may be accomplished by the grounding of the generator(s) and/or power transformer(s). Grounding transformers may be utilized in lieu of source grounding. A brief overview of each of these grounding methods is given below.

II. LOW-RESISTANCE GROUNDED SYSTEM

In low-resistance grounding of the source generator, the generator neutral is connected to ground through a resistor, as shown in Fig. 1, Part 1. The resistor limits the ground fault current to several hundred amperes (typically 200 – 600 A). The fault current is selected to minimize fault damage but at the same time allow sufficient current for selective tripping of the protective devices. The lower limit was historically based on electro-mechanical relay sensitivity and the upper limit is based on resistor losses during a ground fault and damage to cable shields.

With multiple sources, the total ground fault current can be very high. Low-resistance grounding is generally used for generators connected to a common bus where relaying selective with feeder relaying is required. For bus-connected generators operated in parallel with transformers, connecting the wye-connected winding of the transformer to the generator bus would allow the transformer neutral to provide one ground when the generator is out of service.

There are many advantages which can be attained by using low-resistance grounding. These include sufficient fault current magnitudes to allow sensitive and selective relaying with feeders and bus-tie breakers, easy inclusion of additional sources, limitation of transient overvoltages to moderate values, and potential cost savings over other grounding methods.

There are some disadvantages associated with low-resistance grounding. The main disadvantage is the possibility of significant burning of the generator stator iron laminations from high ground fault currents, as explained in Part 1. Also, with multiple ground sources, high currents due to parallel sources can cause severe fault damage, and large variations

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of available fault current can cause relay coordination problems. Consideration should be given to selecting appropriate surge arresters for the grounding method.

For a system with multiple sources, some of the variations in the low-resistance grounding method are discussed below.

a) Single Point Grounding

Single point grounding requires that only one source be grounded at any given time. This is the simplest method of low-resistance grounding. Since there is only one ground source, it provides lower ground fault current than with multiple point grounding. Also, relay coordination is simple since there is no variation in ground current. In addition, third-harmonic circulating currents are eliminated.

The principle disadvantage of single point grounding is that if the grounded power source is out of service, the system will operate ungrounded unless an alternate ground is established. This requires special operating procedures. Grounding the system neutral through a neutral deriving transformer on the bus is an effective means of overcoming this disadvantage.

b) Multiple Point Grounding

In this method, the neutrals of individual sources (transformers and generators) are each grounded through a separate resistor with ground fault current from each source limited to the selected value. Multiple point grounding offers simplified operation and is most commonly used with low-resistance grounding, assuring that the system will always be grounded. However, resistor selection can be difficult.

When several sources are paralleled, the total ground fault current can increase to high values, causing severe fault damage. In such cases, the grounding resistance should be high enough to limit the fault current to a safe value when all of the parallel sources are in service, and should be low enough so that when source(s) are removed, sufficient fault current flows for relay operation.

Addition or removal of parallel sources causes wide variations in fault current and makes relay coordination difficult. Another problem is that the parallel paths to ground introduce the possibility of circulating third harmonic currents, which can cause overheating of the generators at less than full load.

c) Common Ground with Neutral Switching (not Recommended):

Here, each source is connected to a common neutral point through a switching device and the neutral point is grounded through the low resistance. The advantages include low ground fault current due to single ground, known maximum ground current, minimizing of the problems of varying ground current with addition or removal of generators, and simplified relay coordination. This is a previously adopted method but no longer being used due to safety issues as explained below.

There are several disadvantages with this method of grounding. The most significant is a safety issue i.e., attempting to switch the neutral at the same instant a ground fault occurs could be extremely hazardous to operating personnel, unless adequate switching devices and safety precautions are provided. Also, cost is increased due to the need for several neutral switches or circuit breakers. In addition, unless a key-interlock system is used, special operating procedures are required to close another operating ground point prior to taking the first one out. This may introduce operator errors causing ungrounded operation.

All ground sources should be in close proximity in order to allow quick interchanging of neutral switching operations, to minimize conductor length of neutral bus connection for effective grounding, and to avoid inadvertent opening of interconnection thereby preventing ungrounded operation. If the neutral is left connected when a generator is taken out of service, all the phase voltages will be elevated in magnitude during a ground fault. Also, there is a possibility of accidental contact with an energized bus that leads to the ground bus.

For these reasons, the practice of employing a common ground with neutral switching should be avoided.

III. EFFECTIVELY GROUNDED SYSTEM

For effectively grounded systems, the neutral is connected to ground through a sufficiently low impedance, intentionally inserted such that the ratio X_0/X_1 is positive and less than 3, and the ratio R_0/X_1 is positive and less than 1. These specific criteria are to limit the build-up of voltages in excess of limits established for apparatus, circuits, or systems so grounded. "Solidly grounded" systems have no impedance inserted intentionally between neutral and ground.

Since the natural zero sequence impedance of a synchronous generator is typically about half the subtransient positive sequence reactance, the ground fault current that wants to flow from a solidly grounded generator is greater than the three-phase fault current. However, NEMA standards [1] do not require that standard generators be braced for the mechanical stresses associated with unbalanced fault currents in excess of the magnitude of a three-phase fault at the terminals of the generator. Therefore, the neutrals of standard generators should not be connected to ground without some limiting impedance.

There are, however, instances in which the generator will be applied on 4-wire systems. Low-voltage emergency generators are typically designed with sufficient bracing to permit them to be solidly grounded, but medium-voltage generators almost always must have impedance inserted into the neutral to limit the ground fault current through the generator to less than the bolted three-phase magnitude.

IV. REACTANCE GROUNDED SYSTEM

Low-reactance grounding of generators is normally reserved for special applications such as those unusual instances in which the generator is connected to a bus that serves distribution loads directly at the generator terminal voltage, and where some of the loads on the distribution feeders are single-phase and connected phase-to-ground. In this special case, natural unbalances between the loads on an individual phase results in a current flow through the generator neutral. Any significant impedance between the generator neutral and ground would inhibit this current flow and thereby interfere with the ability of the generator to serve this unbalanced load. Therefore, there is a need to minimize any neutral impedance in these applications.

At the same time, NEMA standard generators cannot be effectively grounded for reasons described above [1]. These opposing objectives can be satisfied by a compromise minimum selection criterion for a generator neutral grounding reactor. That minimum reactor is one that will limit the available phase-to-ground fault current to no greater than the available three-phase fault current. In addition, generator grounding reactors must have a short time current rating sufficient for the available magnitude of phase-to-ground fault current. Standards provide for a minimum continuous thermal capability of a neutral grounding reactor equal to 10% of the short-time current rating of the reactor [2]. One of the checks that the application engineer must make is to verify that this continuous capability is sufficient for the maximum anticipated unbalanced load current.

A more challenging problem in applying neutral grounding reactors is that generators do not produce a perfectly smooth sinusoid of voltage, and any triplen harmonic content in this voltage will result in a circulating harmonic current. In most cases, the third harmonic is of concern. It is necessary to predict by some means the magnitude of harmonic voltage produced by each generator on the system in order to determine the worst-case circulating current. This is necessary to verify that the reactor has sufficient thermal capacity to withstand this current [3]. Fortunately this problem is not frequently encountered. If the problem does occur it can be prevented by the use of a 2/3 pitch winding for the generator.

Reactance grounding based on limiting the phase-to-ground fault current to the level of the three-phase fault current generally does not result in protection problems because there is ample fault current to be detected by conventional relays. In fact, a common problem is the presence of unbalanced load current that may limit the ability to employ traditional ground relays to measure residual current.

One little-known practice that is still used in some areas is to apply high-inductance neutral grounding reactors on unit-connected generators. These “Petersen Coil” or ground-fault neutralizers are selected with an inductance to match the magnitude of distributed zero sequence capacitance in the generator and the bus work up to the delta-connected generator step-up transformer winding. The advantage of this application is that fault current will be negligibly small for a system phase-to-ground fault compared to other methods [4, 5, 6].

However, it should be noted that this practice has its own problems. When the current associated with single-phase-to-ground faults is limited by neutral impedance, the consequence is that the voltage triangle shifts and there is a sustained overvoltage on the unfaulted phases. If this voltage stress is not relieved, it can accelerate insulation failure.

To be effective, the inductance of Petersen Coils must be tuned to the distributed capacitance in the system. This sometimes presents insurmountable problems in instances in which switching causes the distributed capacitance to change with various operating conditions of the system.

V. HIGH-RESISTANCE GROUNDED SYSTEM

A key advantage of high-resistance grounding is that transient overvoltages can be substantially reduced from that present on an ungrounded system.

a) System High-resistance Grounding

In high-resistance grounding, the ground current magnitude is typically limited to 10 A or less, a value equal to the normal maximum charging current magnitude for an industrial power system. Industry practice through the years has shown that ground fault currents limited to less than 10 A produce minimal damage at the fault point. Therefore, the faulted circuit need not be tripped off-line immediately when the fault first occurs. This low level of ground current requires protection schemes that are especially developed for unit-connected high-resistance grounded generators. However, if significantly greater ground fault currents are allowed to flow continuously, then unacceptable damage is sustained. For systems rated 11kV or higher, practice requires tripping due to arcing effects at this voltage.

b) Generator High-resistance Grounding

When a generator is connected to the plant distribution bus at the medium voltage level, high-resistance grounding can be a good solution for grounding the generator neutral. The generator can be high-resistance grounded regardless of the grounding method used to ground the system. While high-resistance grounding is a good choice for minimizing damage to a generator, it does not lend itself to large systems where it may not be possible to keep ground fault currents to less than 10 A. Particular attention should be given such that all system components should be rated for continuous duty at line-to-line voltage, including cable and voltage transformers. Another aspect of high-resistance grounding is that corona starts playing a significant part towards damage for systems with line-to-line voltages greater than about 7.2 kV, if continuous duty is desired (i.e., continue operating indefinitely under ground fault conditions).

c) Unit-Connected Generator Grounding

High-resistance grounding of a generator neutral is illustrated in Fig. 11. Even though this method of grounding is typically utilized on unit-connected generators, it is gaining acceptance in the industrial arena. This scheme can be economically attractive since it allows the generator to have the optimum voltage for its size.

High-resistance grounding of the generator utilizes a distribution transformer with a primary voltage rating greater than or equal to the line-to-neutral voltage rating of the generator and a secondary rating of 120V or 240V. The distribution transformer should have sufficient overvoltage capability so that it does not saturate on single-line-to-ground (SLG) faults with the generator operated at 105% of rated voltage. The secondary resistor is usually selected so that for a SLG fault at the terminals of the generator, the power dissipated in the resistor is approximately equal to the reactive volt-amperes of the zero sequence capacitive reactance of the generator windings, its leads, the windings of any transformers connected to the generator terminals, and any surge capacitors installed in this area.

For high-resistance grounding to be effective, the size of the resistor must be carefully selected for each system [7]. IEEE Standard C37.101 [8] provides a detailed example of how to determine the size of the ground resistor to meet the requirements cited above, as well as calculate the resulting ground currents and voltages. Under ground fault conditions, the resistive current must dominate over the system capacitive current but not to the point of permitting excessive current to flow and thereby, excluding continuous operation.

VI. UNGROUNDED SYSTEM

A close look at all the electrical parameters in the following ungrounded system example, will illustrate the effect grounding has on current and voltage under "bolted" ground fault conditions.

In Fig. 12, a sustained ground fault occurs on a 4.16 kV ungrounded system. Fig. 13a illustrates the system voltage profile prior to the ground fault condition. Since the system is capacitively coupled to ground through relatively high impedance, a phase-to-ground fault causes the entire system to be displaced above ground as indicated in Fig. 13b. The system will remain in this position until the fault is cleared, or another phase breaks down to form a phase-to-ground-to-phase fault.

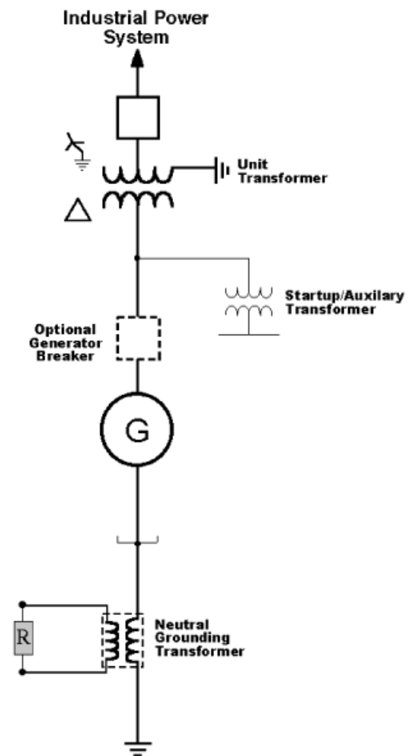

Fig. 11. High-Resistance Grounding of Unit-Connected Generator Configuration

As shown in Fig. 12, the ground fault current returns through the distributed capacitance (insulation system) of the unfaulted phases. As indicated, only 5.2 A will flow. The dashed lines in Fig. 13 represent the phase-to-phase voltage relationship so that a delta system can also be visualized.

$|I_{A(0)}| = |I_{B(0)}| = (4160\text{ V})/\text{-}j1387\Omega = 3\text{ A}$

$I_{GF} = 3I_0 = 3\text{A x COS}\angle 30° + 3\text{A x COS}\angle 30° = 5.2\text{ A}$

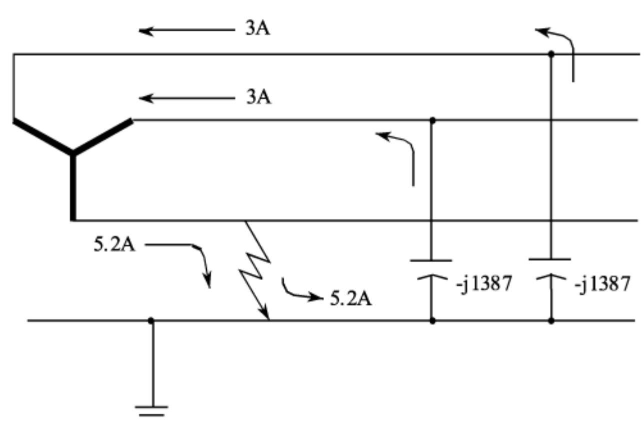

Fig. 12. Ground Faults on Ungrounded Systems

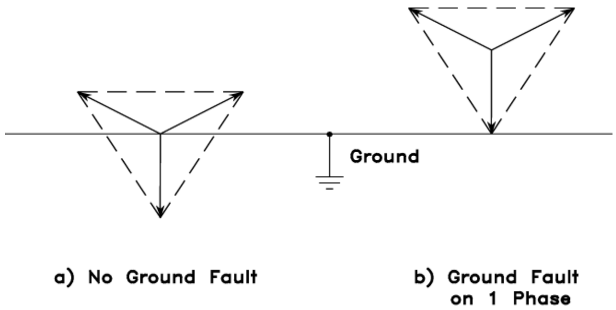

Fig. 13. Voltages During Ground Fault on Ungrounded System

Before about 1960, an ungrounded system was frequently selected for medium-voltage systems rated 5 kV or less if service continuity was of primary concern. The perception was that ungrounded systems have higher service continuity. This was based on the argument that the ground fault current is low and that negligible burning or heating will occur if the fault is not cleared. Therefore, phase-to-ground faults could be left on the system until it was convenient to find and clear them. This perception has some validity if the criterion is limited to "bolted" or "hard" faults. However, in the real world the vast majority of faults start as low level arcing ground faults. When arcing ground faults are considered, the following conditions are seldom addressed:

1) Multiple Ground Faults
2) Resonant Conditions
3) Transient Overvoltage

Multiple ground faults can and do occur on ungrounded systems. While a ground fault on one phase of an ungrounded system may not initiate an automatic trip, the longer the ground is allowed to remain the greater is the likelihood of a second ground occurring on another phase, because the unfaulted phases have phase-to-phase voltage impressed on their phase-to-ground insulation. In other words, the insulation is over-stressed by 73%. Also, there is an accelerated degradation of the insulation system due to the collective overvoltage impinged upon it through successive ground-faults over a period of several years. If the system insulation has not been selected for this duty, insulation degradation can accelerate even faster over time.

Although not that common, resonant conditions may result in ungrounded systems when one phase is grounded through an inductance, for example, a ground within the winding of an instrument transformer. When this happens, the high circulating currents result in high voltages across the unfaulted phases.

Transient overvoltage due to restriking or intermittent ground faults can and do develop substantial overvoltage on ungrounded electrical systems with respect to ground. The mechanism explaining how this occurs is best explained in many available publications [7, 9, 10, 11, 12, 13, 14, 15]. There have been many documented cases within industry where multiple equipment failures (e.g.-motors) over an entire 480 V system have occurred while trying to locate a ground fault. Measured line-to-ground voltages of 1,500 V or higher in these instances are not that uncommon. In all instances, the cause has been traced to a low-level intermittent arcing ground fault on an ungrounded system. Similar failures have been documented for medium-voltage (2.4 kV - 13.8 kV) systems. Fig. 14 shows the picture of a 3600 V submersible pump motor that failed due to this mechanism of voltage build-up. Two phases failed simultaneously to ground (grounded shaft).

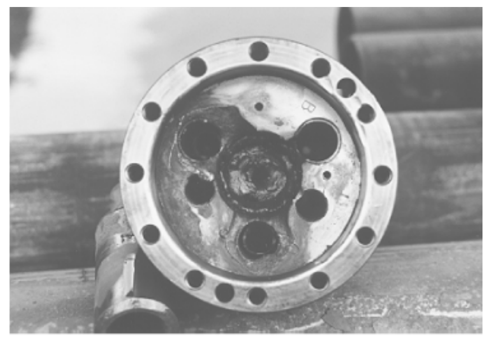

Fig. 14. Failed Motor due to Ground Fault Transient Overvoltage Build-Up

For these reasons, industry within North America is increasingly avoiding application of ungrounded systems. The ungrounded system would not be a good choice for any medium voltage system, especially those with expensive generation.

VII. GENERATOR AND SYSTEM SOLUTIONS

The design engineer faced with the dilemma of protecting the generator for internal ground faults and providing grounding for the system has traditionally chosen one system and lived with the risks. The traditional choice for medium-voltage systems has been low-resistance grounding. This is an excellent choice for medium-voltage power systems, except for the generator itself under internal ground faults. The various solutions for grounding and protecting generators are discussed below.

a) Generator Ungrounded and System Low-resistance Grounded

One solution to the above drawback would be to leave the generator ungrounded and low-resistance ground the external power system, as shown in Fig. 15. For ground faults external to the generator, the system would normally function as a low-resistance grounded system. However, if the ground fault occurred internal to the generator, the system would backfeed current into the ground fault and the generator protection would trip the generator breaker off-line. Once the generator breaker is opened, the generator would be left ungrounded with an arcing ground fault present, and subjected to the transient overvoltage condition as mentioned earlier. The generator excitation system cannot reduce the field excitation fast enough to eliminate damage. Also, if the generator alone is operating without the external source, then the system will be functioning as an ungrounded system. Because of these risks, this method of system grounding is not recommended.

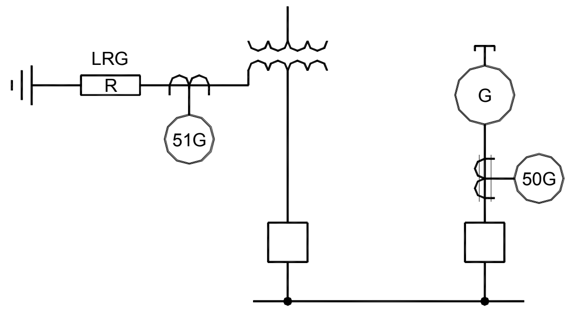

Fig. 15. Generator Ungrounded and System Low-Resistance Grounded

b) Generator High-resistance Grounded and System Low-resistance Grounded

Fig. 16 shows another example where the external power system is low-resistance grounded and the generator neutral is high-resistance grounded. For ground faults internal to the generator, the power system will provide current until the generator breaker opens. Once the breaker opens, the generator will remain high-resistance grounded; thereby, preventing transient overvoltages from damaging the generator. This grounding method provides the best of both worlds; the system is low-resistance grounded allowing quick tripping and isolation of any ground faults while the generator is high-resistance grounded, essentially eliminating ground fault damage and transient overvoltage damage. Where the number of cables or size of bus makes zero sequence (core-balance) CT's impracticable, 87GN protection must be substituted for the 50G function shown. See Part 3 paper for 87GN protection.

While this appears to be a good solution, it does have its limitations. The system will be high-resistance grounded when the generator is operating alone. System ground faults will not be easily detected. However, if the generator will never be operated alone without being synchronized to the external power source (which is low-resistance grounded), then this is a good choice.

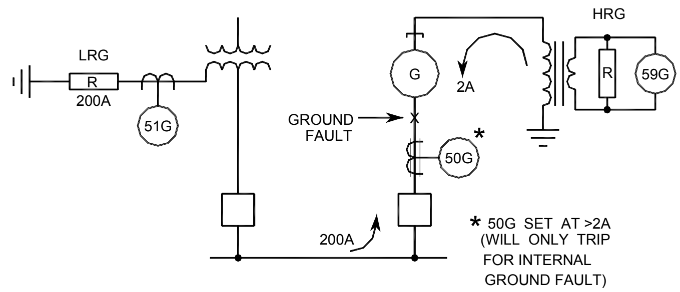

Fig. 16. Generator High-Resistance Grounded and System Low-Resistance Grounded

c) **Hybrid System**

If the power system is designed to operate either with both sources in parallel or with either source being independent, then the hybrid system shown in Fig. 17 provides a good alternative. The generator is both low-resistance grounded and high-resistance grounded. Under normal conditions, the low-resistance path prevails and controls the magnitude of fault current available from the generator. If the ground fault is in the generator zone itself, the 87GN and/or 51G protection simultaneously trips the generator breaker and the switching device in series with the low-resistance resistor. This leaves the generator high-resistance grounded during the ensuing interval as the field flux decays, thereby limiting the fault current to a level that will do significantly less damage. At the same time, the continuous presence of the high-resistance grounding equipment prevents any excessive transient overvoltage excursions during the fault clearing period.

This hybrid solution is a novel approach that has received only limited attention in the technical literature. It should be noted that the requirements imposed on the components involved in this hybrid solution are stringent, and it is very important that careful consideration be given to selecting appropriate component ratings for the application.

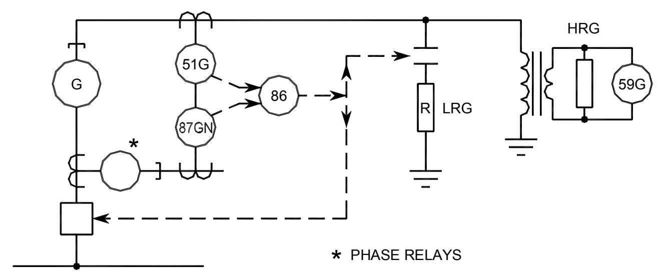

Fig. 17. Hybrid System

d) **Generator and External Source High-resistance Grounded, and Bus Low-resistance Grounded**

A variation of the above options is shown in Fig. 18 where the external source and the generator are high-resistance grounded with the bus being low-resistance grounded via a grounding transformer. This approach can be made to work equally well provided it can be assured that the bus ground will be present at all times.

This grounding method would allow the system to continue to operate with the uncleared high-resistance ground fault present if the condition is alarmed and the personnel are available to respond and locate the fault for clearing it in a timely manner (bus ground off-line or for an extremely low level ground fault). Otherwise, it would need to operate as a conventional low-resistance grounded system. This operational consideration would only be practicable for very small systems less than 7.2 kV.

For larger or higher voltage systems that cannot be adequately high-resistance grounded, the 51G relay must trip the generator and source transformer breakers rather than the grounding transformer breaker when there is an uncleared ground fault downstream. Careful consideration must be given to all potential normal and abnormal operating scenarios, including those configurations that may be called upon under unplanned contingencies to permit plant operation to continue in the event of some unexpected component failure.

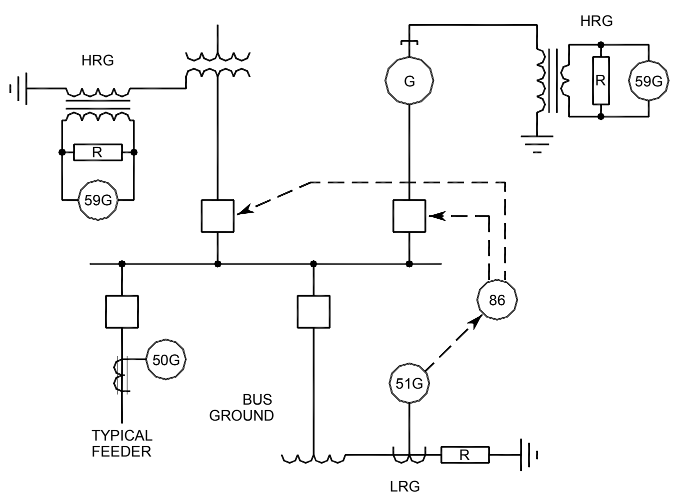

Fig. 18. A Variation of Hybrid System

e) **All Sources High-resistance Grounded**

Another approach would be to employ high-resistance grounding of all sources on the system, thereby limiting the total system ground fault current to a few tens of amperes. A more difficult challenge at higher voltages (above 7.2 kV) is the need to quickly detect and clear faults before a single-line-to-ground fault can escalate and involve other phases. In all instances, selective fault clearing is more difficult when the available fault current is severely limited. There are technologies available that will address this problem at the expense of greater complexity in the protection system.

For those systems with existing delta connected generators and transformers, the grounding solutions as illustrated in figures 16, 17 and 18 can be realized using grounding transformers to derive the neutral grounding point. Three single-phase transformers or a zig-zag grounding transformer can be employed to create either high-resistance grounding or low-resistance grounding, depending on the system design [12, 16].

VIII. SUMMARY

This paper presented Part 2 of a four-part Working Group Report on generator grounding and ground fault protection. Part 2 discussed the various grounding methods used in industrial installations, reviewing their advantages and limitations. The intent of this paper was to present alternative ways of minimizing medium-voltage generator damage from internal ground faults as identified in Part 1. The schemes as presented in figures 16, 17 and 18, are meant to provide the primary concepts of maintaining a low-resistance grounded power system and the benefits of a high-resistance grounded generator, under several possible scenarios. Using some form of these hybrid system grounding techniques will allow power system engineers to both protect the generator and provide reliable power system protection using proven low-resistance grounding designs. It is this committee's recommendation that some form of these choices be selected but with the understanding that no part of the system should be ever left completely ungrounded, especially the costly generator itself.

Part 1 of this Working Group Report provided an introduction and discussion of the generator damage mechanism during stator ground faults. Part 3 describes the protection methods for the various types of grounding and Part 4 includes a conclusion and bibliography of additional reference material on the subject of generator grounding and ground fault protection.

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GROUNDING AND GROUND FAULT PROTECTION OF MULTIPLE GENERATOR INSTALLATIONS ON MEDIUM-VOLTAGE INDUSTRIAL AND COMMERCIAL POWER SYSTEMS

PART 3: PROTECTION METHODS

An IEEE/IAS Working Group Report

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Abstract - **The paper discusses typical grounding practices and ground fault protection methods for medium voltage generator stators, highlighting their merits and drawbacks. Particular attention is given to applications of multiple generators connected to a single bus. The paper also provides an overview of the generator damage mechanism during stator ground faults. Problem areas associated with each type of grounding are identified and solutions are discussed. The paper also provides a list of references on the topic. The paper is intended as a guide to aid engineers in selecting adequate grounding and ground fault protection schemes for medium voltage industrial and commercial generators for new installations, for evaluating existing systems, and for future expansion of facilities, to minimize generator damage from stator ground faults. These topics are presented in four separate parts, Part 1 through Part 4. Part 1 covers scope, introduction, user examples of stator ground failure, and theoretical basis for the problem. Part 2 discusses various grounding methods used in industrial applications. Part 3 describes protection methods for the various types of grounding and Part 4 provides a conclusion and bibliography of additional resource material.**

I. GENERAL

For internal generator ground faults, the generator should be shut down as quickly as possible. However, for an external ground fault such as a feeder fault, a time-delayed shut down is usually employed to permit selective isolation of the faulty circuit. Along with the time-delayed tripping, an instantaneous alarm will provide early warning for the operator to take necessary action to minimize generator damage from prolonged fault current flow. IEEE Guide C37.101 [1] for Generator Ground Protection provides a wide range of generator ground protection schemes for different generator grounding and system grounding configurations. A summary of the recommended protective schemes and grounding arrangements to which they may be applied is given in Table 1 of this IEEE guide. Typical generator ground fault protection methods include:

- Percentage phase differential protection (device 87)
- Ground differential protection (device 87GN)
- Ground time-overcurrent protection (device 51G)
- Instantaneous ground overcurrent protection (device 50G)
- Wye-broken-delta vt ground overvoltage protection (device 59G)
- Stator winding zero-sequence neutral overvoltage protection (device 59GN)

Application of these protective functions requires subjective judgment. Larger generators will commonly be equipped with all of these functions, while some functions might be omitted from smaller generators on the basis that the incremental value in limiting damage does not justify the increase in cost. Refer to IEEE guide C37.101 [1] for a detailed discussion regarding settings, sensitivities, advantages and disadvantages of these protection schemes and available variations.

All of the above protective functions should initiate a complete shut down of the generator, including tripping of the generator main and field circuit breakers and closing of the prime mover throttle valve.

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II. PERCENTAGE PHASE DIFFERENTIAL PROTECTION (DEVICE 87)

Conventional percentage differential protection for phase-to-phase winding faults (Fig. 19) will provide the ability to detect most internal ground faults, depending on the available ground fault current. If the maximum ground fault current is below the phase percentage differential pick-up, the phase differential relays will not provide any ground fault protection. In such cases a ground differential scheme as discussed below may be needed to provide adequate protection of the generator.

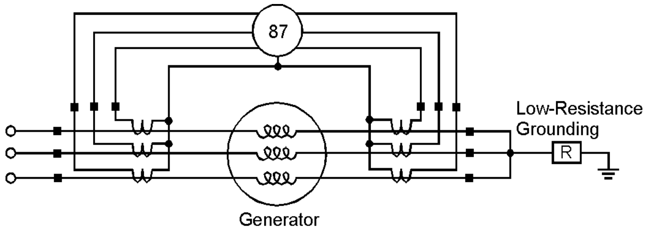


Fig. 19. Generator Percentage Phase Differential Protection

III. GROUND DIFFERENTIAL PROTECTION (DEVICE 87GN)

Due to the high fault currents associated with low-resistance grounded systems, it is important to provide sensitive, high-speed ground differential protection for generators. As discussed above, with low-resistance grounding, the phase differential relays may not be sensitive enough to detect ground faults internal to the generator, especially, since the maximum ground fault current may be limited to values below the phase differential pick-up. In such cases, a ground differential protection scheme as shown in Fig. 20 would be desirable. When properly applied a ground differential scheme may be able to detect ground faults to within 10% of the generator's neutral without the risk of false tripping on external faults. A ground directional overcurrent relay is generally used in this application with differential current as the operating quantity and neutral current as the polarizing quantity. The differential comparison is biased such that a positive restraint exists for an external fault. Depending upon the rating of, and the burden presented to the phase transformers, this scheme provides excellent security against misoperation for external faults while providing sensitive detection of internal ground faults.

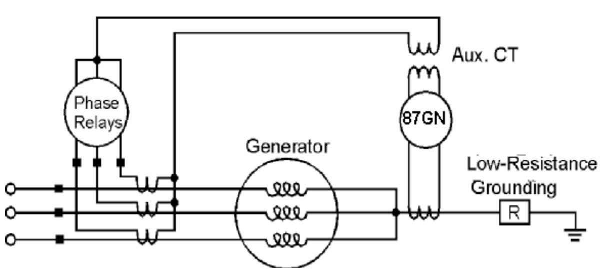


Fig. 20. Generator Ground Differential Protection

IV. GROUND TIME-OVERCURRENT PROTECTION (DEVICE 51G)

As previously mentioned, one of the most important advantages of low-resistance grounding is the ability to selectively coordinate ground overcurrent protection for downstream faults; thereby tripping only the faulted part of the system. For example, consider a ground fault occurring on a load feeder supplied from a generator bus, as shown in Fig. 21. The load feeders will be protected using sensitive instantaneous ground overcurrent relays (device 50G) on each feeder , permitting high speed clearing of the fault. In the event of an uncleared feeder fault, an inverse time-overcurrent relay (device 51G) on the bus tie breaker will provide back-up protection, isolating the faulted bus section. Further back-up protection will be provided by the inverse time-overcurrent relays (device 51G) on the grounded neutrals of the sources. Although, time-overcurrent ground relays provide sensitive, high-speed protection for ground faults, coordination can be difficult with multiple sources since the ground current magnitude will vary with addition or removal of sources.

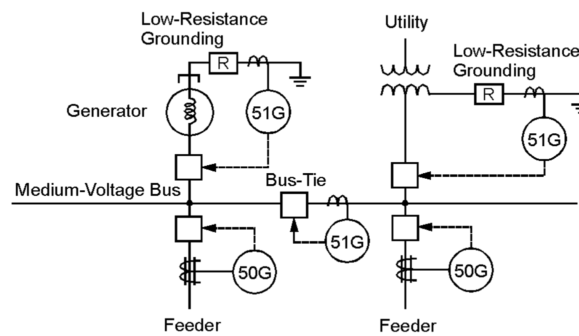


Fig. 21. Generator Ground Time Overcurrent Protection

However, there is a possibility of serious generator damage from the prolonged high fault currents, especially when a ground fault occurs near the terminals of the generator. This damage may be reduced by using an instantaneous ground-overcurrent relay (device 50G) in conjunction with the time overcurrent relay. The instantaneous relay will detect faults near the generator neutrals. It may also provide back up protection for feeder faults.

V. INSTANTANEOUS GROUND OVER-CURRENT PROTECTION (DEVICE 50G)

This is also called a generator self-balancing differential ground relay scheme and is shown in Fig. 22. A window (toroidal) type (also called core-balance or zero-sequence) current transformer that surrounds the generator phase and neutral leads measures the ground current coming from the generator and the system for a ground fault in the generator. The current transformer output operates an instantaneous overcurrent relay to trip the generator. For a ground fault in the system external to the generator, the current transformer output will be zero. Therefore, the relay can be safely set to a low value for optimum protection of the generator. The limit of sensitivity can be affected by having to energize a large block of transformer load and by the physical position of leads in the window of the toroid.

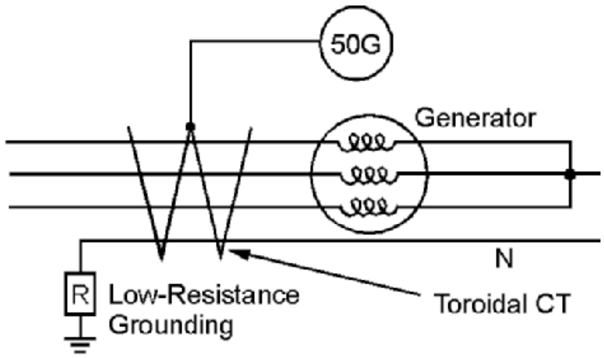


Fig. 22. Instantaneous Ground Overcurrent (Self-Balancing Differential Ground Current) Protection

VI. WYE-BROKEN-DELTA VT, GROUND OVERVOLTAGE PROTECTION (DEVICE 59G)

This protection system is generally used for the high-resistance grounded generators. This protection scheme is a variation of the stator winding zero-sequence neutral overvoltage protection scheme that is described below. In this scheme as shown in Fig. 23, an overvoltage device (device 59G) is connected to a separate set of broken-delta secondary windings of the voltage transformer (vt), whose primaries are connected to the generator terminals in grounded wye configuration. A ground fault in the generator stator winding is detected by measuring the voltage across the broken delta secondary windings of the voltage transformer. For example, during a single-phase-to-ground fault in the generator, the vectorial 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 across the terminals of the 59G device operating circuit will be the vectorial sum voltage divided by the voltage transformer ratio. It should be noted that full line-to-line voltage appears across each voltage transformer during a ground fault; therefore, they should be rated accordingly. A loading resistor may be placed across the broken delta to control possible ferroresonance.

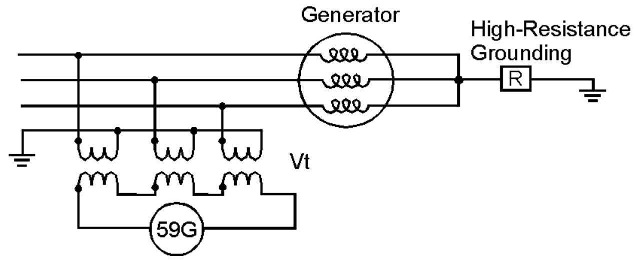
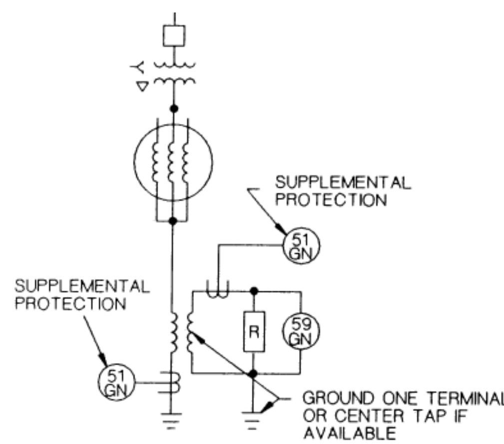


Fig. 23. Wye-Broken-Delta Vt, Ground Overcurrent Protection

VII. STATOR WINDING ZERO-SEQUENCE NEUTRAL OVERVOLTAGE PROTECTION (DEVICE 59GN)

The most conventional and widely used protection scheme for high-resistance grounded systems is a time-delayed overvoltage relay (device 59GN) connected across the grounding resistor, as shown in Fig. 24. The relay used for this application should be tuned to fundamental frequency voltage and be insensitive to third-harmonic voltages that are present at the generator neutral under normal operating conditions.



51GN Neutral Overvoltage Relay
59GN Neutral Overvoltage Relay Tuned to the Fundamental (60Hz) Frequency

Fig. 24. High-Resistance Grounded, Unit-connected Generator, Zero-Sequence Voltage Protection

Since the grounding resistance is large compared to the generator impedance and other impedance in the circuit, the full phase-to-neutral voltage will be impressed across the grounding device for a phase-to-ground fault at the generator terminals. The voltage at the relay is a function of the distribution transformer ratio and the location of the fault. The voltage will be a maximum for a terminal fault and will decrease in magnitude as the fault location moves towards the generator neutral. Typically, the overvoltage relay has a minimum pickup setting of approximately 5 V. With this setting and with typical distribution transformer ratios, this scheme is capable of detecting faults to within about 2-5% of the stator neutral. The time setting for the overvoltage relay is selected to provide coordination with other system protective devices. Specific areas of concern are:

1) When grounded wye-grounded wye voltage transformers (vt) are connected at the generator terminals, the neutral ground overvoltage relay should be coordinated with the vt fuses to prevent tripping the generator for vt secondary ground faults. This would require very careful selection of vt fuses.

2) The ground voltage relay (device 59GN) may have to be coordinated with system relaying for system ground faults. System phase-to-ground faults will induce zero-sequence voltages at the generator neutral due to capacitive coupling between the windings of the unit transformer. This induced voltage will appear on the secondary of the grounding distribution transformer and can cause operation of the 59GN voltage relay.

A time overcurrent ground relay (device 51GN) can be used as backup protection when the generator is grounded through a distribution transformer with a secondary resistor as shown in Fig. 24. The current transformer supplying the overcurrent relay may be located either in the primary neutral circuit or in the secondary circuit of the distribution transformer.

VIII. ADDITIONAL PROTECTION METHODS

Additional protection methods are used to provide more sensitive protection against ground faults in generators that are high-resistance grounded. These include 100% stator winding ground fault protection and the use of a generator neutral breaker.

a) 100% Stator Winding Ground Fault Protection

Conventional protection for stator ground fault detection on high-resistance grounded systems has been discussed in the previous section. These protective schemes are straight-forward and dependable. However, these relays would typically provide sensitive protection for only about 95% of the stator winding. This is because the fault in the remaining 5% of the winding, near the neutral, does not cause sufficient 60 Hz residual voltage and residual current to operate these relays. Even if fault current magnitudes for ground faults close to the neutral point are negligible in causing any immediate damage, potential severe damage can be caused from a second fault, especially when the first fault is near the neutral. Furthermore, if the second fault occurs in the same winding, the generator differential relay may not operate at all since this condition can be regarded as an internal turn-to-turn fault. Therefore, complete winding protection should be considered for large generators.

Special protection schemes based on detection or absence of third-harmonic voltages or neutral/residual voltage injection techniques are available to detect ground faults in the generator stator close to the neutral points that may otherwise go undetected using the typical protection schemes mentioned above. However, these are only applicable on high-resistance grounded, unit-connected generators. Third-harmonic voltage based techniques are widely used to provide such protection. They are applicable where there is sufficient third-harmonic neutral voltage to apply such schemes.

The techniques based on the use of third-harmonic voltage can be divided as follows:

i) Third-harmonic neutral undervoltage technique

ii) Third-harmonic residual terminal overvoltage technique

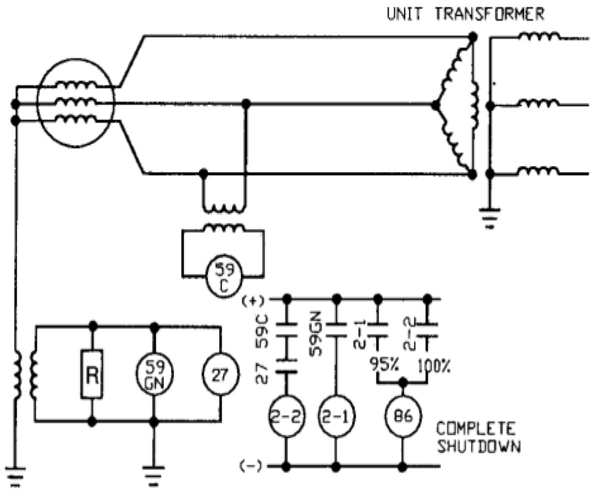
iii) Third-harmonic comparator technique

i) Third-harmonic neutral undervoltage technique

This technique uses the fact that for a fault near the neutral, the level of third-harmonic voltage at the neutral decreases. Therefore, an undervoltage relay (device 27) operating from third-harmonic voltage measured at the generator neutral can be used to detect ground faults near the neutral. The ground faults in the remaining portion of the windings can be detected by conventional ground fault protection such as an overvoltage relay (device 59GN) which operates on the 60 Hz neutral voltage. The combination of both relays can provide 100% stator winding protection. A protection scheme using this technique is shown in Fig. 25. See IEEE Guide for Generator Ground Protection [1] for details.

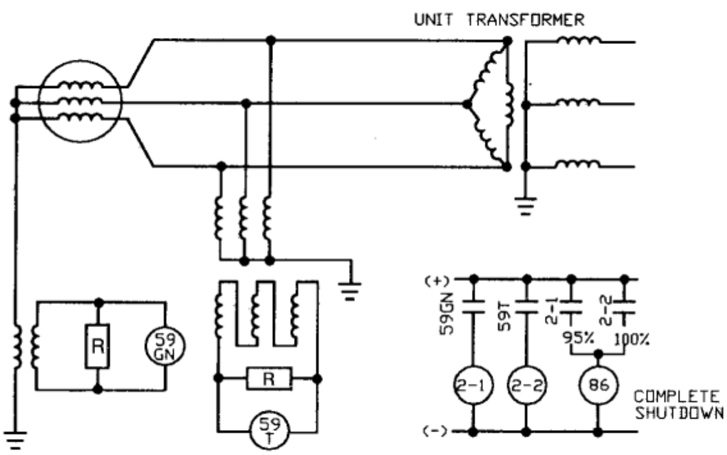
ii) Third-harmonic residual terminal overvoltage technique

This technique is based on the fact that for a fault near the neutral, the level of third-harmonic voltage at the generator terminals increases. Therefore, an overvoltage relay using third-harmonic voltage at the terminals of a generator can be used for detecting faults near the neutral. As before, the ground faults in the remaining portion of the windings can be detected by the conventional 95% protection, e.g., an overvoltage relay which operates on 60 Hz neutral voltage. Both of these relays can provide 100% protection of stator windings by covering different portions of the windings. A protection scheme using this technique is shown in Fig. 26.



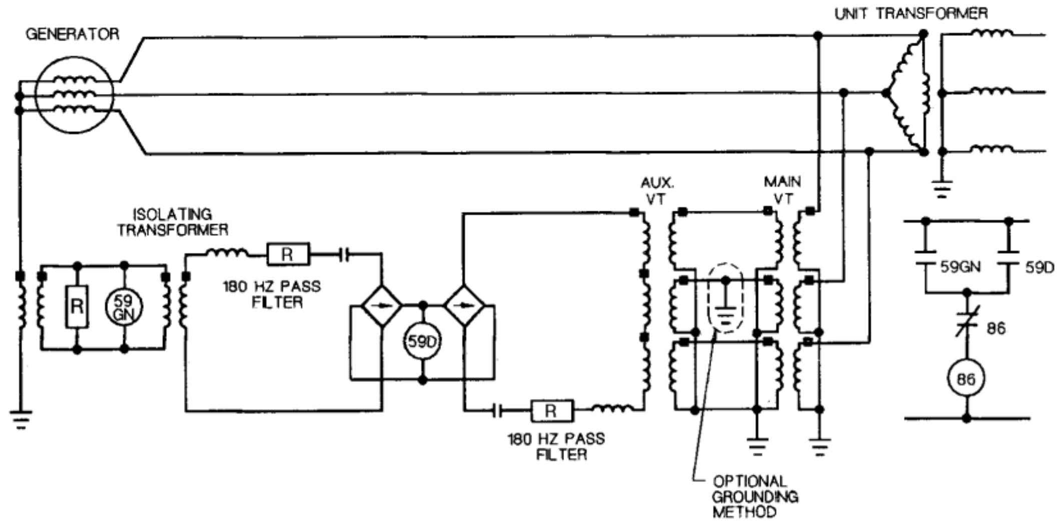
59C	Instantaneous Overvoltage Supervisory Relay
59GN	Overvoltage Relay Tuned to the Fundamental (60 Hz) Frequency
27	Undervoltage Relay Tuned to the Third Harmonic (180 Hz) Frequency
2-1, 2-2	Timers

Fig. 25. High-Resistance Grounded Generator, Third-Harmonic Undervoltage Ground Fault Protection Scheme



59GN	Overvoltage Relay Tuned to the Fundamental (60 Hz) Frequency
59T	Overvoltage Relay Tuned to the Third Harmonic (180 Hz) Frequency
2-1, 2-2	Timers

Fig. 26. High-Resistance Grounded Generator, Third-Harmonic Residual Terminal Voltage Based Ground Fault Protection Scheme



59GN Overvoltage Relay Tuned to the Fundamental (60 Hz) Frequency
59D Overvoltage Differential Relay Tuned to the Third Harmonic (180 Hz) Frequency

Fig. 27. High-Resistance Grounded Generator, Third-Harmonic Comparator Based Ground Fault Protection Scheme

iii) Third-harmonic comparator technique

This scheme compares the magnitude of the third-harmonic voltage at the generator neutral to that at the generator terminals. The scheme is based on the premise that the ratio of the third-harmonic voltage at the generator terminals to that at the generator neutral is almost constant during the normal operation of a generator. This ratio is upset for a ground fault near the neutral or near the terminals of a generator, and this fact is used to detect these faults. The ground faults in the remaining portion of the windings are detected by the conventional 95% ground fault protection such as 60 Hz overvoltage or overcurrent relay operating from the neutral voltage or current respectively. Fig. 27 shows a diagram of the comparator scheme.

b) Generator Neutral Breaker

While this is a possible aid in minimizing stator ground fault damage, the cost and potential risks of using a neutral breaker result in few application of these devices. As explained in Part 1 of the paper under damage mechanism for a stator ground fault, tripping the generator main breaker alone does not interrupt the current from the faulted generator. Providing a generator neutral breaker will minimize stator damage (iron burning) from internal faults. If a neutral breaker cannot be justified, stator damage can be significantly reduced by accelerating decay of field flux by field forcing to zero using de-excitation circuits.

IX. SUMMARY

This paper presented Part 3 of a four-part Working Group Report on generator grounding and ground fault protection. Part 3 discussed the various protection methods applied to the various grounding systems described in Part 2 of this report. A review of their advantages and limitations were given along with alternative solutions.

Part 1 of this Working Group Report provided an introduction and discussion of the generator damage mechanism during stator ground faults. Part 2 described the various grounding methods used in industrial applications, highlighting their advantages and limitations. Part 4 provides a conclusion and bibliography of additional reference material on the subject of generator grounding and ground fault protection.

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GROUNDING AND GROUND FAULT PROTECTION OF MULTIPLE GENERATOR INSTALLATIONS ON MEDIUM-VOLTAGE INDUSTRIAL AND COMMERCIAL POWER SYSTEMS

PART 4 - CONCLUSION AND BIBLIOGRAPHY

An IEEE/IAS Working Group Report

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Abstract - **The paper discusses typical grounding practices and ground fault protection methods for medium voltage generator stators, highlighting their merits and drawbacks. Particular attention is given to applications of multiple generators connected to a single bus. The paper also provides an overview of the generator damage mechanism during stator ground faults. Problem areas associated with each type of grounding are identified and solutions are discussed. The paper also provides a list of references on the topic. The paper is intended as a guide to aid engineers in selecting adequate grounding and ground fault protection schemes for medium voltage industrial and commercial generators for new installations, for evaluating existing systems, and for future expansion of facilities, to minimize generator damage from stator ground faults. These topics are presented in four separate parts, Part 1 through Part 4. Part 1 covers scope, introduction, user examples of stator ground failure, and theoretical basis for the problem. Part 2 discusses various grounding methods used in industrial applications. Part 3 describes protection methods for the various types of grounding and Part 4 provides a conclusion and bibliography of additional resource material.**

I. CONCLUSIONS

This paper has shown that the phenomenon that is causing the reported extreme core burning of faulted generator stators is based on two factors:

1) As system complexity has increased, the number of resistor grounds on systems has increased. This has caused the total available ground fault current to increase. As a practical matter, the opening time of generator breakers cannot be made significantly faster than the typical 6 cycles (100 ms for a 60 Hz ystem) value. A major component of the burning is therefore attributable to the magnitude of current that will flow during this tripping time, that is, to the number of ground sources on the system.

2) Current that rises through the neutral of the faulted generator will not be interrupted by tripping the generator breaker, and will persist for several seconds until the field demagnetizes. A considerable amount of burning damage will be done during this time if the generator neutral is low-resistance grounded.

Therefore, solutions to this problem must involve several elements:

a) The number and ratings of low-resistance grounding resistors on the system should be kept to a minimum. Techniques to accomplish this include designing the system around the concept of "zero-sequence islands" in which the number and rating of transformer ground sources within each island is strictly limited, or the use of a single bus-connected neutral deriving transformer instead of multiple neutral resistors on multiple power transformers.

b) The faulted generator should be high-resistance (10 A maximum) grounded, especially during the time after the generator breaker opens and while the field excitation is decaying. If necessary, a hybrid form of generator neutral grounding may be used in which the neutral is both low-resistance grounded and high-resistance grounded. The generator will be low-resistance grounded during normal operation, but a neutral switching device is provided to trip this resistor any time that the generator must be tripped for a stator ground fault. This leaves the generator high-resistance grounded during the ensuing interval as the field flux decays, thereby limiting the fault current to a level that will do significantly less damage.

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c) If it can be assured that the generator will never be operated alone without being synchronized to the external power source, then a good solution would be to employ high-resistance grounding of the generator and low-resistance grounding of the external source. For ground faults internal to the generator, the low-resistance grounding of the external source allows quick tripping of the generator breaker to isolate the fault, leaving the generator high-resistance grounded, thereby eliminating damages.

d) Another option would be high-resistance grounding of both the generator and the external sources with the bus being low-resistance grounded via a grounding transformer supplied through a breaker. This grounding method would allow the system to continue to operate with the uncleared high-resistance ground fault present if the condition is alarmed and the fault is located and cleared in a timely manner. However, if adequate high-resistance grounding cannot be achieved, then it would be necessary to trip both the generator and external source when there is an uncleared downstream fault. Careful consideration must be given to all potential normal and contingency operating scenarios to permit plant operations to continue in the event of some unexpected component failures.

It is important that any solution must be carefully engineered with particular attention in selecting equipment components that are suitably rated for the application.

Practical solutions on new systems are relatively straightforward and involve application of the above mentioned two factors. On existing systems the problem of minimizing fault damage is more challenging. Furthermore, there is no one set of steps that will suffice for all existing systems. Therefore, it is necessary to consider carefully the architecture of each system to arrive at what will almost certainly be a compromise between the objective of minimizing potential fault damage and certain other operating objectives.

A serious problem with existing systems is that their architecture is often complicated by the manner in which they have evolved over many years. It is also often the case that there is a perception that this complexity equates with reliability because it affords many different contingency operating modes. This in turn can lead to a situation where there is a desire to meet the grounding criteria mentioned above for all possible operating arrangements.

Therefore, the first step in identifying a solution for existing systems is to identify what are the expected realistic operating modes of the system. That is, while it is certain that the system is expected to operate normally with everything intact, it is important to understand what kinds of outage contingencies must be allowed for.

A reality is that it may be impossible to achieve risk mitigation for all practical operating conditions of complex systems. In this instance, it will be necessary to choose between accepting the risk of machine damage and limiting the number of operating contingencies that can be accommodated on the system.

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