IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part III—Generator Auxiliary Systems

Sponsor

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Abstract: Basic factors and general considerations in selecting the class and means of neutral grounding for electrical generating plant auxiliary power systems are given in this guide. Apparatus to be used to achieve the desired grounding are suggested, and methods to specify the grounding devices are given. Sensitivity and selectivity of equipment ground-fault protection as affected by selection of the neutral grounding device are discussed, with examples.

Keywords: electrical generating plants, electrical utility systems, generator auxiliary systems, ground-fault protection, grounding, neutral grounding

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Introduction

(This introduction is not a part of IEEE Std C62.92.3-1993, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part III—Generator Auxiliary Systems.)

This guide is part of a series on neutral grounding in electrical utility systems. When the series of documents are approved and published, they will replace IEEE Std 143-1954 , IEEE Guide for Ground-Fault Neutralizers, Grounding of Synchronous Generator Systems, and Neutral Grounding of Transmission Systems.

IEEE Std 143-1954 is a revision of AIEE No. 954, Oct. 1954, which was a compilation of the following three *AIEE Transaction* papers:

AIEE Committee Guide Report, "Application of Ground-Fault Neutralizers," *AIEE Transactions (Power Apparatus and Systems)*, vol. 72, pt. III, pp. 183–190, Apr. 1953.

AIEE Committee Report, "Application Guide for the Grounding of Synchronous Generator Systems," *AIEE Transactions (Power Apparatus and Systems)*, vol. 72, pt. III, pp. 517–530, June 1953.

AIEE Committee Report, "Application Guide on Methods of Neutral Grounding of Transmission Systems," *AIEE Transactions (Power Apparatus and Systems)*, vol. 72, pt. III, pp. 663–668, June 1953.

The contents of Parts I–V of the revision of IEEE Std 143-1954 are based on the foregoing documents but are amplified and updated with new material from the IEEE tutorial course, "Surge Protection in Power Systems" [(79H)144-6-PWR], and other sources.

Part III covers the considerations and practices relating to grounding of generating station auxiliary power systems. The related parts are: Part I, Introduction (Theory and performance characteristics of classes of neutral grounding); Part II, Grounding of Synchronous Generator Systems; Part IV, Distribution; and Part V, Transmission Systems and Subtransmission Systems.

It is impossible to give recognition to all those who have contributed to the technology and practices of grounding of power systems since work involving the preparation of this guide has been in progress for over 30 years. However, the assistance of members, past and present, of the Neutral Grounding Devices Subcommittee of the Surge-Protective Devices Committee, and other similar groups with comparable purposes, should be acknowledged.

Disclaimer

This guide is specifically written for electrical utility systems and does not recognize the neutral grounding requirements for dispersed storage and generation. These requirements must recognize the restrictions imposed by the specific network to which the dispersed storage or generation is connected. Neutral grounding of dispersed storage and generation needs to be coordinated with the electrical utility system.

At the time this guide was approved, the Working Group for Part III of the Neutral Grounding Devices Subcommittee had the following membership:

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At the time this standard was published, it was under consideration for approval as an American National Standard. The Accredited Standards Committee on Surge Arresters, C62, had the following members at the time this document was sent to letter ballot:

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CLAUSE PAGE

IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part III—Generator Auxiliary Systems

1. Overview

1.1 Scope

This guide summarizes the general considerations in grounding of generating station auxiliary power systems and discusses the factors to be considered in selecting between the appropriate grounding classes and in specifying equipment ratings. This guide applies to both medium-voltage and low-voltage auxiliary power systems. Grounding and bonding to achieve practical safeguarding of persons is fulfilled by electrically connecting equipment frames and enclosures and interconnecting wiring raceways to the station grounding network (see IEEE Std 142-1991 [1]), as required by ANSI C2-1993. References to safety in this guide mean freedom from equipment damage. The emphasis is on reliability and availability of auxiliary system service achieved through control of ground-fault currents and transient overvoltages.

This guide is specifically written for electrical utility systems and does not recognize the neutral grounding requirements for dispersed storage and generation. These requirements must recognize the restrictions imposed by the specific network to which the dispersed storage or generation is connected. Neutral grounding of dispersed storage and generation needs to be coordinated with the electrical utility system.

1.2 Purpose

The purpose of this guide is to present some basic considerations for the selection of neutral grounding parameters that will provide for the control of ground-fault currents and overvoltage on auxiliary systems of electrical utility three-phase generators.

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

2. References

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

Accredited Standards Committee C2-1993, National Electrical Safety Code (ANSI).[2]

IEEE Std 32-1972 (Reaff 1991), IEEE Standard Requirements, Terminology, and Test Procedures for Neutral Grounding Devices (ANSI).[3]

IEEE Std 80-1986 (Reaff 1991), IEEE Guide for Safety in AC Substation Grounding (ANSI).

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

IEEE Std 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (IEEE Green Book) (ANSI).

IEEE Std C62.92.1-1987 (Reaff 1993), IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part I—Introduction (ANSI).

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

IEEE Std C62.92.4-1991, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part IV—Distribution (ANSI).

3. Introduction

3.1 Principal characteristics

The principal performance characteristics of the various classes of system neutral grounding, as well as the major considerations in selecting an appropriate class, are presented in IEEE Std C62.92.1-1987. Application techniques for high-resistance grounding are developed in the discussion and examples of IEEE Std C62.92.2-1989. These considerations are directly applicable to grounding generating station auxiliary service systems. The user of this guide is presumed to be familiar with these two standards.

3.2 Past and present practice

Station auxiliary systems have in the past been quite commonly operated ungrounded, and some still are. It has long been recognized that ungrounded systems are actually grounded without intent through the system capacitance to ground. Under certain fault conditions, such systems are susceptible to high transient overvoltages that can damage rotating machines and cable insulation. Consequently, neutral grounding is being increasingly used on station auxiliary systems to control transient overvoltages [B22] .[4]

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[2]The National Electrical Safety Code is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

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

[4]The numbers in brackets correspond those of the bibliography in clause 7.

Table 1 presents the grounding practices for 389 auxiliary power systems in 199 new utility power generating plants as recorded in the *Electrical World* Steam Station Design Surveys No. 13 through No. 18, 1974 through 1984. All systems reported in table 1 are those for which both a voltage and a grounding class were recorded.

When intentionally grounded, low-voltage systems have until recently usually been solidly grounded. Ground faults were expected to produce sufficient current to permit selective coordination of phase protective equipment to isolate the fault if the fault circuit was not too long and the ground-fault return circuit was of low enough impedance. Low-voltage direct-acting devices have usually had the capability to clear the faults fast enough to prevent excessive fault damage. There has been recent increased use of resistance grounding of large 480 V systems, as reported in table 1, and even of ground-fault protective tripping using equipment commonly employed on industrial systems [B18] . Only one 208 V directly grounded system was reported.

Table 1—Grounding practices on power plant auxiliary power systems

Voltage level	High resistance		Low resistance		Direct grounding		Ungrounded		Total in voltage class	
(kV)	Number	(%)	Number	(%)	Number	(%)	Number	(%)	Number	(%)
High										
23	1	0.3							1	0.3
Medium										
12-13-14	8	2.1	17	4.4	10	2.6	3	0.8	38	9.8
10			1	0.3					1	0.3
7–8	14	3.6	46	11.8	13	3.3	3	0.8	76	19.5
5					1	0.3			1	0.3
4	30	7.7	62	15.9	28	7.2	9	2.3	129	33.2
2.5	1	0.3							1	0.3
Low										
0.6 and less	34	8.7	74	19.0	24	6.2	10	2.6	142	36.5
Total in grounding class	88	22.6	200	51.4	76	19.5	25	6.4	389	100
NOTE — Practices for 199 plants and 389 systems. Percents are percentages of the total.										

Medium-voltage systems in new plants: 15 systems were ungrounded (6%), 52 systems were directly grounded (21%), 126 systems were low-resistance grounded (51%), and 54 systems were high-resistance grounded (22%). More than half the station auxiliary systems at these voltages have been grounded through a low resistance permitting up to one-third of the three-phase fault current amperes. This current range has permitted good selective protection using commonly available relays and phase current transformers in residual connection (IEEE Std 142-1991). Nearly a quarter of the reported systems adopted high-resistance grounding. The availability of core balance (window or through-type) zero-sequence current transformers and associated relays has made possible selectively coordinated protection for the low values of ground-fault current associated with high-resistance grounding [B19] .

4. Basic considerations

4.1 Basic factors

The basic factors to be considered in selecting a grounding class are

a) Required level of service continuity and equipment safety
b) Duration of outage and cost of lost service
c) Tolerable ground-fault damage criteria for switchgear and rotating machines
d) Extent of damage and cost to repair
e) Magnitude of transient and fundamental frequency overvoltages
f) Desired level of protection against abnormal voltages
g) Magnitude of ground-fault current
h) Limiting level of ground-fault current
i) Desired selectivity, sensitivity, and speed of ground-fault relaying
j) Redundancy level of process equipment; capability to maintain function with some redundant auxiliaries forced out
k) Process time requirements for orderly shutdown or transfer of function
l) Process operation tolerance to fault locating techniques

4.2 Service continuity

Whether an auxiliary power system is intentionally grounded or not, it is presumed that generating station systems are equipped with ground detectors and alarms so that grounds will not be allowed to remain on the system unintentionally. Service continuity of ungrounded systems, or systems grounded through high resistance without selective relaying, may be continued for a limited period after the fault to allow an orderly procedure for locating the fault. This can contribute to high service continuity. Long search times and successive removal of several circuits from service for fault location can result in decreased continuity. Some nuclear plant “safety-related” systems are normally grounded and operate ungrounded only during emergency conditions so that service continuity will not be jeopardized by tripout on a single-phase ground fault. Two situations are critical and have influenced the choice to provide intentional grounding. If a ground fault is not located promptly and subsequently a second ground fault occurs somewhere on the system, a short circuit will exist between these two points and substantial portions of the system, usually at least two feeders, will be forced out of service without warning. The second situation arises from a high transient overvoltage. This can cause several simultaneous insulation failures to ground on one phase in several machines or at separated locations. To locate these faults requires pulse current injection and tracing. Otherwise, the difficulty of removing circuits from service in various combinations of pairs, triplets, etc., to disconnect all faults simultaneously may be prohibitive. However, ungrounded low-voltage systems that have high-quality system insulation with generous margins can provide a high level of service continuity if ground faults are infrequent and maintenance and repair are prompt and well executed. Users whose experience shows that ground faults may be kept sufficiently infrequent may prefer to operate low-voltage systems ungrounded, or with high resistance and without ground-fault relaying, to enjoy freedom from trip-outs with no warning. Some sensitive electronic equipment (computers, microprocessors) may not be suitable for connection to ungrounded or high-resistance grounded systems. Ground-fault transient or temporary overvoltages may saturate power supplies, burn out surge suppressors, and cause fires. Sensitive loads need to be selected or equipped so as to be compatible with the grounding.

Grounded and relayed systems achieve high continuity by controlling and limiting the damage caused by ground faults, and by selective fast disconnection of faulted auxiliaries and system elements to minimize interruption of the system. The success of this approach depends upon adequately redundant auxiliaries, quick transfer of function to alternate auxiliaries, adequacy of preventive and restorative maintenance, and speedy repair.

4.3 Damage criterion

The ranges of ground-fault currents associated with each class of grounding are displayed in Table 1 of IEEE Std C62.92.1-1987. It may be noted that the grounding impedance of all non-effectively grounded systems limits the ground-fault currents to a small fraction of the three-phase short-circuit current. Ground faults may occur involving significant amounts of fault resistance or of fault arc voltage drop, which is an appreciable portion of the driving voltage. This is particularly true of systems operating at 600 V or less. Consequently, ground-fault currents may occur that are less than normal load currents or that are so low as to be not readily detectable by the usual phase-protective devices. In such situations, a damage criterion is sometimes established. The criterion sets the level to which ground-fault current will be restrained and the allowable duration before tripping to limit further damage. Damage criteria have usually been stated in ampere-seconds or kilowatt-seconds based on an assumed ground-fault arc voltage of 100 V (measured range from 50 V at 0.2 in length to 150 V at 1 in for a 1000 A arc) [B8] . 30 kW-sec was determined as a threshold of insignificant damage, equivalent to vaporizing 1.2 cm^3 of aluminum or 0.5 cm^3 of copper. Later experiments have shown that damage by ground-fault arcs on low-voltage systems is not linear with arc current, being approximately proportional to the 1.5 power of arc current ($I^{1.5}$)and proportional to duration. Damage level was found to be essentially independent of arc length and arc voltage drop. A criterion for allowable damage based on this relationship and on the ability of present technology to detect and interrupt ground-fault currents, which is approximately proportional to equipment rated current, was proposed by Stanback in 1975 [B24] . The allowable damage criterion states that arc current to the exponent 1.5, times the duration in seconds, is constant and equal to 250 times the equipment-rated amperes ($I_f^{1.5}\, t = 250\, I_R$). With this criterion, the ampere-seconds of tolerable ground-fault arc current ($I_f t$) becomes equal to 250 I_R $(I_f)^{-1/2}$. Applying this criterion to usual equipment ratings and actual (not prospective) ground-fault current levels results in ampere-second damage criteria in the hundreds to tens of thousands (see table 2). The calculated phase-to-ground short circuit at a device and the rated current of the device would determine the ampere-second damage level to which the circuit should be protected. The required fault clearing time is obtained by dividing the ampere-second damage criterion by the fault current.

Table 2—Allowable damage criteria for copper or aluminum

I_f	I_R = 200 A		I_R = 800 A		I_R = 2000 A	
(A)	$I_f t$ (As)	t (s)	$I_f t$ (As)	t (s)	$I_f t$ (As)	t (s)
200	3 500	17.70	14 000	71.00	35 000	177.00
2 000	1 100	0.56	4 400	2.24	11 000	5.59
10 000	500	0.050	2 000	0.20	5 000	0.50
20 000	350	0.018	1 400	0.071	3 500	0.177

I_f= Actual fault current
I_R= Equipment rated current
t= Fault duration (in seconds)
$I_f t$= Damage criterion (in ampere-seconds); $I_f t = 250\, I_R (I_f)^{-1/2}$ As

If one wishes to relate these criteria to kilowatt-cycles or kilowatt-seconds, an arbitrary assumed arc voltage of 100 will require dividing the table values by 10 to obtain kilowatt-seconds. The damage criteria in table 2 permit longer durations for smaller currents and larger equipment ratings. The rate and amount of metal melting and vaporization are related to the rate of heat release. The tolerable or sustainable damage is somewhat related to the size or rating of the equipment conductors.

4.4 Magnitude of overvoltages

4.4.1 Fault to ground

4.4.1.1 Ungrounded system

When an ungrounded system experiences a fault to ground, transient voltage on the unfaulted phases can exceed normal line-to-ground voltage. The sustained voltages to ground on the unfaulted phases will reach line-to-line values. The voltage and current relationships between phase conductors, neutral, and ground are affected by the distributed capacitance of circuits and equipment windings to ground. With no intentional conductive path to ground, this capacitance establishes a return path for ground-fault current as follows: from ground through the capacitances of the unfaulted phases to system neutral and out the faulted phase to the fault. If fault resistance is low, the predominant impedance is capacitance; current zero occurs at the fault at voltage crest. It becomes possible for the high voltage to re-ionize the arc path and for the arc to restrike. Such an intermittent fault may be established with the arc restriking every half-cycle, equivalent to switching a capacitor every half-cycle. A cumulative buildup of voltage may then occur if the recovery rate of insulation strength increases after each extinction (a situation not likely to occur in an open arc but prevalent in confined spaces within multiconductor cables, raceways, and machine windings). High transient peak voltages may occur and will be limited either by the insulation recovery rate and strength at the fault, or by the system insulation strength.

4.4.1.2 Intentionally grounded system

Accidental conductor grounding on intentionally grounded systems will cause lower transient overvoltage and lower sustained overvoltage of the unfaulted phases than when the system is ungrounded. Neutral grounding is effective in reducing the possibility and magnitude of transient voltage build-up from intermittent ground faults. The grounding reduces neutral-to-ground voltage displacement and reduces the possibility of high natural frequency voltage oscillations following arc restriking. Analytical studies and system operating experience have demonstrated that the magnitude of transient overvoltage on the unfaulted phases can be limited to approximately 2.5 times the normal line-to-neutral crest value with resistance grounding (IEEE Std C62.92.1-1987). The grounding resistance is selected so that the kilowatt loss in the neutral equals or exceeds the system three-phase capacitive kilovoltamperes to ground.

Sustained fundamental frequency overvoltages are reduced using neutral grounding by two primary effects. The system grounding connection permits a ground-fault current to flow, producing internal voltage drop in the system sources and thereby tending to reduce the system voltage. Further, the system neutral becomes grounded through both the neutral grounding impedance and the fault impedance. These act like a series voltage divider in establishing the earth voltage at some point partway between the system neutral and the faulted phase if the two impedances have generally similar ratios of inductance to resistance (L/R). A sustained rise in voltage of the unfaulted phases will be less than 1.73 times the line-to-neutral voltage. If the system neutral is effectively grounded, the sustained overvoltage on unfaulted phases will not exceed 1.4 times normal line-to-neutral voltage (IEEE Std C62.92.1-1987). The fundamental frequency overvoltage in such cases can influence selection of surge arrester ratings where these may be applied on auxiliary systems for protection of motors against switching surges.

Voltage instrument transformer banks connected in wye and with the common or neutral point connected to ground to provide ground detection do not constitute system grounding. However, their secondary circuits are sometimes continuously loaded with resistors so that a few amperes of current will flow to ground in the event of a ground fault. To attempt to ground a system with voltage transformers requires a resistive loading that may be considerably above the accuracy voltampere rating of the transformers and may approach the thermal voltampere rating.

If voltage transformers are not heavily loaded in this manner, they may contribute to overvoltage and unbalanced conditions on an otherwise ungrounded system. The magnetizing impedance of lightly loaded transformers, in series with the system capacitance, may be the cause of neutral instability or neutral inversion usually associated with a condition described as “ferroresonance.” As defined in IEEE Std 100-1992, ferroresonance is a “phenomenon usually characterized by overvoltages and very irregular wave shapes and associated with the excitation of one or more saturable inductors through capacitance in series with the inductor.” Even systems that are normally grounded may be subject to this condition if the location of the neutral ground is such that it can be isolated from the voltage transformers during a switching operation. Voltage transformers on auxiliary systems subject to switching isolation from neutral grounding should be loaded with resistors to control such overvoltages ([B4] , [B15]).

4.4.2 Lightning surges

Grounding reduces the deleterious effects of lightning surges in two ways. The grounding system will frequently help to dissipate and distribute the surge energy between the phases, thus reducing the severity of the insulation stress. In an indirect but more important manner, by holding system overvoltages down, the grounding system permits application of surge arresters with lower sparkover values and a higher protective margin for the equipment. The influence of lightning is minimal in the choice of grounding methods for station auxiliary systems. The surges transferred through transformers from overhead lines are dissipated to a very low value among the multiple circuits emanating from station service buses.

4.4.3 Contact with higher voltage systems

This type of exposure is rare in well-designed generating stations since circuits are universally made of insulated cable, well segregated, and protected. However, the prevalent use of a cable ladder or tray in many modern plants does introduce hazards, particularly if the cables are not fireproofed and different voltage systems are run on the same tray with barriered separation. The occurrence of a fault to a tray by a medium-voltage circuit can impose a substantial transient overvoltage on the tray before fault clearing. Such a condition may break down insulation of lower voltage circuits on the same tray, particularly in the presence of fire, and can thus subject low-voltage systems to destructive overvoltage. Neutral grounding of the lower voltage system can mitigate these effects. The possibility of contact with higher voltage systems, though slight in the case of station auxiliary systems, does exist and should be given consideration appropriate to the risks associated with the type of construction chosen.

4.4.4 Resonant voltages—inadvertent tuned ground contact

An ungrounded system can experience very high overvoltages if one of the phases faults to ground through an inductive element. Faults can readily occur in the control transformers, relays, and contactors connected at line voltage. Since impedances are high, normal fuse protection on line-voltage control circuits is not likely to clear. A series voltage divider is formed, which establishes the system connection to earth voltage between two elements, composed of the inductance of the system to ground through the fault and the capacitance of the system to ground (through which the fault current re-enters the system). If these approach resonance, very high voltages appear across the separate elements in quadrature with the faulted phase voltage to ground. A high voltage is thus impressed between the system neutral and ground. The high voltage is an amplification of the phase voltage to ground, amplification being dependent on the quality coefficient (Q) of the fault current circuit and the closeness of tuning. Such an occurrence can cause extremely high sustained system overvoltages at fundamental or a harmonic frequency until the fault burns free, is cleared, or multiple failures of motor windings or other system insulation force catastrophic shutdown [B4] . Damaging effects of such overvoltages can be minimized by using controls at a different voltage level. The inductance of control transformer primary windings is considerably lower than that of relay and contactor coils and less likely to resonate with low values of capacitance. However, a suitable choice of neutral grounding techniques can eliminate the hazard entirely.

4.4.5 Switching overvoltages

Switching overvoltages caused by forcing current zero or restriking of an interrupter result from trapping energy in the circuit. Magnetic energy exists in the fields that surround the circuit during current flow. When current is forced to zero, these fields suddenly collapse on the conductor; the energy is converted to voltage and stored as trapped charge in the system capacitance. The mechanism involves energy transfer between circuit inductance and capacitance, a springy oscillatory system, at its resonant frequency of several thousand hertz. When disturbed in this manner, the voltage will overshoot its static value unless purposefully damped. The high frequency and overshoot can produce a high rate of rise of voltage, which may increase much faster than the recovery of insulation strength in the interrupter arc path. If restrike occurs, a greater voltage overswing in the opposite polarity direction can result.

Switching overvoltages have not usually been a source of trouble on station auxiliary systems. More importantly, the recent introduction of vacuum interrupter type switchgear as a standard construction may result in switching surge exposure of station auxiliary systems where they have not previously been subjected to such a hazard. These situations require evaluation in choosing the method of system grounding. System grounding can alleviate exposure to switching surges by providing a drainage path for dissipating the trapped energy, thus holding the system voltage to near normal values.

4.5 Sensitivity and selectivity of ground-fault relaying

Sensitivity refers to the degree to which low-current faults may be detected by relaying; for example, high-impedance faults or faults near the neutral in a motor winding. Selectivity refers to the degree to which relays and associated interrupters connected on series portions of systems are able to detect faults and open the circuit at the nearest upstream interrupter to cause a minimum interruption of service. The objectives of ground-fault relaying are to obtain an appropriate level of sensitivity and selectivity for a given application.

In an ungrounded system it is difficult to obtain relays that are sufficiently sensitive to detect high-impedance faults reliably. Selective coordination of relays is usually not possible for single-line-to-ground faults. An ungrounded system usually operates with the system neutral floating near ground potential if the capacitances between phases and ground are reasonably balanced. When a ground fault occurs on one phase, the voltage to ground on that phase approaches zero. The other two phases are raised in voltage with respect to ground by the amount of the faulted phase voltage to ground minus the voltage drop of fault current flow through the fault impedance. The raised voltage of the unfaulted phases results in increased current flow through these phase capacitances to ground. The current leaves the system through the ground fault. A way of visualizing the situation is to imagine a single-phase voltage source, equal and opposite to the pre-fault voltage, connected at the fault location at the instant of the fault so the net fault voltage is zero. This voltage source will circulate current through the fault into the ground, through the capacitances to ground of the unfaulted phases back to the system neutral, through the faulted phase to the fault. The system capacitance to ground is usually small. The impedance is large, and consequently the ground fault current is also small. In order to increase current flow during ground faults sufficiently for selective relaying, it is necessary to provide a grounding source (a lower impedance connection between system neutral and ground).

At the other extreme, a solidly grounded system provides high levels of ground-fault current that are quite adequate for relaying purposes. The larger currents that will flow from low fault-voltage locations within the winding near the neutral of motors, generators, or transformers will allow relaying to be quite sensitive. The driving voltage at the point of fault is not impeded by phase capacitances to ground. The fault current circulating path in a grounded system is from the fault to ground, through the earth (or building structure or equipment grounding conductor) to the neutral ground connection, and back to the fault. The fault path impedance is usually quite small. The larger ground-fault currents caused by solid grounding bring increased danger of damage to equipment. The consideration of increased damage leads to a need for ground-fault current limitation by impedance grounding.

Between these extremes lie various kinds and degrees of impedance grounding. For auxiliary power systems in generating stations, the most frequent choice is resistance grounding, usually classified into high or low resistance (IEEE Std C62.92.1-1987). High-resistance grounding restricts the fault current to a resistive component of fault current at least equal to the capacitive fault current and usually no greater than two times the capacitive current. It thus limits the total ground-fault current to between 1.4 and 2.2 times the capacitive fault current, and swings the phase angle of fault current from 90° leading voltage to between 45° and 27° leading voltage. The grounding resistance provides damping of the ground-fault circuit natural frequency oscillations. It prevents fault arc restrikes by altering the current phase angle, and thus provides limitation of transient overvoltages.

Low-resistance grounding is characterized in IEEE Std C62.92.1-1987 as neutral grounding where the ratios of symmetrical component impedances at the fault are

a) Zero-sequence reactance to positive sequence reactance between zero and ten
b) Zero-sequence resistance to zero-sequence reactance equal to or greater than two

Low-resistance grounding may permit ground fault currents as high as 25% of a three-phase fault current. For medium-voltage systems, the grounding resistor used in low-resistance grounding is usually selected to allow between 200–2000 A of ground-fault current. Low-resistance grounding will limit the transient line-to-ground voltage at the onset of a fault to 2.5 times the crest of the line-to-ground operating voltage; see Note 3 to Table 1 of IEEE Std C62.92.1-1987.

The selection of low-resistance grounding is usually a compromise between capital cost of the resistor and protective relaying, and the risk and cost of equipment damage due to ground faults. Low-resistance grounding permits coordinated relay protection using conventional phase and ground-fault relays with the ground-fault relays connected in the residual connection of wye-connected current transformers, or in the corner of delta-connected current transformers. Zero-sequence transformers are not required. A false residual current and false tripping may be caused by saturation error during motor starting in-rush. Fault damage can be substantially greater than would result from the low ground-fault currents of high-resistance grounding. Low-resistance grounding is frequently used to permit the application of reliable selective ground-fault protective relaying with some benefit in reduced fault damage to equipment by the limitation of ground-fault current.

Auxiliary power systems that may at times be supplied directly from a generator at generator voltage instead of from a transformer are likely to be grounded with high resistance. The resulting limitation of fault transient voltages and low fault currents is consistent with the lower insulation level achievable in rotating machine windings, and the vulnerability to iron core damage if high current faults to ground were to occur in the slot portion of the winding.

When the ground fault current is very low, selective relaying is usually not feasible. Alarms actuated by current or voltage at the grounding connection are employed to indicate ground faults somewhere on the system. Some relay selectivity is possible with ground-fault currents at the level of 100 A, though care must be taken to allow for the saturation error of zero-sequence current transformers (window or through-type). Careful centering of cables in the window may be required and errors may need to be measured to set relays properly. Careful attention must be paid to running of cable shield ground leads back through the window to avoid nullifying the system. Several steps of relay selectivity are possible for fault currents greater than 400 A, as well as a high degree of sensitivity, permitting detection of faults in machine windings to within 10% to 5% of winding length from the neutral. As the ground-fault current is reduced below this level of several hundred amperes by increased grounding impedance, the objective of selectivity with sensitivity becomes less attainable.

4.6 Magnitude of ground-fault current

The method of neutral grounding directly influences the magnitude of ground-fault current. Several factors are suggested for consideration. In the case of an ungrounded system, the ground-fault current is a function of system capacitance to ground. For an ungrounded station auxiliary system, ground-fault currents on the order of 10 A or less would be expected. The use of high-resistance grounding results in fault currents up to twice those for the ungrounded case. As the resistance is lowered, the fault current will increase. Low-resistance grounding usually permits fault currents in the order of 200–2000 A, while solid grounding permits considerably higher fault current on the order of 15 000–20 000 A on medium-voltage systems and 50 000–100 000 A on low-voltage systems.

The extreme range of ground-fault current magnitude resulting from the different grounding methods will greatly influence

- Damage at the point of fault
- Sensitivity of ground relaying
- Mechanical stress on equipment
- Circuit breaker interrupting duty

4.7 Emergency, standby, vital, and safety-related ac and dc systems

The considerations in grounding emergency, standby, vital, or safety-related ac systems are the same as for any ac system as described in previous subclauses. The basic factors are the same. However, on these systems, service continuity is of primary importance. The purpose of emergency, standby, vital, or safety-related ac systems is to assure continuity of service to important and necessary loads upon loss of the normal ac supply. Thus, anything that can reasonably be done in the grounding system to assure continuous electric service is very desirable. It is also necessary that transient overvoltages be limited to safe values.

Low-voltage ac systems are usually solidly grounded where the line-to-ground voltage on ungrounded conductors will be 150 Vac or less. Three phase systems of 50–1000 V that serve phase-m-neutral loads should also be solidly grounded.

240 V delta-connected systems and 480 Vac and 600 Vac wye-connected systems that do not have single phase-m-neutral loads need not be solidly grounded. For wye-connected systems 480 Vac and above (without line-to-neutral loads), there are advantages to high-resistance grounding of the system. High-resistance grounding will help control transient overvoltages while permitting service continuity during ground fault until the fault can be cleared.

Loads on dc systems are generally those that require service continuity during ac system failures. This includes dc turbine emergency lube oil pumps and controls. Thus, for service continuity, dc systems are generally ungrounded.

5. Grounding classes usually applied

5.1 Ungrounded

Historically, a major reason for ungrounded operation of auxiliary systems has been the additional degree of service continuity that it may afford in case of a fault between one phase and ground. Such a fault need not result in a service interruption, but there exists the possibility of the occurrence of a second ground fault on a different phase before the first fault is cleared, which would result in a phase-to-phase fault. The possibility of a second ground fault may be increased by the transient overvoltages that may result from the initial fault to ground when the neutral is not grounded (IEEE Std 142-1991).

Selective ground relaying in ungrounded systems is usually not attempted. Though relaying may be used to indicate the existence of a system ground fault for purposes of alarm, the location of the fault may be difficult to determine because of the very low magnitude of fault current.

Phase voltages to ground are usually used as a means of detecting the occurrence of ground faults on a system. Ground detection circuits may introduce ferroresonance on ungrounded systems when three voltage transformers are connected wye primary with the neutral grounded, or when a single voltage transformer is used with its primary connected line-to-ground. Ferroresonance may cause high voltages to ground and excessive primary current, which may result in damage to voltage transformers or blowout of primary fuses. The basic method of preventing ferroresonance is to prevent the voltage across the voltage transformer primary from becoming high enough to result in saturation. There are several methods to achieve this. One is to select a voltage rating for the transformer that is high enough to avoid saturation. Frequently, resistance is added either in the corner of a delta secondary or between primary neutral and ground to force some of the neutral displacement voltage across the loading resistor and thus limit the voltage across the voltage transformer.

The magnitude of ground-fault current is quite low in ungrounded systems. During single line-to-ground faults, mechanical stress on equipment and damage at the point of fault are minimized. However, breaker interrupting duty is not reduced. If not cleared promptly, a ground fault on one phase may lead to a fault on another phase at another location and with the resulting damage of a phase-phase fault. The second fault may be initiated by the heat release at the first fault, by the full phase-phase voltage imposed line-to-ground on the two unfaulted phases, or by the high transient overvoltage that may occur at incidence of the first fault. In modem plants with shielded cables, a second ground fault, should one occur, is more likely in equipment than in the cables.

Studies ([B3] , [B5] , and [B7]) have shown that restriking arcs in circuit breakers or faults in solid insulation may lead to high transient overvoltages in ungrounded systems. These overvoltages are suspected of causing insulation failures in otherwise unrelated equipment during ground faults. To avoid these possibilities, it is becoming a frequent practice to use high-resistance grounding when the operating characteristics of an ungrounded system are desired. The elimination of high transient overvoltages will benefit connected rotating machinery and sensitive electronic equipment. However, the latter may still be at risk during a ground fault unless properly protected or isolated. See 4.2.

5.2 Resistance grounding

The ground-fault damage associated with resistance grounding is less than for a phase-phase fault on an ungrounded system or for a ground fault in the case of a solidly grounded neutral. The mechanical stress on equipment is reduced, usually as the square of fault current. The breaker duty for resistance-limited ground faults is much lower than phase fault duty and is not a major factor.

5.2.1 High resistance

Resistance grounding can be divided into two distinct classes: high resistance and low resistance (IEEE Std C62.92.1-1987). For high-resistance grounding, the resistor current is usually chosen to be at least equal to the capacitive charging current of the system in order to prevent the buildup of high transient overvoltages. Frequently, the resistance is made lower to make the resistive current somewhat larger than the capacitive current. This ensures elimination of transient overvoltages and allows additional cable additions to the system without degrading the grounding performance. Operation of high-resistance grounding is similar to that of an ungrounded system; i.e., ground faults are usually alarmed but not automatically isolated by tripping the circuit. However, improvements in zero-sequence current transformers (through-type, window, or split-core) have made possible limited selectivity in relay applications.

5.2.2 Low resistance

Low-resistance grounding generally provides fault currents from a few hundred to a few thousand amperes. With these values, it is usually possible to obtain satisfactory selectivity and sensitivity with ground relaying connected in the current transformer residual circuit. When the ground-fault current is approximately equal to the largest current transformer primary current rating, such objectives may be readily realized. As the fault current is reduced below this value, the objectives are attained with increasing difficulty. In cases where ground-fault currents are reduced to the 150–500 A range, the use of zero-sequence current transformers permits satisfactory relaying sensitivity and selectivity. As ground fault currents go below the 150 A level, approaching high-resistance grounding, the relaying sensitivity and selectivity are reduced; satisfactory operation is increasingly difficult and greater portions of motor windings near the neutral will be unprotected.

5.3 Effective grounding (solid or direct)

Effective grounding is usually obtained by a direct connection between system neutral and the earth with no intentional impedance. When the system neutral is effectively grounded, the transient overvoltages are held to a minimum as compared to the other grounding methods. Ground relaying, because of the high fault-current levels, is both sensitive and selective. The high fault current, if not cleared promptly, causes maximum fault damage and mechanical stress on equipment. It may also be sufficiently greater than three-phase currents to become a consideration in the selection of circuit breaker interrupting ratings.

5.4 Grounding dc control systems

Historically, dc control systems have not been grounded because of the following advantages:

- Increased service continuity
- Prevention of spurious control circuit operation due to ground faults in control circuits

Overall, not grounding the dc systems increases the reliability of the control circuits because a single ground fault will not cause circuit interruption and usually will not cause control circuit misoperation. Some dc control circuits with connected capacitance to ground could misoperate upon ground fault on the dc or the supplying ac system. The possibility of another ground fault on the other leg of the dc system must be considered. Multiple ground faults can cause loss of control function and/or spurious control circuit operation. For this reason, ground detection circuits are used on dc systems. The ground detection system must be able to detect a ground fault on any leg of the dc system. This includes the center leg of three-wire dc systems. Ungrounded dc systems with ground fault detection circuitry have been used by the utility industry for many years. DC systems are not subject to the overvoltage and resonance problems that may occur on ungrounded ac systems.

6. Selecting the grounding device

6.1 Grounding—general

The choice between use of ungrounded, solid, low-resistance or high-resistance neutral grounding in generating station auxiliary system applications is usually based on the particular experience or preference of the individual utility. A number of articles have been published that record problems of destructive overvoltages and arcing faults on 480 V and 600 V systems that were not intentionally grounded in some manner ([B10], [B11] , [B12] , [B14] , [B16] , [B17] , [B20] , [B21] , [B23] , [B25] , [B26] , and [B27]). Caution is advised when using such systems. Ground-fault monitoring and an alarm are strongly recommended. Of the described methods of grounding auxiliary systems, only resistance grounding requires selection of specific grounding equipment. The ungrounded system requires only ground detection and alarm initiating devices. The solidly grounded system requires only an adequate neutral grounding conductor. The discussion in this clause is an overview of the method for selecting the grounding resistor in each type of low-resistance or high-resistance grounding application, along with some arguments regarding either method.

6.2 Selection of a neutral grounding resistor

The selection of a neutral grounding resistor requires determination of the ground-fault current necessary for relaying purposes (if required) and consideration of the resistor voltage rating, ohmic value, thermal and current rating, mechanical stresses, and time rating.

The voltage rating of a resistor in the neutral-to-ground connection of a wye winding is determined by the system line-to-neutral voltage, since this is the maximum steady-state fault voltage that will be applied to the resistor. This voltage and the initial current required for relaying purposes determine the ohmic value of neutral resistance. System reactances are negligibly small when compared to the resistor and rarely need to be considered. The current rating will be the same as the initial current selected for relaying purposes. The initial current will flow upon the occurrence of the fault and will diminish as heating increases the resistance, thereby lowering the current. The resistor time rating should be selected on the basis of the relaying employed for fault detection. If selective relaying is employed, the duration of the fault will probably be less than a second, and a resistor having a 10 s rating may be employed. In cases where the current is limited to low levels and an alarm is used to indicate ground faults, continued operation in the presence of ground faults would indicate that longer time ratings should be employed, such as the 10 min or extended lime rating.

Two examples of equipment selection are presented for guidance in the following subclauses, low-resistance grounding and high-resistance grounding.

6.2.1 Low-resistance grounding

Low-resistance grounding achieves the three desirable objectives of limiting transient overvoltages to acceptable values; limiting fault-current magnitude to minimize damage levels; and permitting sufficient fault current for fast, selective relaying. The selectivity depends upon the characteristics and coordination of the protective equipment.

A reasonable value of ground-fault current for an auxiliary system in a generating station, as provided by a low-resistance grounding resistor, is between 200–400 A. Using 400 A, the damage criterion from the equation in table 2 for an 800 A circuit breaker would be 10 000 As, or 400 A for 25 s. A typical 4160 V station service transformer with a 15 000 kVA rating might be grounded with a 400 A, 1 s or 10 s neutral grounding resistor insulated for 2400 V (V_{1-n}). The ohmic value of the resistor (R) is determined from $R = V_{1-n}/3I_0 = 2400/400 = 6\ \Omega$. There is a relationship between relay sensitivity and magnitude of the ground-fault current. Accepted relay practice should be used that is compatible with the level of ground-fault current permitted by the resistor. The material reduction in ground-fault current damage afforded by the grounding resistor is evidenced by considering that the maximum ground-fault current with solid neutral grounding would approach 30 000 A.

Ground-fault current selectivity at 400 A or less may require the use of zero-sequence current transformers (CTs), also referred to as window-type, through-type, or ring-type CTs. The core of the CT surrounds all three phases, making the net core flux zero for all but ground return currents. The relaying can be made more sensitive and faster than when single-phase CTs are used because the latter may produce spurious residual currents at times of asymmetrical motor inrush currents.

Since the core of the CT must surround all three phases, use of this type of current sensor may be limited to cable circuits. However, very sensitive ground sensor current transformers have become available in configurations suitable for use with busways and bus ducts.

Ground relaying sensitivity of 10% of maximum ground-fault current under minimum conditions is a typically acceptable value. It protects that portion of the winding that is more than 10% of the winding length away from the neutral. Improved sensitivity can be obtained by using a lower value of resistance, permitting a higher ground-fault current, or if relaying considerations allow by a lower current setting. In the example above, with the 6 Ω resistor and 400 A ground-fault current, a 10 A relay pickup will provide $(10/400) \times 100 = 2.5\%$ sensitivity. 97.5% of the winding would be considered protected.

Normally a 10 s rated resistor is selected for low-resistance grounding because the ground faults are cleared rapidly by relays tripping circuit breakers. In the example above, the power dissipation rating of the resistor (P_r) is determined by

$$P_r = \frac{I^2 R}{1000} = \frac{400^2 \times 6}{1000} = 960\ \text{kW} \quad (1)$$

A typical instantaneous relay used for this application operates in less than one cycle for a fault of this magnitude, so a 10 s rating for the resistor is very conservative.

6.2.2 High-resistance grounding

High-resistance grounding has been used by over 20% of newer systems (table 1) for grounding auxiliary systems in generating stations. It limits ground-fault current to very low values for minimum damage. Equipment may be allowed to continue to operate in the presence of the fault until an orderly replacement or shutdown can be made. This method also limits transient overvoltages to acceptable values and allows sensitive fault monitoring of the system. However, it should be recognized that there may be increased risk of motor failures due to high stress on insulation during sustained line-ground faults. This is caused by line-line voltage being imposed between phase and ground on the two unfaulted phases. If the fault is in a motor winding, and if, during continued operation with the first fault, a second ground fault should occur elsewhere on the system on another phase, then severe damage such as burning of stator iron laminations can result. This type of double ground failure is a line-line fault. The damage can occur at widely separated locations.

6.2.2.1 Resistor in wye neutral

The ohmic value for a high-resistance grounding resistor is selected to produce ground-fault current with a resistive component (I_r) at least equal to the value of capacitive current (I_c) as distributed over the entire connected subsystem for that voltage. Thus, when $I_r = I_c$, then the system ratio of zero-sequence capacitive reactance (X_{c0}) to zero-sequence resistance (R_0) is equal to $X_{c0}/R_0 = 1$. This value, which is preferred to be equal to or greater than 1.0, assures that transient overvoltages on the connected subsystem will be within acceptable limits. To allow for increase in the amount of connected cable, the resistor should be chosen such that I_r is greater than I_c and may be as much as $I_r = 2I_c$.

Example

As an example of high-resistance grounding, consider a 13.8 kV system for which X_{c0} = 4000 Ω/phase, so I_{c0} = 13 800/(1.732 × 4000) = 2.0 A/phase. It is desirable to select a neutral resistor that will provide $I_{r0} = 2I_{c0}$ = 4.0 A resistive component of fault current per phase. Neutral current during a ground fault is $3I_{r0}$ = 12 A. The resistor (R) would be determined by $R = V_{1-n}/3I_{r0}$ = 13 800/(1.732 × 3 × 4.0) = 664 Ω.

A resistor of 664 Ω in the primary neutral of a 13.8 kV system is expensive and is not usual practice. The resistor may be connected to the secondary of a distribution transformer located in the neutral of a wye-connected power transformer supplying the subsystem. This distribution transformer can be rated for system line-to-neutral voltage, as the maximum offset of the neutral is V_{l-n} during ground faults. Using a 7970–120 V distribution transformer, the required resistor is reduced in ohmic value by the inverse square of the turns ratio, or

$$R = 664(120/7970)^2 = 0.15\Omega, \text{ and rated 120 V} \tag{2}$$

The current rating (I) is found from

$$I = (120\text{ V}/0.15) = 797\text{ A} \tag{3}$$

The continuous power dissipation rating (P_r) is

$$P_r = I^2R = 797^2 \times 0.15/1000 = 96\text{ kW} \tag{4}$$

The kilovoltampere rating of the distribution transformer (kVA) in the neutral should be based on

$$\text{kVA} = 3I_{r0} \times V_{1-n} = \frac{3 \times 4 \times 7970}{1000} = 96\text{ kVA} \tag{5}$$

If a 13 800–240 V distribution transformer were used in the neutral connection, the secondary resistor should be rated 0.20 Ω and 690 A [664 × (240/13 800)^2 = 0.20; and 240/1.732/0.20 = 690]. The power dissipation would remain 96 kW.

6.2.2.2 Overload capability

If faults will be cleared quickly, the short-time overload capability of distribution transformers may be considered in selecting the appropriate rating. Table 1 of IEEE Std C62.92.2-1989 lists the permissible short-time overload factors for distribution transformers used in neutral grounding. These factors are

Duration of overload	Multiple of rated kilovoltamperes
10 s	10.5
60 s	4.7
10 min	2.6
30 min	1.9
2 h	1.4

If selective ground-fault relaying were applied in the example system so that a 10 s rated resistor was considered adequate, then a 10 kVA or 15 kVA transformer might be selected.

6.2.2.3 Resistor in delta corner

The previous example treated a wye-connected system. For a delta-connected system, it is necessary to establish a ground source to be able to implement high-resistance grounding. This can be done using three distribution transformers connected wye-grounded on the primary and with the secondaries connected delta with one corner left open for insertion of the grounding resistor. The transformers must be rated for full line-to-line voltage on the primary; during a line-to-ground fault the neutral point is temporarily connected to the voltage of the faulted phase, and the voltage to ground of the other two phases is at full line-to-line voltage until the fault is removed. The primary winding voltage for the example must now be 13 800 V. The grounding resistor is connected in the open comer of the delta of the three distribution transformers. The next step is to determine the value of this secondary resistance.

Example

From the previous example, the resistance of 664 Ω (which is too expensive to connect in the primary neutral) must be related to the open-corner delta secondary resistor by the proper voltage and current. The voltage across the resistor (V_r) during ground faults will be three times the prefault primary line-to-neutral voltage transferred through the winding ratio into the secondary (208 V in the case of a 13 800–120 V transformer). This is because the voltages to ground of the two unfaulted primary phases have increased by $\sqrt{3}$, and their phase displacement has closed to 60°. Summation of these two phase-to-ground voltages by their series connection in the delta secondary results in $V_r = V_{l-n} \times 1.732 \times 1.732$.

The current through the delta corner resistor will be one-third the equivalent of the primary grounding resistor example because I_{r0}, not $3I_{r0}$, circulates through each winding of the delta. The multiplication of these two factors requires the resistance in the secondary delta to be nine times the resistance of an equivalent primary neutral resistor for a 1:1 ratio transformer.

The value of resistance required in the delta may be determined in two ways. The first uses the 9 factor and winding ratio.

$$R = 664(120/13800)^2 \times 9 = 0.45\ \Omega \tag{6}$$

The second method uses the secondary voltages and currents.

$$V_r = 7970\ \text{V} \times 3(120/13\,800) = 208\ \text{V} \tag{7}$$

$$I_r = 4\text{ A} \times (13\,800/120) = 460\text{ A} \tag{8}$$

$$\text{The resistor rating } R = 208/460 = 0.45\ \Omega \tag{9}$$

The power dissipation rating of the resistor (P_r) = $I^2R = 460^2 \times 0.45$ = 96 kW, the same as before. During a ground fault, the primary winding of each phase of the grounding bank will carry one-third of the groundfault current, I_0, or 4 A for the example. The secondaries of all three phases will carry I_0, or 460 A for the example. The kilovoltampere rating of the three distribution transformers (kVA) should be based on kVA = 13 800 × 4/1000 = 55 kVA per phase each. This is 0.57 times the kilovoltampere rating of a transformer in the neutral of a wye-connected primary, but the delta-connected primary requires three units instead of one.

Applying the short-time overload factors, a bank of three 5 kVA or 7.5 kVA transformers may be adequate for a 10 s rating.

6.2.2.4 Resistor change with temperature

When selecting grounding resistors, the resistance tolerance of ±10% and the increase of resistance with temperature may be important in coordinating with relay sensitivity and speed. The 10 s and 60 s resistor ratings may increase in resistance by as much as 90% at the end of their rated period, whereas 10 min and extended time rated resistors will normally increase less than 15 %. Of course, the resistance change in a 10 s rated resistor may be negligible for a fault cleared in a few cycles. But if breaker failure is experienced and backup relays are called into play, they may not see sufficient fault current to trip unless the resistor tolerance and increasing resistance are included in the coordination analysis.

If it is planned to continue operating temporarily in the presence of a ground fault, a voltage relay would be normally connected across the resistor to the alarm when a ground fault occurs. This relay should be selected to have a voltage rating that can withstand the continuous voltage during ground faults, In the delta-connected system example, this would be in the range of 200 V. The relay may be set to a lower voltage, such as 10 V. At this setting, motor winding ground faults would be detected if they occurred more than 5% of the winding length away from the neutral.

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Annex A Ground-fault protection

(Normative)

A.1 Automatic or manual

Ground-fault protection involves either automatic or manual disconnection of the faulted portion of the system from its supply source. If the disconnection is manual, then identification of the faulted portion may be either automatic or manual. This annex will discuss automatic disconnection and some techniques for either automatic identification or for manual tracing.

A.2 Low-resistance grounded systems

A.2.1 Time selective tripping

Systems that are grounded by means other than high resistance or tuned reactance must detect the fault current and interrupt it quickly to control the amount of damage. To provide effective detection and protective tripping, all individual circuits must be equipped with selectively coordinated ground-fault relays. It ground-fault currents are small, then relays may require zero-sequence current transformers. This must be carded down to the lowest level for which individual protection is required. For example, if a medium-voltage or a low-voltage auxiliary system is equipped with only delta-wye connected transformers to lower voltage, then ground faults on a lower voltage system will not affect ground fault relays on the higher voltage system. If ground-fault tripping protection is provided at the secondary wye of such a transformer, then ground-fault protective tripping may have to be carried at least to every piece of equipment on that voltage system.

For instance, if the loss of all circuits served by a lighting cabinet can be tolerated for a ground fault on any one, then it may be appropriate to provide ground-fault tripping only on a main breaker. If it cannot be tolerated, then it may be preferable not to provide any ground-fault tripping at this voltage level and to apply only phase tripping.

Automatic protective tripping for ground faults is usually provided in one of two ways. One way is a conventional time-coordinated sequence of selective tripping in which instantaneous relay response is applied closest to the load. Successively longer delayed tripping is applied at circuit branching locations nearer the source. This simple system may provide poor damage limitation for ground faults close to the source where interruption is slow. A usual approach to improve this situation near the source is to provide an instantaneous ground fault trip, set fairly high so as to avoid responding to faults very far downstream in the system. This tactic may be only moderately successful with electromechanical relays because of the substantial accuracy tolerance and variable repeatability. Microprocessor relays may offer greater accuracy and repeatability. However, care must be exercised. If an instantaneous element is specified, it may not be able to be set high enough to avoid tripping for faults well down in the system, thus losing the desired selectivity. If an instantaneous element cannot be used, some microprocessor relays require replacement of the complete unit at considerable expense in order to eliminate the ground instantaneous feature.

A.2.2 Zone selective tripping

Another method of providing selective ground fault protection is zone selective. Zone selectivity requires that a relay-breaker communicate with the relay next above it nearer the source and any relays directly below it. All relays are equipped with both an instantaneous trip and a time-current selectively coordinated element. When a relay senses a ground-fault current, it sends a restraint signal over a pair of wires to the relay nearer the source. The restraint signal prevents the instantaneous feature from operating, but leaves the delayed tripping in operation to back up the downstream breaker. Each relay-breaker trips instantaneously if it receives no restraint signal. In this manner, excessive damage due to delayed tripping may be prevented.

A.2.3 Selective identification

There are pieces of equipment available that can provide automatic identification of circuits that have carried a ground-fault current. Each circuit must be equipped with a zero-sequence current transformer. These pieces of equipment are usually used on high-resistance grounded systems. To prevent nuisance records caused by transients, the recording device requires that the fault current persist for a number of cycles. Such delay cannot usually be tolerated for lower resistance grounding due to excessive damage.

A.3 Ungrounded and high-resistance grounded systems

Ungrounded systems cannot be arranged to interrupt a faulted circuit automatically. High-resistance grounded systems are very rarely, if ever, equipped to interrupt automatically due to the difficulty in providing selectivity reliably at very low current levels.

Annex B Ground-fault location

(Normative)

B.1 General

Ground-fault location for low-resistance grounded and effectively grounded auxiliary power systems is straightforward in that the protective devices generally provide satisfactory sensitivity and selectivity. The particular feeder, branch circuit, or piece of equipment that suffers a ground fault is selectively tripped by the protective relaying. However, ungrounded and high-resistance grounded systems usually have ground faults alarmed but not automatically isolated by tripping the circuit involved. Fault current magnitudes are small and the location can be difficult to determine.

B.2 Automatic ground-fault location

Automatic selective identification equipment may be applied to ungrounded and high-resistance grounded systems. When applied to ungrounded systems, the equipment includes a high-resistance neutral grounding resistor for wye systems and a grounding transformer for delta systems. Consequently, application of automatic selective identification of ground-faulted circuits usually requires conversion of the system to high-resistance grounding. The selective identification is provided by recording those circuits that have carried fault current by an array of relays. Each relay is actuated by its own zero-sequence current transformer.

B.3 Manual ground-fault location

Manual identification systems may be as simple as sequentially opening each disconnecting device in the ground-faulted system and observing the ground detecting instruments to determine whether the ground fault has been removed. When a feeder is identified near the source, then the search is carried down into the system to the next branching away from the source and toward the load. There are pieces of ground detecting equipment (and pieces of high-resistance grounding equipment) that are arranged to impose either an audio-frequency signal or a pulsing two-level ground-fault current in the ground-fault circuit path. The course of these currents may be traced through the system from the source to fault by using an appropriate sensing device and following the circuit.

B.3.1 High-resistance grounded system

Ground faults can be located by de-energizing pieces of equipment one at a time and observing the ground-fault detection system. This may disrupt the operation of the station, be quite time consuming, and sometimes be hazardous. A high-resistance grounding system utilizing pulsing ground-fault detector apparatus is available to overcome those difficulties. The system provides the following:

a) High-resistance grounding
b) Immediate warning when a ground fault occurs
c) System enabling to continue operation with a single ground fault present
d) A means for pulsing the current into the ground fault so that it can be traced to the point of fault
e) A means for measuring the system charging current

The system neutral is derived by three small transformers (5 kVA to 10 kVA) connected wye-broken delta. The primary neutral is grounded through a current transformer and ammeter, so that ground-fault current can be measured. The secondary broken delta is connected through a resistor with taps so that the proper resistance can be used to control the current, which will flow into a ground fault. The component of ground-fault current controlled by the high-resistance neutral ground must be slightly greater than the system charging current. A contactor is wired to selected taps of the resistor. A voltage relay is wired in parallel with the resistor. With no ground fault on the system, the voltage at the broken delta is zero. When a ground fault occurs, this voltage increases to a maximum of three times the nominal secondary voltage of one of the grounding transformer windings. A ground fault is alarmed. The operator then initiates a control circuit that causes the pulsing contactor to close periodically. When closed, the contactor bypasses a portion of the resistor, causing the grounding resistance to decrease and the ground fault current to increase. This action produces ground fault current pulses on the auxiliary system. These pulses can be traced to the point of fault with a clamp on ammeter that encircles all three phases of the power conductors.

B.3.2 Ungrounded system

As in the high-resistance grounded system, ground faults can be located by de-energizing equipment one at a time. This method suffers the same disadvantages discussed before. An artificial neutral package may be used to create an intermittent return path for the ground-fault current to distinguish it from the system charging current. The artificial neutral package consists of a bank of resistors temporarily connected to each phase in wye configuration with a pulsing contactor in the neutral connection to ground. A ground fault is alarmed. After connecting the artificial neutral package, the operator then initiates a control circuit that causes the pulsing contactor to close periodically. This produces ground-fault current pulses on the auxiliary system just like those described in B.3.1. These pulses can be traced to the point of fault with a clamp on the ammeter that encircles all three phases of the power conductors.