

*IEEE Recommended Practice for
Grounding of Industrial
and Commercial Power Systems*



IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems



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Foreword

(This Foreword is not a part of ANSI/IEEE Std 142-1982, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.)

This recommended practice is a revision of IEEE Std 142-1972. The subjects covered by this document are divided into four parts corresponding to the four sections.

Section 1 covers the problems of system grounding, that is, connection to ground of the neutral, of the corner of the delta, or of the midtap of one phase. The advantages and disadvantages of grounded versus ungrounded systems are discussed. Information is given on how to ground the system, where the system should be grounded, and how to select equipment for the grounding of the neutral circuits.

Section 2 deals with the problems of connecting the frames and enclosures of electric apparatus, such as motors, switchgear, transformers, buses, cables, conduits, building frames, and portable equipment, to a ground system. It also outlines the fundamentals of making the inter-connection or ground-conductor system between electric equipment and the ground rods, water pipes, etc.

Section 3 deals with the problems of static electricity—how it is generated, what processes may produce it, how it is measured, and what should be done to prevent its generation or to drain the static charges to earth to prevent sparking. The methods of protecting structures against the effects of lightning are also covered; since the system for protecting structures against lightning consists entirely of conductors to earth, it is considered within the scope of this document to discuss the general aspects of the problem.

Section 4 deals with the problems of obtaining a low-resistance connection to the earth. The use of ground rods, connections to water pipes, etc, are discussed.

Looking at the problem from an overall standpoint, the grounding of the system would in most cases be done by making a metallic connection directly or through an impedance between transformer or generator neutrals and the building grounding system that is described in Section 2. The grounding system described in Section 2 in turn is connected to earth through the system of ground rods and water pipes described in Section 4.

The protective system for static and lightning protection discussed in Section 3 would likewise be connected to the ground rods and water pipe system, as outlined in Section 4.

The major revisions are contained in Section 3, with only minor changes in Sections 1, 2, and 4.

This recommended practice was reviewed and approved by the Power Systems Technologies Committee of the IEEE Industry Applications Society. This revision was prepared by the Power Systems Grounding Subcommittee, of the Power Systems Technologies Committee. At the time it approved this recommended practice, the subcommittee had the following membership:

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Grounding of Industrial and Commercial Power Systems

4th Edition

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1. System Grounding

1.1 Introduction. Whether or not to ground an electrical system is a question that must be faced sometime by most engineers charged with planning electrical distribution. A decision in favor of a grounded system leads to the question of how to ground.

It is the purpose of this section to assist the planning engineer in answering these and other more detailed questions on the subject by presenting basic reasons for grounding or not grounding and by reviewing general practices and methods of system grounding.

Practices of the grounding of synchronous generators [7]¹ and of distribution and transmission systems [9], particularly those operated at 23 kV and higher, have been summarized in other guides. The practices set forth in those guides are applicable to industrial power systems to various degrees, depending on the type

and extent of the industrial system under consideration and on the character of service required at the points of power consumption.

Where an industrial power system consists of power-generating equipment, transmission circuits, and distribution circuits, the reasons for grounding these components are often the same as those for grounding similar components of public utility systems and other large power systems, and the methods of grounding would generally be similar under like conditions of service. But in some cases the reasons for grounding and the methods of grounding certain components of an industrial power system may differ according to the requirements of manufacturing or process operations.

The National Electrical Code [2], sponsored by the National Fire Protection Association, contains regulations pertaining to system and equipment grounding applicable to industrial, commercial, and health-care facilities. These

¹The numbers in brackets correspond to those of the references listed in 1.15.

rules are considered minimum requirements for the protection of life and property and should be carefully reviewed during the course of system design.

1.2 Definitions. Definitions of terms in addition to those appearing in this section may be found in ANSI/IEEE Std 100-1977 [1].

The varieties of system grounding are the following.

ungrounded system. A system, circuit, or apparatus without an intentional connection to ground, except through potential-indicating or measuring devices or other very-high-impedance devices.

NOTE: Though called ungrounded, this type of system is in reality coupled to ground through the distributed capacitance of its phase windings and conductors. In the absence of a ground fault, the neutral of an ungrounded system under reasonably balanced load conditions will usually be close to ground potential, being held there by the balanced electrostatic capacitance between each phase conductor and ground. Figure 1(a) shows an ungrounded system with voltage relations for balanced phase-to-ground capacitance.

grounded system. A system of conductors in which at least one conductor or point (usually the middle wire or neutral point of transformer or generator windings) is intentionally grounded, either solidly or through an impedance.

NOTE: Various degrees of groundings are used, from solid or effective grounding to the high-impedance grounding obtained from a small grounding transformer used only to secure enough ground current for relaying, to the high-resistance grounding which secures control of transient overvoltage but may not furnish sufficient current for ground-fault relaying. Figures 1(b) and (c) shows two points at which a system may be grounded and the corresponding voltage relationships. Note that according to NEMA SG 4-1975 [6] there are system voltage limitations for corner grounding.

grounded solidly. Connected directly through an adequate ground connection

in which no impedance has been intentionally inserted.

NOTE: This term, though commonly used, is somewhat confusing since a transformer may have its neutral solidly connected to ground, and yet the connection may be so small in capacity as to furnish only a very-high-impedance ground to the system to which it is connected. In order to define grounding positively and logically as to degree, the term *effective grounding* has come into use. The term *solidly grounded* will therefore be used in this standard only in referring to a solid metallic connection from system neutral to ground; that is, with no impedance intentionally added in the grounding circuit.

grounded effectively. Grounded through a sufficiently low impedance such that for all system conditions the ratio of zero-sequence reactance to positive-sequence reactance (X_0/X_1) is positive and less than 3, and the ratio of zero-sequence resistance to positive-sequence reactance (R_0/X_1) is positive and less than 1.

NOTE: The effectively grounded system permits the application of surge arresters with less than line-to-line voltage ratings. Ground fault currents will be approximately of the same magnitude as three-phase fault currents.

resistance grounded. Grounded through impedance, the principal element of which is resistance.

NOTE: The high-resistance-grounded system is designed to meet the criterion of $R_0 \leq X_{C0}$ in order to limit transient overvoltages due to arcing ground faults. The ground-fault current is usually limited to less than 10 A. X_{C0} is the distributed per-phase capacitive reactance to ground of the system.

The low-resistance-grounded system permits a higher ground-fault current (on the order of 25 A to several hundred amperes) to obtain sufficient current for selective relay performance. For the usual system the criterion for limiting transient overvoltages is $R_0/X_0 \geq 2$.

inductance grounded. Grounded through impedance, the principal element of which is inductance.

NOTE: The conditions of an inductance-

grounded system are that X_0/X_1 lie within the range of 3-10 and $R_0/X_0 \leq 1$. The ground-fault current becomes 25% or more of the three-phase fault current. Inductance grounding becomes "effective" grounding if X_0/X_1 is reduced to 3 or less.

1.3 Factors Influencing the Choice of Grounded or Ungrounded System

1.3.1 Service Continuity. For many years a great number of industrial plant distribution systems have been operated ungrounded at one or more voltage levels. In most cases this has been done with the thought of gaining an additional degree of service continuity. The fact that any contact occurring between one phase of the system and ground is unlikely to cause an immediate outage to any load may represent an advantage in many plants, varying in its importance according to the type of plant.

Grounded systems, in most cases, are designed so that circuit protective devices will remove a faulty circuit from the system regardless of the type of fault. A phase-to-ground fault generally results in the immediate isolation of the faulted circuit with the attendant outage of the loads on that circuit. However, experience has shown [10], in a number of systems, that greater service continuity may be obtained with grounded-neutral than with ungrounded-neutral systems.

1.3.2 Multiple Faults to Ground. While a ground fault on one phase of an ungrounded system generally does not cause a service interruption, the occurrence of a second ground fault on a different phase, before the first fault is cleared, does result in an outage. If both faults are on the same feeder, that feeder will be opened. If the second fault is on a different feeder, both feeders may be deenergized.

The longer a ground fault is allowed to remain on an ungrounded system, the greater is the likelihood of a second one

occurring on another phase, resulting in an outage. The advantage of an ungrounded system, in not immediately dropping load upon the occurrence of a ground fault, may be largely destroyed by the practice of ignoring a ground fault until a second one occurs and repairs are required to restore service. With an ungrounded system it is extremely important that an organized maintenance program be provided so that ground faults are located and removed as soon as possible after their detection.

An adequate detection system, possibly in conjunction with an audible alarm, is considered essential for operation of an ungrounded system. In addition, it is advisable in ungrounded systems to employ ground-fault tracing equipment which permits maintenance personnel to locate a ground fault with the system energized and without the necessity of interrupting service on any circuit during the process of fault locating.

Experience has shown that multiple ground faults are rarely, if ever, experienced on grounded-neutral systems.

1.3.3 Arcing Fault Burndowns. In recent years, especially in low-voltage power systems, many cases of arcing fault burndowns have been reported in which severe damage to or complete destruction of electrical equipment was caused by the energy of arcing fault currents [15]. In typical cases an arcing fault becomes established between two or more phase conductors in an ungrounded system, or between phase conductor(s) and ground in a solidly grounded-neutral system. The fault arc causes the release of enormous amounts of energy at the fault site, resulting in the violent generation of hot gases and arc plasma. The accompanying heat is so intense that it vaporizes copper or alumi-

num conductors and surrounding steel enclosures and distills toxic and flammable gases from organic insulation systems. Frequently the devastation is so complete that the equipment involved must be totally replaced [16].

It is characteristic of arcing fault burn-downs that the normal phase-overcurrent devices do not operate to remove the initial fault quickly. Arcing fault current levels may be so low that such devices either are not actuated at all (because fault currents are below pickup settings) or are actuated only after a long period of time, too late to prevent burn-down.

The low-current arcing faults are characteristic of open or covered buses, particularly in switchgear or metal-enclosed switching or motor control equipment. Instances of burn-down have also occurred in high-capacity buses having relatively wide spacing, served from the utility network at 480Y/277 V through protective devices rated 2000 A or larger. Such spacing can limit the current of a single arc to approximately 1500 A, which is not enough to operate the phase protective devices, so arcing continues for many minutes.

It is generally recognized that prevention of arcing fault burn-downs, at the present state of protective system design, must rely upon fast and sensitive detection of the arcing fault current, accompanied by an interruption of the faulty circuit within approximately 10–20 cycles. In the solidly grounded-neutral system, this fast sensitive detection is possible since an arcing fault will produce a current in the ground path, either because the fault begins as a line-to-ground fault or because it will almost instantly involve ground, even though initiated as a line-to-line arcing fault. Under normal (nonground fault) conditions

there is no significant current in the ground return path. Therefore, monitoring the solidly grounded-neutral system for currents in the ground circuit provides an easy means for detecting and removing destructive arcing faults to ground. This type of protection is universally applicable throughout the power system, and the sensitivity and speed of such relaying are independent of load current values and phase-overcurrent device settings.

An inherent problem of ground-fault protection devices typically installed in low-voltage main circuit breakers, service breakers, etc, is that a ground fault in a cable or equipment of a small subfeeder or branch of the system is likely to trip the large main circuit breaker, shutting down the entire installation. Nonselective tripping can be a problem unless coordinated ground-fault protection devices are installed at each feeder, subfeeder, and at each load branch of the system. Where isolation of only the faulted portion of a system is important, much care must be used in applying ground-fault protection equipment.

Thus the solidly and low-resistance grounded-neutral systems provide a basis for easily securing protection against ruinous phase-to-ground arcing fault burn-downs. (Unfortunately, no comparably reliable and universally applicable means of protection against low-level *line-to-line* arcing fault burn-downs has been devised.)

1.3.4 Location of Faults. On an ungrounded system, a ground fault does not open the circuit. Some means of detecting the presence of a ground fault on the system should be installed. Lamps connected to indicate the potential from each phase to ground will show the presence of a ground fault and which phase is involved, but will not show on which

feeder the fault has occurred. Locating a ground fault on one of the several feeders may require removing from service one feeder at a time until the ground detector indicates that the faulted feeder has been removed from the system. Should it happen that the same phase of two different feeders becomes faulted to ground at the same time, the faulted feeders cannot be located by removing them from the system one at a time. It may be necessary to remove all feeders and restore them to service one at a time, checking the ground detector as each feeder is restored.

The location of a grounded feeder on an ungrounded system may be facilitated by the use of various types of locating apparatus [13]. For example, an interrupted direct voltage or superimposed audio signal may be applied to the feeder bus and the tracing current detected in the grounded feeders. Some operators have reported success using locating apparatus not requiring deenergizing system feeders [14]. This, of course, has the advantage of permitting the location of ground faults without waiting for light load periods on the system.

An accidental ground fault on a grounded system is both indicated and at least partially located by an automatic interruption of the accidentally grounded circuit or piece of equipment.

1.3.5 Safety. Many of the hazards to personnel and property existing in some industrial electrical systems are the result of poor or nonexistent grounding of electrical equipment and metallic structures. While the subject of equipment grounding is treated in Section 2, it is important to note here that regardless of whether or not the system is grounded, safety considerations require thorough grounding of equipment and structures.

Proper grounding of a low-voltage

(600 V or less) distribution system may result in less likelihood of accidents to personnel than when the system is supposedly left ungrounded. The knowledge that a circuit is grounded generally will result in greater care on the part of the worker.

It is erroneous to believe that on an ungrounded system a person may contact an energized phase conductor without personal hazard. As Fig 1(a) shows, an ungrounded system with balanced phase-to-ground capacitance has normal line-to-neutral voltage between any phase conductor and ground. To accidentally or intentionally contact such a conductor may present a serious, perhaps lethal, shock hazard.

While a ground-fault remains on one phase of an ungrounded or impedance-grounded system, personnel contacting one of the other phases and ground are subjected to 1.73 times the voltage that would be experienced on a solidly neutral-grounded system. The voltage pattern is the same as that shown in Fig 1(c).

Other hazards of shock and fire may result from inadequate grounding of equipment in either grounded or ungrounded systems. Accidental ground faults are inevitable. The current path to ground for a winding-to-frame insulation breakdown in a motor may include greasy shavings or other materials that can be ignited by sparks or localized heating. Such a high-impedance ground circuit may not permit enough current flow to operate protective devices, with the result that a potential fire and safety hazard may exist for some time. There is hazard of a shock to personnel from such a condition, should they bridge all or part of the high-impedance ground path, for example by contacting the frame of the faulty machine. This hazard is particularly bad because there are

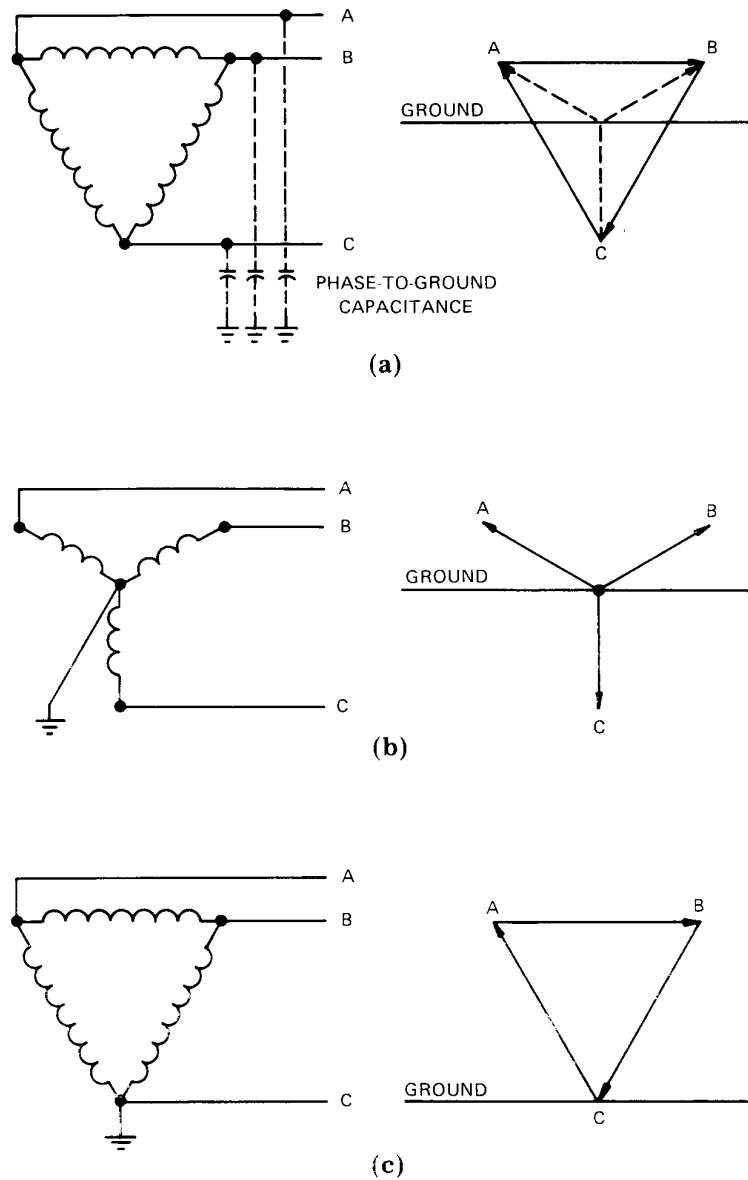


Fig 1
Voltages to Ground under Steady-State Conditions
(a) Ungrounded System (b) Grounded Wye-Connected System
(c) Corner Grounded Delta-Connected System

more possible victims than in the case where persons familiar with electric systems work on a circuit.

On the other hand, the relatively high ground-fault currents associated with solidly grounded systems may present a hazard to exposed workers from hot arc products and flying molten metal, which is not present in ungrounded systems. This problem has become much less serious however, because of the universal use of metal-enclosed equipment.

1.3.6 Abnormal Voltage Hazards. The possible overvoltages on the ungrounded system may cause more frequent failures of equipment than if the system were grounded. In some cases these overvoltages have caused failures on more than one unit of equipment at the same time. These multiple failures are not necessarily confined to one feeder, but may involve equipment on several different feeders.

A fault on one phase of an ungrounded or impedance-grounded system places a sustained increased voltage on the insulation of ungrounded phases in a three-phase system. This overvoltage is 1.73 times the voltage normally on the insulation. This or other sustained overvoltages or the transient overvoltages on the ungrounded system may not immediately cause failure of insulation, but may tend to reduce the life of the insulation.

The reduced overvoltages experienced on grounded systems are less likely to damage equipment or insulation.

1.3.7 Power System Overvoltages (See [11, chap 5]. Some of the more common sources of overvoltage on a power system are the following:

- (1) Lightning
- (2) Switching surges
- (3) Static
- (4) Contact with a high-voltage system

- (5) Line-to-ground faults
- (6) Resonant conditions
- (7) Restriking ground faults

1.3.8 Lightning (See Section 3 and [17].) Most industrial systems are effectively shielded against direct lightning strokes. Many circuits are either underground in ducts or within grounded metal conduits or raceways. Even open-wire circuits are often shielded by adjacent metallic structures and buildings. Surge arresters applied at the incoming service limit the surge voltages within the plant which result from strokes to the exposed service lines. Other arrestor applications may be necessary within the plant to protect low-impulse-strength devices such as rotating machines. Where a plant is supplied from a substation stepping down from some higher voltage, surge arresters are desirable on the low side of the transformer, since the leading edge of an incoming surge (prior to the primary arrester flashover point) is transformed just as are the power frequencies. Such a surge pulse is capable of damaging equipment connected to the secondary winding unless surge protective devices suitable for this equipment are applied.

1.3.9 Switching Surges. Normal switching operations in the system can cause overvoltages. These are generally not more than three times normal voltage and of short duration. Overcurrent devices such as circuit breakers or non current-limiting fuses, in general, interrupt a circuit at a normal current zero, at which time the stored energy in the inductance of the circuit is zero. The overvoltages thus developed result from transient oscillation in the circuit capacitance and inductance, there being stored energy in the circuit capacitance at the time of current interruption. More serious overvoltages can be produced by devices

which interrupt by forcing current zero. Such devices as vacuum interrupters and current-limiting fuses must be carefully applied because of this overvoltage problem. In low-voltage systems, however, the standards citation for current-limiting fuses require that the maximum peak voltage occurring during circuit interruption shall not exceed 3000 V; this is less than the crest of the normal high-potential test voltage applied to equipment in the 600 V class.

Neutral grounding is not likely to reduce the total magnitude of overvoltage produced by lightning or switching surges. It can, however, distribute the voltage between phases and reduce the possibility of excessive voltage stress on the phase-to-ground insulation of a particular phase.

1.3.10 Static. (See Section 3.) Buildup of overvoltage on power system conductors due to static charge is not usually a problem in modern plants with metal-enclosed circuits and equipment. Static charge on moving belts can build up voltages which can be transmitted to the power system unless motor frames are properly grounded. Overhead open-wire lines may be subject to static overvoltages resulting from certain atmospheric conditions. A system ground connection, even of relatively high resistance, can effectively prevent static voltage buildup.

1.3.11 Contact with Higher Voltage System. Contact with a higher voltage system may be caused by a broken high-voltage conductor falling on a lower voltage conductor where both lines cross or are carried on the same poles, or by breakdown between the high- and low-voltage windings of distribution transformers, causing other failures of insulation, possibly at several points. An effectively grounded low-voltage system, though experiencing high values of fault

current for this condition, will hold the system neutral close to ground potential, and thus the overvoltages to ground on the low-voltage system will be greatly reduced.

1.3.12 Line-to-Ground Faults. Common source of sustained overvoltage on an ungrounded system is one phase of a three-phase system becoming grounded. In this case the insulation of the other phases is subjected to a voltage 73% above normal. A solidly grounded-neutral system would not permit this overvoltage. While this voltage seldom approaches the insulation levels of equipment and circuits, the cumulative effect of higher than normal voltage stresses may somewhat reduce insulation life.

1.3.13 Resonant Conditions. An ungrounded system may be subjected to resonant overvoltages. With the high phase-to-ground capacitance of larger systems, there may be a condition of approximate circuit resonance during a line-to-ground fault through an inductance such as a faulty coil in a motor starter. The voltage to ground of the unfaulted phases will then be considerably in excess of line-to-line voltage. An overvoltage due to resonant or near-resonant conditions can be encountered on a small system where tuned inductive-capacitive circuits are used for such purposes as the operation of welders. For example, if the welder is equipped with a series capacitor for power factor improvement, the voltages across the capacitor and across the transformer winding are each many times the supply-line-to-line voltage. A fault between the capacitor and the welder transformer imposes this high voltage on the insulation of the ungrounded system. A grounded-neutral system would prevent this overvoltage by holding the phases to their approximate normal voltages to ground.

1.3.14 Restriking Ground Faults. Field experience and theoretical studies have shown that arcing, restriking, or vibrating ground faults on ungrounded systems can, under certain conditions, produce surge voltages as high as 6 times normal. The conditions necessary for producing these overvoltages require that the dielectric strength of the arc path build up at a higher rate after each extinction of the arc than it did after the preceding extinction. This phenomenon is unlikely to take place in open air between stationary contacts because such an arc path is not likely to develop sufficient dielectric recovery strength. It may occur in confined areas where the gas pressure may increase after each conduction period. Neutral grounding is effective in reducing transient voltage buildup from such intermittent ground faults by reducing neutral displacement from ground potential and the destructiveness of any high-frequency voltage oscillations following each arc initiation or restrike.

1.3.15 Cost. The cost differential between grounded and ungrounded neutral systems will vary, depending on the method of grounding, the degree of protection desired, and whether a new or an existing system is to be grounded.

For the new system in the design stage, power transformers with wye-connected secondaries and wye-connected generators are available as standard options, and there is no cost factor for establishing the system neutral. The additional cost items are the neutral grounding resistor or reactor if the system is to be impedance grounded, and the cost of ground fault relaying.

To ground an existing ungrounded delta-connected system requires an additional cost item, namely, the grounding transformer(s) for establishing the sys-

tem neutral. Also, the existing protective relay schemes may have to be modified to obtain sensitive ground-fault detection. For the existing system, practical consideration may dictate the application of a high-resistance grounding scheme, with alarm only on the occurrence of a ground fault. This eliminates the requirement for adding sensitive ground current relays to each feeder circuit.

The decision to convert an existing ungrounded system to grounded operation is usually made for the purpose of limiting transient overvoltages. Older systems with cables, and motor and transformer windings that have degraded insulation levels due to aging, atmospheric conditions, and sustained overvoltages are particularly vulnerable to failure due to transient overvoltages resulting from arcing ground faults. Therefore the cost for converting to grounded operation is small when compared to the cost of possibly having to replace cables or rewind motor or transformers.

1.3.16 Trends in the Application of System Grounding. The basic reasons for system grounding are the following.

- (1) To limit the difference of electric potential between all uninsulated conducting objects in a local area
- (2) To provide for isolation of faulted equipment and circuits when a fault occurs
- (3) To limit overvoltages appearing on the system under various conditions

Many industrial power system operators believe that an ungrounded system offers greater service continuity than a grounded system, because a line-to-ground fault does not cause immediate tripping of the faulted circuit. On the other hand, a second ground fault on another phase of a circuit other than that where the original fault occurred

causes a phase-to-phase fault, large short-circuit current flow (with attendant hazards), and tripping of both faulted circuits. Also, the effect of sporadic low-level arcing, at the first failure location, produced by the capacitive "grounding" currents from the two ungrounded phases, may cause the whole system-to-ground voltage to rise to 4 or more times normal voltage (to ground), causing severe stress on all of the insulation. It is such an overstress that can cause the failure at a second location, almost concurrent with the first failure. The various grounding systems eliminate this phenomenon by changing the fault current from entirely capacitive to something nearer a true resistive current.

Consequently, a major factor to consider in selecting a grounded or ungrounded system is the quality of electrical maintenance available. Well-maintained ungrounded systems, in which the first ground fault is promptly located and corrected, probably have greater service continuity than solidly grounded systems. However, many users whose maintenance practices are not quite so extensive feel that a grounded-neutral system gives them more continuous service than an ungrounded system.

There has been an increasing trend toward grounding industrial systems in order to overcome some of the disadvantages attributed to ungrounded operation. In recent years a substantial percentage of new industrial substation transformers have been purchased with wye-connected low-voltage windings, with the insulated neutral brought to external termination suitable for neutral grounding.

In new installations these transformers offer the advantage that they can be operated ungrounded, while having the neutral available for grounding, if desired, at some future time.

1.4 Methods of System Grounding

1.4.1 Grounding the System Neutral.

Most grounded systems employ some method of grounding the system neutral at one or more points. These methods (Fig 2) are referred to as the following:

- Solid grounding

- Resistance grounding

- Reactance grounding

- Ground-fault-neutralizer grounding

Each method, as named, refers to the nature of the external circuit from system neutral to ground rather than to the degree of grounding. In each case the impedance of the generator or transformer, whose neutral is grounded, is in series with the external circuit. Thus a solidly grounded generator or transformer may or may not furnish effective grounding to the system, depending on its impedance.

1.4.2 Solid Grounding Solid grounding refers to the connection of the neutral of a generator, power transformer, or grounding transformer directly to the station ground or to the earth. Because of the reactance of the grounded generator or transformer in series with the neutral circuit, a solid ground connection does not provide a zero-impedance neutral circuit.

If the reactance of the generator or transformer is too great with respect to the total system reactance, the objectives sought in grounding, principally freedom from transient overvoltages, may not be achieved. Thus it is necessary to determine the degree of grounding provided in the system. A good guide in answering this question is the magnitude of ground-fault current as compared to the system three-phase current. The higher the ground-fault current in relation to the three-phase fault current the greater the degree of grounding in the system. In terms of resistance and

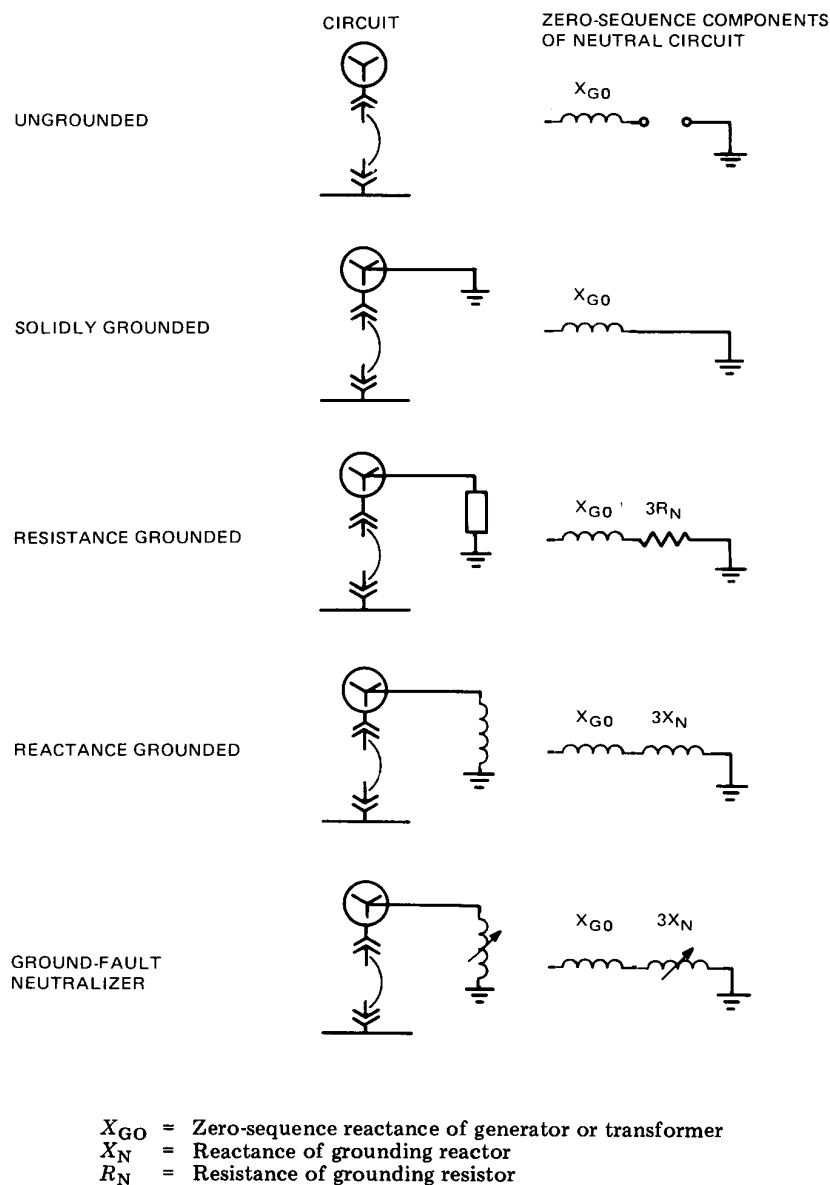


Fig 2
System Neutral Circuit and Equivalent Diagrams for Ungrounded
and Various Types of Grounded-Neutral Systems

reactance, effective grounding of a system is accomplished only when $R_0 \leq X_1$ and $X_0 \leq 3X_1$, and such relationships exist at any point in the system. The X_1 component used in the above relation is the Thévenin equivalent positive-sequence reactance of the complete system including the subtransient reactance of all rotating machines.

In most generators solid grounding, that is, without external impedance, may permit the maximum ground-fault current from the generator to exceed the maximum three-phase fault current which the generator can deliver and for which its windings are braced. Consequently, neutral-grounded generators should be grounded through an impedance which will limit the ground-fault current to a value no greater than the generator three-phase fault current. In the case of three-phase four-wire systems, the limitation of ground-fault current to 100% of the three-phase fault current is usually practical without interfering with normal four-wire operation.

Surge arresters for grounded-neutral service (rated near but not less than 80% of line-to-line voltage) require that the system be effectively grounded. This will carry with it a line-to-ground circuit current of at least 60% of the three-phase short-circuit value.

1.4.3 Resistance Grounding. In resistance grounding the neutral is connected to ground through one or more resistors. In this method, with the resistor values normally used, and except for transient overvoltages, the line-to-ground voltages that exist during a line-to-ground fault are nearly the same as those for an ungrounded system.

A system properly grounded by resistance is not subject to destructive transient overvoltages. For resistance-grounded systems at 15 kV and below,

such overvoltages will not ordinarily be of a serious nature if the resistance value lies within the following boundary limits: $R_0 \leq X_{C0}$, $R_0 \geq 2X_0$. The corresponding ground-fault current is far less than is normally used for low-resistance grounding, but is the design criterion for high-resistance grounding.

Resistance grounding may be either of two classes, high resistance or low resistance, distinguished by the magnitude of ground-fault current permitted to flow. Both types are designed to limit transient overvoltages to a safe level (within 250% of normal). However, the high-resistance method usually does not require immediate clearing of a ground fault since the fault current is limited to a very low level. This low level, typically on the order of 5 A, must be at least equal to the system total capacitance-to-ground charging current. The protective scheme associated with high-resistance grounding is usually detection and alarm rather than immediate tripout. In general the use of high-resistance grounding on systems where the line-to-ground fault current exceeds 10 A should be avoided because of the damage potential of an arcing current larger than 10 A in a confined space.

The low-resistance method has the advantage of immediate and selective clearing of the grounded circuit, but requires that the minimum ground-fault current be large enough to positively actuate the applied ground-fault relay. High-resistance grounding is a method that can be applied to existing medium-voltage ungrounded systems to obtain the transient overvoltage protection without the modification expense of adding ground relays to each circuit.

Systems grounded through resistors require surge arresters suitable for use on ungrounded-neutral circuits, that is, with

a voltage rating at least equal to the line-to-line voltage.

The reasons for limiting the current by resistance grounding may be one or more of the following:

- (1) To reduce burning and melting effects in faulted electric equipment, such as switchgear, transformers, cables, and rotating machines
- (2) To reduce mechanical stresses in circuits and apparatus carrying fault currents
- (3) To reduce electric-shock hazards to personnel caused by stray ground-fault currents in the ground return path
- (4) To reduce the arc blast or flash hazard to personnel who may have accidentally caused or who happen to be in close proximity to the ground fault
- (5) To reduce the momentary line voltage dip occasioned by the occurrence and clearing of a ground fault
- (6) To secure control of transient overvoltages while at the same time avoiding the shutdown of a faulty circuit on the occurrence of the first ground fault (high-resistance grounding)

1.4.4 Reactance Grounding. The term *reactance grounding* describes the case in which a reactor is connected between the system neutral and ground. Since the ground-fault current that may flow in a reactance-grounded system is a function of the neutral reactance, the magnitude of the ground-fault current is often used as a criterion for describing the degree of grounding. In a reactance-grounded system, the available ground-fault current should be at least 25% and preferably 60% of the three-phase fault current to prevent serious transient overvoltages ($X_0 \leq 10X_1$). This is considerably higher than the level of fault current desirable in a resistance-grounded system, and therefore, reactance grounding is usually

not considered an alternative to resistance grounding.

In practice, reactance grounding is generally used only in the case cited in 1.4.2, in which a generator neutral is to be connected to provide four-wire service. In this event it may be necessary to add a low-value reactor to limit the available ground-fault current through the generator to a value no greater than the three-phase fault current contributed by the generator.

1.4.5 Ground-Fault Neutralizer (Resonant Grounding) (See [8].) A ground-fault neutralizer is a reactor connected between the neutral of a system and ground and having a specially selected, relatively high value of reactance.

A line-to-ground fault causes line-to-neutral voltage to be impressed across the neutralizer, which passes an inductive current. This current is 180° out of phase and is approximately equal in magnitude (when the neutralizer is tuned to the system) to the resultant of the system charging current of the two unfaulted phases. The inductive and capacitive components of current neutralize each other, and the only remaining current in the fault is due to resistance, insulator leakage, and corona. This current is relatively small, and since it is in phase with the line-to-neutral voltage, the current and voltage pass through a zero value at the same instant. In addition, the rate of rise of the recovery voltage on the faulted phase is very low. Therefore the arc is extinguished without restriking, and flashovers are quenched without removing the faulted line section from service. It should be noted that failures in solid insulations such as paper, varnished cambric, and rubber are not self-healing as insulator flashovers are, and not extinguished by the use of the ground-fault neutralizer.

On systems for which faults in air are relatively frequent, ground-fault neutralizers may be very useful by reducing the number of circuit breaker operations required to remove faults, thus improving service continuity. They have been used primarily on systems above 15 kV, consisting largely of overhead transmission or distribution lines. This method is a second choice to resistor grounding, which provides ground relaying to disconnect the faulted circuit.

In some cases, where it has not been deemed desirable by the plant operators to trip a circuit on the occurrence of a ground fault, special arrangements have been used to limit the damage due to the flow of charging current and yet be able to easily locate the faulty feeder. One method is to use a ground-fault neutralizer in the neutral to limit the ground-fault current and to reduce switching surges to safe values. In some cases it may be desirable to pass enough ground-fault current to operate relays that give a signal or trip the circuit breaker of the faulty feeder. This is done by a current-sensing relay in combination with a resistor in parallel with the neutralizer. Because of the current to be switched, a power circuit breaker should be used for switching the resistor. The resistor and relay are selected as if only the resistor were used. Such a scheme is expensive and is employed only in very special cases.

One of the disadvantages of resonant-grounded systems is that care must be taken to keep the ground-fault neutralizer tuned to the system capacitance to minimize the development of transient overvoltages. Thus when sections of the system are switched on or off, it may be necessary to adjust the neutral reactance by changing the neutralizer tap. This can be accomplished by providing an ammeter and a control switch for remote

control of a motor-driven tap changer on the neutralizer, so that when parts of the system are switched, the neutralizer can be readjusted. Because of those complications, the ground-fault neutralizer is very rarely used in industrial and commercial systems.

1.4.6 Grounding at Points Other than System Neutral. In some cases low-voltage systems (600 V and below) are grounded at some point other than the system neutral. This has been done to obtain a grounded system at a minimum expense where existing delta transformer connections do not provide access to the system neutral.

1.4.7 Corner-of-the-Delta Grounding. In low-voltage systems, which in the past have nearly all been supplied from transformers with delta-connected secondaries, grounding of one phase, (*corner-of-the-delta*) grounding has sometimes been used as a means of obtaining a grounded system. Advantages are the following:

(1) Possible cost advantage over other grounding methods for existing delta systems

(2) Possibility of slightly better protection with two-element motor starters when they are located in the two ungrounded phases; with properly connected circuits, ground-faults in the control circuit will neither start the motor nor prevent stopping the motor by means of the push button

Disadvantages are the following:

(1) An inability to supply dual-voltage service for lighting and power load

(2) The necessity of positive identification of the grounded phase throughout the system to avoid connecting meters, instruments, and relays in the grounded phase

(3) A higher line-to-ground voltage on

two phases than in a neutral-grounded system

(4) The possibility of exceeding interrupting capabilities of marginally applied circuit breakers, because for a ground fault, the interrupting duty on the affected circuit breaker pole exceeds the three-phase fault duty

Because of its limitations, this type of grounding has not been widely used in industrial systems.

1.4.8 One Phase of a Delta System Grounded at Midpoint. Where existing systems at 600 V and below are supplied by three single-phase transformers with midtaps available, it is possible to gain some of the advantages of neutral grounding by grounding the midtap of one phase. This method does not provide all the advantages of system neutral grounding. Such connections are also used to obtain a limited amount of 240/120 V single-phase power in a three-phase 240 V system.

1.5 Selection and Design of System Grounding Arrangements

1.5.1 Obtaining the System Neutral.

The best way to obtain the system neutral for grounding purposes in three-phase systems is to use source transformers or generators with wye-connected windings. The neutral is then readily available. Such transformers are available for practically all voltages except 240 V. On new systems, 208Y/120 or 480Y/277 V wye-connected transformers may be used to good advantage instead of 240 V. Wye-connected source transformers for 2400, 4160, and 13 800 V systems are available as a standard option, whereas 4800 and 6900 V wye-connected source transformers may be priced at a premium rate. The alternative is to apply grounding transformers.

1.5.2 Grounding Transformers. System neutrals may not be available, particu-

larly in many old systems of 600 V or less and many existing 2400, 4800, and 6900 V systems. When existing delta-connected systems are to be grounded, grounding transformers may be used to obtain the neutral. Grounding transformers may be of either the zigzag, the wye-delta, or the T-connected type. One type of grounding transformer commonly used is a three-phase zigzag transformer with no secondary winding. The internal connection of the transformer is illustrated in Fig 3. The impedance of the transformer to balanced three-phase voltages is high so that when there is no fault on the system, only a small magnetizing current flows in the transformer winding. The transformer impedance to zero-sequence voltages, however, is low so that it allows high ground fault currents to flow. The transformer divides the ground fault current into three equal components; these currents are in phase with each other and flow in the three windings of the grounding transformer. The method of winding is seen from Fig 3 to be such that when these three equal currents flow, the current in one section of the winding of each leg of the core is in a direction opposite to that in the other section of the winding on that leg. This tends to force the ground-fault current to have equal division in the three lines and accounts for the low impedance of the transformer-to-ground currents.

A wye-delta-connected three-phase transformer or transformer bank can also be utilized for system grounding. As in the case of the zigzag grounding transformer, the usual application is to accomplish resistance-type grounding of an existing ungrounded system. The delta connection must be closed to provide a path for the zero-sequence current, and the delta voltage rating is selected for

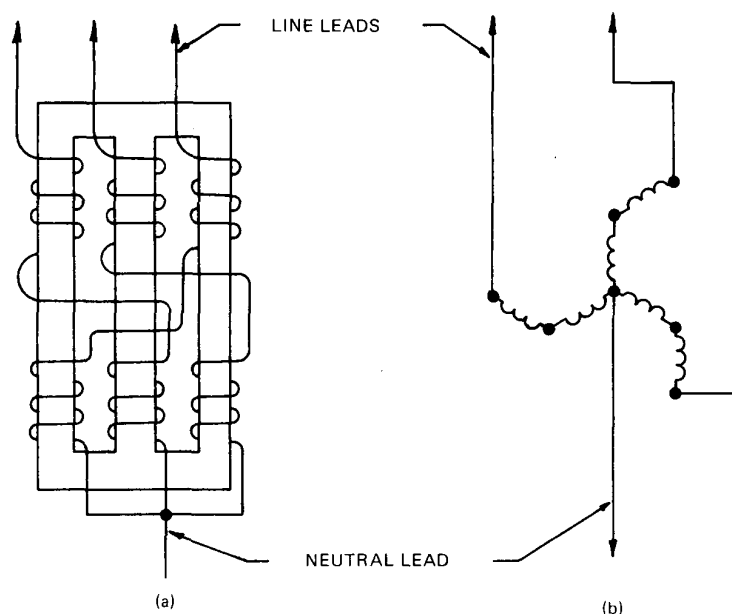


Fig 3
(a) Core Windings (b) Connections of Three-Phase Zigzag Grounding Transformer

any standard value. A resistor inserted between the primary neutral and ground, as shown in Fig 4, provides a means for limiting ground-fault current to a level satisfying the criteria for resistance-grounded systems. For this arrangement, the voltage rating of the wye winding need not be greater than the normal line-to-neutral system voltage. For high-resistance grounding it is sometimes more practical or economical to apply the limiting resistor in the secondary delta connection. Three single-phase distribution class transformers are used, with the primary wye neutral connected directly to ground. The secondary delta is closed through a resistor which effectively limits the primary ground-fault current to the desired low level. For this

alternative application, the voltage rating of each of the transformer windings forming the wye primary should not be less than the system line-to-line voltage.

The rating of a grounding transformer, in kilovoltamperes, is equal to the rated line-to-neutral voltage in kilovolts times the rated neutral current. Most grounding transformers are designed to carry their rated current for a limited time only, such as 10 s or 1 min. Consequently they are much smaller in size than an ordinary three-phase continuously rated transformer with the same rating.

It is generally desirable to connect a grounding transformer directly to the main bus of a power system, without intervening circuit breakers or fuses, to prevent the transformer from being in-

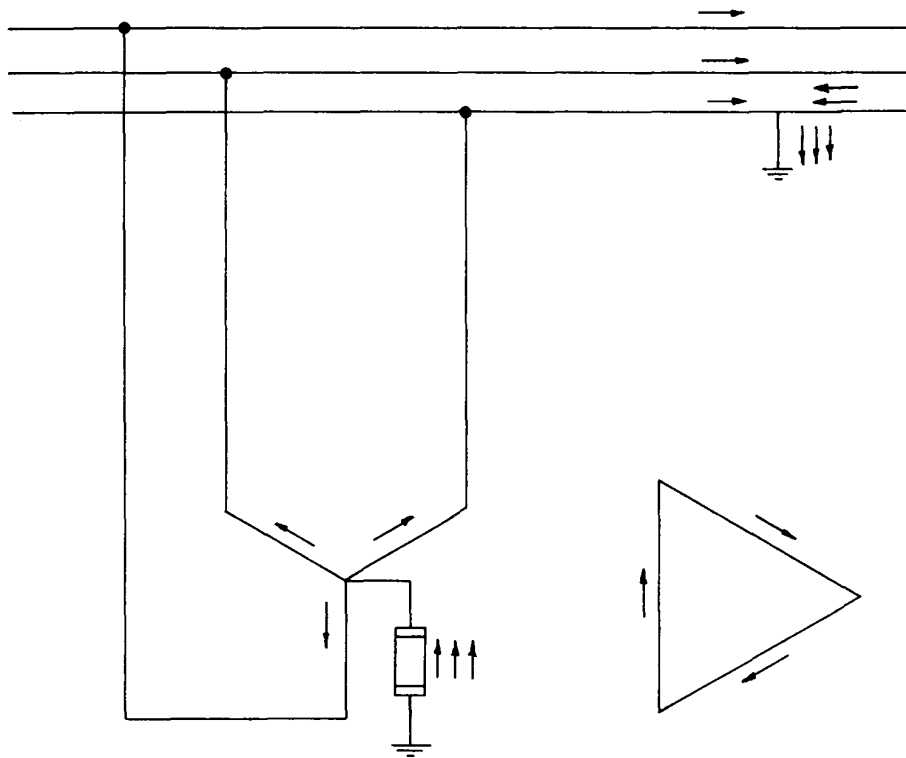


Fig 4
Vectors Representing Current Flow in Wye-Delta Transformer
Used as Grounding Transformer with Line-to-Ground Fault

advertently taken out of service by the operation of the intervening devices. (In this case the transformer is considered part of the bus and is protected by the relaying applied for bus protection.) Alternatively the grounding transformer should be served by a dedicated feeder circuit breaker, as shown in Fig 5(a), or connected between the main transformer and the main switchgear as illustrated in Fig 5(b). If the grounding transformer is connected as shown in Fig 5(b), there should be one grounding transformer for each delta-connected bank supplying power to the system, or enough ground-

ing transformers to assure at least one grounding transformer on the system at all times. When the grounding transformer is so connected, it is included in the protective system of the main transformer.

1.5.3 Suggested Grounding Methods for Systems 600 V and below. Low-voltage systems are frequently operated solidly grounded. The principal reason for this is the extensive use of 480 Y/277 V systems with line-to-neutral connected loads, and the requirement in the National Electrical Code,

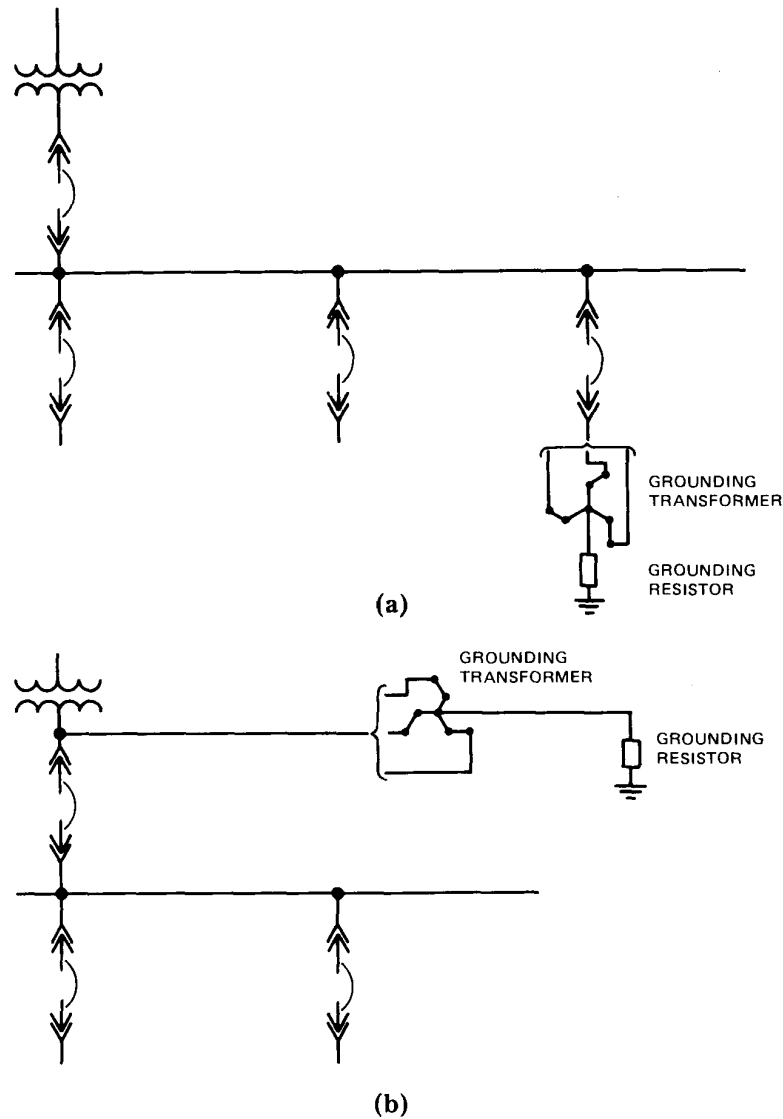


Fig 5
Methods of Connecting Grounding Transformer to a Delta-Connected or Ungrounded Power System to Form Neutral for System Grounding

ANSI/NFPA 70-1981 [2] for solidly grounding the neutral of such systems.

For the low-voltage system without line-to-neutral loading, solid grounding or high-resistance grounding are the

practical choices. Low-resistance grounding is usually not considered since it would require the use of sensitive ground-fault protective devices throughout the system. For reasons of economy the

solidly grounded system depends on adequate ground-fault current at locations remote from the source to operate phase fault devices. It is therefore especially important that the equipment grounding network provide a very-low-impedance return path for the ground-fault current. High-resistance system grounding, with alarm only, can be used if service continuity is of prime importance and if the faulted circuit can be located and isolated with little delay.

1.5.4 Systems 2.4–15 kV. Modern power systems in this range of voltages are usually low-resistance grounded to limit the damage due to ground faults in the windings of rotating machines and yet permit sufficient fault current for the detection and selective isolation of individual faulted circuits.

Ground faults are detected by an over-current relay connected in the residual circuit of the three-phase current transformers (Fig 6), or by a relay connected to a window- or doughnut-type (zero-sequence) current transformer which encloses all the phase conductors (Fig 7). When any loads are connected line to neutral, then the window-type current transformers must also enclose the neutral conductor. Using either method, positive tripping can be accomplished with low magnitudes of ground-fault current. However, the sensitivity of the residual scheme is limited by the relatively high ratios of phase current transformers, so greater sensitivity is available with the zero-sequence current transformer method. For this reason low-resistance grounding is commonly used, except for those cases where the size of the system is so small that the maximum available fault current is not high enough to be objectionable.

Alternatively, high-resistance grounding, as discussed in 1.4.3, can be used.

This contributes to better service continuity by permitting continued operation with one ground fault. However, it does so at the sacrifice of selectivity in ground-fault protection, because the fault current is normally too low to allow use of time-overcurrent relays.

At the present time there are 2.4 kV systems in operation without the system neutral grounded. More and more engineers, however, are applying system neutral grounding to 2.4 kV systems. The conventional method is to provide sufficient ground-fault current to permit selective relaying through the application of ground relays.

1.5.5 Systems above 15 kV. Systems above 15 kV are nearly always effectively grounded, because these are usually circuits with open lines in which surge arresters rated for grounded neutral service are desirable for better overvoltage protection and lower cost. These may be either distribution or transmission circuits. Recent trends are toward higher voltages for distribution [19]. In addition, rotating equipment is seldom connected directly to these systems; hence limiting ground-fault currents to prevent the burning of laminations is a less important factor than in lower voltage systems. In addition, voltages above 15 kV are not usually carried inside buildings, hence personnel hazards due to high fault currents are not a factor. Finally, the cost of resistors for resistance grounding at these voltages is prohibitive.²

²In recent years, electric utility distribution voltages above 15 kV have become quite common. Utility distribution networks above 15 kV are almost invariably effectively grounded; this must be considered when designing the primary distribution system of an industrial or commercial facility which is supplied at these voltages. If resistance grounding is desirable, a delta-wye transformation between the utility and the user system is usually used to provide zero-sequence isolation of the latter.

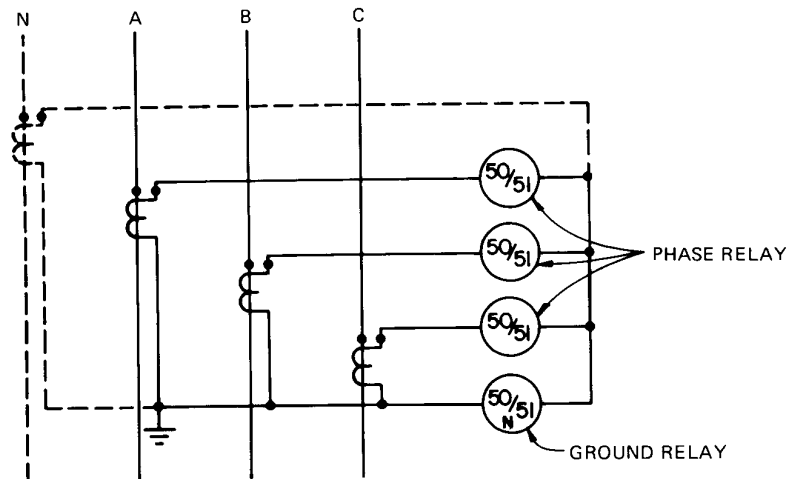


Fig 6
Ground-Fault Detection Diagram Using
Overcurrent Relay in Residual Circuit

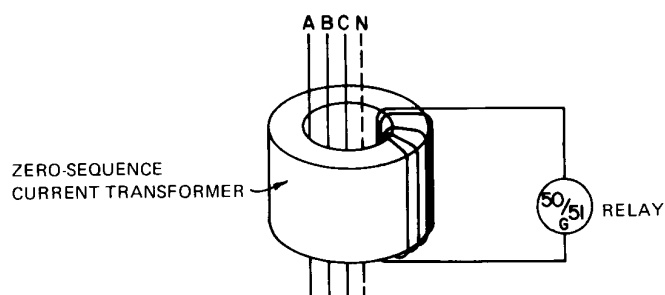


Fig 7
Ground-Fault Detection Diagram Using Overcurrent Relay Connected
to Zero-Sequence (Doughnut) Current Transformer

1.5.6 Criteria for Limiting Transient Overvoltages. (See [12].) Transient overvoltages can be limited effectively to safe values if the following criteria are observed:

(1) In resistance-grounded systems the resistor ground-fault current should be at least equal to, but preferably greater than, the charging current of the system.

(2) In reactance-grounded systems the ratio of X_0/X_1 should be 10 or less, where X_0 is the zero-sequence inductive reactance of the system, including that of the neutral reactance, and X_1 is the positive-sequence inductive reactance of the system, including the subtransient reactance of all rotating machines.

(3) Where a combination of grounding transformer and neutral-grounding resistor is used, the grounding transformer impedance should be low relative to the neutral resistance. The ratio of R_0/X_0 should be equal to or greater than 2, where R_0 is the zero-sequence resistance of the circuit, including the neutral resistor, and X_0 is the zero-sequence inductive reactance of the circuit, including that of the transformer and resistor.

1.6 Selection of System Grounding Points

1.6.1 Ground at Each Voltage Level. Delta-wye or wye-delta transformers effectively block the flow of zero-sequence current between systems. Hence it is necessary to ground at each voltage level to achieve the advantages of neutral grounding in all parts of the system. Each voltage level may be grounded at the neutral lead of a generator, power transformer bank, or grounding transformer. Any generator or transformer used for grounding should, as far as possible, be one that is always connected to the system. Alternatively, a sufficient number of generators or transformers should be grounded to ensure at least

one ground connection on the system at all times.

1.6.2 Ground at the Power Source and Not at the Load. The use of an available neutral at a load point, such as a wye-delta step-down transformer or a wye-connected motor, is not recommended as a point for system grounding. The principal disadvantage is that a number of these load neutrals must be grounded to ensure that the system remains grounded if one or more of these loads is out of service.

Consequently, the ground-fault current may be excessively high when all grounded points are in service. Since power sources are fewer in number than loads and are less likely to be disconnected, they are preferred as grounding points. Other disadvantages of grounding at the load are the following:

(1) Standard low-voltage unit substations have delta-connected primaries; therefore special transformers are required if the primaries are to be used as grounding points.

(2) Since the ground-fault current is dependent on the number of feeders or grounding points in operation, it may vary widely depending on system operating conditions. This makes selective relaying more difficult and may require additional directional ground relaying to avoid false tripping of healthy feeder circuits.

(3) The windings of many motors are not braced to withstand the unbalanced forces associated with ground faults

1.6.3 Ground Each Major Source Bus Section. When there are two or more major source bus sections, each section should have at least one grounded-neutral point, since the bus tie circuit may be open. If there are two or more power sources per bus section, there should be provision for grounding at least two

sources on each section. For four-wire distribution systems, grounding of the neutral conductor requires special consideration for reasons of safety and proper detection of ground fault (see IEEE Std 242-1975 [4] and [18]).

1.6.4 Neutral Circuit Arrangements. When the method of grounding and the grounding point have been selected for a particular power system, the next question to consider is how many generator or transformer neutrals will be used for grounding and whether (1) each neutral will be connected independently to ground, or (2) a neutral bus with a single ground connection will be established.

1.6.5 Single Power Source. When a power system has only one source of power (generator or transformer), grounding may be accomplished by connecting the source neutral to earth either directly or through a neutral impedance. Provision of a switch or circuit breaker to open the neutral circuit is not necessary because neutral circuits have practically zero potential with respect to ground, except during the short interval of a fault; hence breakdowns are not likely. Also, it is not desirable to operate the system ungrounded by having the ground connection open while the generator or transformer is in service. In addition, the neutral switching equipment greatly increases the cost of grounding.

In the event that some means of disconnecting the ground connection is required in a particular case, a metal-clad circuit breaker should be used rather than an open disconnect switch for indoor installations. The latter is hazardous to personnel if a ground fault should occur while the switch is being opened or closed.

1.6.6 Multiple Power Sources. For installation involving two or three gener-

ators or power transformers individual neutral impedances are frequently used. With this arrangement the neutral of each generator or main transformer bank is connected directly to its neutral impedance without intervening switching equipment. No special operating instructions are required since each impedance is automatically connected whenever its source is connected. In the case of resistance grounding, each resistor rating should be based on providing sufficient current for satisfactory relaying when its source is operating independently, and also to limit the total ground current when the sources are paralleled.

When total ground-fault currents with several individual resistors would exceed about 1000–4000 A, neutral switchgear and a single resistor should be considered for resistance-grounded systems.

When individual resistors are used, circulation of third-harmonic currents between paralleled generators is not a problem since the resistance limits the circulating current to negligible values.

When there are more than two or three generators or power-supply transformer banks at one installation, it is economically desirable to use only one resistor. Each power source is then connected to the resistor through a neutral bus and neutral switching equipment. This arrangement keeps the ground-fault current to a practical minimum, since the ground current from the station is never greater than what can be supplied through a single resistor. It also ensures the same value of ground current regardless of the number of generators or transformers in use and simplifies ground relaying.

The primary purpose of the neutral circuit breakers is to isolate the generator or transformer neutrals from the neutral bus when the source is taken out

of service, because the neutral bus is energized during ground faults.

Circuit breakers are preferred to disconnecting switches for indoor installations to ensure safety to personnel. If disconnecting switches are used, as in some outdoor installations, they should be elevated or metal enclosed and interlocked in such a manner as to prevent their operation except when the transformer primary and secondary switches or generator main and field circuit breakers are open.

It is sometimes desirable to operate with only one generator neutral circuit breaker closed at a time to eliminate any circulating harmonic or zero-sequence currents. When the generator whose neutral is grounded is to be shut down, another generator is grounded by means of its neutral circuit breaker before the main and neutral circuit breakers of the first one are opened. However, with similar generators and reasonably equal load division, circulating currents are negligible, and it is often found practical to operate with neutral circuit breakers of two or more generators closed. This simplifies operating procedure and increases assurance that the system will be grounded at all times. In the case of multiple transformers, all neutral isolating devices may be normally closed because the presence of delta-connected windings (which are nearly always present on at least one side of each transformer) minimizes the circulation of harmonic current between transformers.

When only one source is involved, but others are to be added to the station in the future, space should be allowed to add neutral switchgear when this becomes necessary.

1.7 Calculation of Ground-Fault Currents

1.7.1 General. The magnitude of the

current that will flow in the event of a line-to-ground fault on a grounded system is determined by the impedance from the source to the fault plus the impedance of the ground return path, including the impedances of grounding transformers, resistors, and reactors. For interconnected systems the calculation of the current may be rather complicated. For simpler cases an approximation of the available fault current may be obtained.

1.7.2 Resistance Grounding. When a single line-to-ground fault occurs on a resistance-grounded system, a voltage appears across the resistor (or resistors) nearly equal to the normal line-to-neutral voltage of the system.

In low-resistance grounded systems the resistor current is approximately equal to the current in the fault. Thus the current is practically equal to the line-to-neutral voltage divided by the resistance used in ohms. Standard grounding resistors have a voltage rating equal to the line-to-neutral voltage and a current rating equal to the current that flows when this voltage is applied to the resistor. Thus, for example, a maximum ground-fault current of approximately 1000 A will be obtained on a system when using a 1000 A resistor. This very simple method of calculating the ground-fault current is only suitable when the ground-fault current is small compared to the three-phase fault current.

The method just outlined applies to faults on lines or buses or at the terminals of machines or transformers. If the fault is internal to a rotating machine or transformer, the ground-fault current will be less. The reduction in current is primarily due to the internal voltage of the apparatus. In the case of wye-connected equipment, this internal voltage is at full value at the terminals and is zero at the

neutral. If the fault occurs at the neutral of any apparatus, no voltage will appear across the system grounding resistor, so the fault current will be zero. At intermediate points in the winding between the neutral and a terminal, the fault current will be intermediate between zero and the current due to a terminal fault. For example, at a point 10% of the winding length from neutral, the ground-fault current will be approximately 10% of the value for a terminal fault. For a fault anywhere between this point and a terminal, the current will be more than 10% of the amount for a terminal fault.

In the case of the delta-connected machines, the internal voltage to neutral may be considered to be 100% at the terminals and 50% at the midpoint of the windings. The midpoints have the lowest potential with respect to the electric neutral of any part of the winding. Therefore a ground fault at any point in the winding will produce a ground-fault current of 50% or more of the line-terminal fault value.

1.7.3 Reactance Grounding. In a reactance-grounded system with a single line-to-ground fault, the ground-fault current may be computed from the following expression, where resistance may usually be neglected:

$$I_g = \frac{3E}{X_1 + X_2 + X_0 + 3(X_n + X_{GP})} \quad (\text{Eq 1})$$

where

- I_g = ground-fault current, in A
- X_1 = system positive-sequence reactance, in Ω per phase, including the subtransient reactance of rotating machines
- X_2 = system negative-sequence reactance, in Ω per phase, including the subtransient reactance of rotating machines

- X_0 = system zero-sequence reactance, in Ω per phase
- X_n = reactance of neutral grounding reactor, in Ω
- X_{GP} = reactance of ground return circuits, in Ω
- E = line-to-neutral voltage in V

In most industrial and commercial systems without in-plant generation X_2 can be considered equal to X_1 .

1.7.4 Solid Grounding. In a system with solid neutral connection to ground, the ground-fault current for a single line-to-ground fault may be computed from the following equation:

$$I_g = \frac{3E}{X_1 + X_2 + X_0 + 3X_{GP}} \quad (\text{Eq 2})$$

1.8 Selection of Grounding Equipment Ratings. (See IEEE Std 32-1972 [3].)

1.8.1 General. Grounding resistors, reactors, and grounding transformers are normally rated to carry current for a limited time only. The standard time interval rating usually applicable for industrial systems, with relays arranged to protect the grounding equipment, is 10 s.

The voltage rating of a grounding resistor should be the line-to-neutral voltage rating of the system.

The insulation class of a reactor is determined by the system line-to-neutral voltage. The voltage rating may be less than the line-to-neutral voltage and is calculated by multiplying the rated current by the impedance of the reactor.

The voltage rating of a grounding transformer should be not less than the system line-to-line voltage if the neutral is connected directly to ground or the system line-to-neutral voltage if a resistor is inserted between neutral and ground.

Grounding resistors are rated in terms of the current that will flow through the

resistor with the system line-to-neutral voltage applied.

The rated current of a grounding reactor is the thermal current rating. It is the root-mean-square neutral current, in amperes, that the reactor will carry for its rated time without exceeding standard temperature limitations.

If a grounding transformer neutral is solidly connected to ground, the current that will flow during a ground fault is primarily determined by the reactances of the grounding transformer and the system to which it is connected. When a resistor is used between neutral and ground, the current rating of the grounding transformer is based on the resistor rated current. In either case the transformer is rated to carry the required current for rated time without exceeding its rated temperature limits. Many system grounding devices are short-time rated. Care must be exercised in their application to ensure that the current will be automatically interrupted before the thermal limits of the components are exceeded.

1.8.2 Resistor Ratings. For low-resistance grounded-neutral systems the determination of the resistor value, in ohms, and thus the magnitude of the ground-fault current, is based on the following:

- (1) Providing sufficient current for satisfactory performance of the system relaying scheme

- (2) Limiting ground-fault current to a value that will minimize damage at the point of fault without resulting in system overvoltages.

In most cases the ground-fault current is limited by the neutral resistor to a value considerably less than that which would flow for a three-phase fault. To determine the minimum ground-fault current required, a diagram of the sys-

tem must be available, giving the ratings of current transformers and types of relays for each circuit. This diagram should include consideration of future changes.

The magnitude of the ground-fault current must be sufficient for the operation of all relays that furnish ground-fault protection. In general, if the current is high enough to operate the relays on the higher capacity circuits, it will be adequate for the smaller circuits. As a general rule, ground-fault relays applied on circuits energizing wye-connected machines or transformer windings should operate positively with as little as 10% of the available ground-fault current flowing. For circuits energizing delta-connected machines or transformer windings, and for *upstream* relaying protecting lines or cables, the desired sensitivity is at least 50% of the available fault current. Where differential relays are applied for machine, transformer, bus, or line protection, their sensitivity to ground faults should meet the above criteria unless more sensitive detection is provided by other relays.

Note that the ground-fault current under all system-operating conditions must equal or exceed the minimum required for relaying each circuit connected to the system. This value is established by selecting the highest of those currents that meet the requirements of the several conditions stated above.

1.8.3 Reactor Ratings. The reactance of a neutral-grounding reactor should be chosen to limit the ground current and the current in the faulted phase to the desired value. In order to minimize transient overvoltages, the ground-fault current must not be less than 25% of the three-phase fault current. This corresponds to a ratio of $X_0/X_1 = 10$, where X_0 and X_1 represent the total electrical system values for any

possible ground-fault condition on the system. For reactance grounding of generators, the current in any winding must not exceed the three-phase fault current. This corresponds to a ratio of $X_0/X_1 \geq 1$, where X_0 , and X_1 represent generator reactance only. This establishes the criteria for the maximum and minimum values of neutral reactance. If the neutral reactance is selected in accordance with the following relationship, the current in the winding of the faulted phase will not exceed the three-phase fault current of the machine, regardless of system reactance [11, chaps 5-7]:

$$X_n = \frac{X_1 - X_{G0}}{3} \quad (\text{Eq 3})$$

where

- X_n = reactance of neutral reactor
- X_1 = generator positive-sequence subtransient reactance
- X_{G0} = generator zero-sequence reactance

However, the current that flows through the generator neutral reactor itself is not independent of the system constants and may often exceed the three-phase fault current of the machine. The current rating of a neutral reactor is determined by the number and characteristics of the system sources and whether they are grounded or ungrounded.

This rating can be calculated from Eq 1.

The neutral-grounding reactor should be selected to carry the available current under all practical operating conditions. With any given condition of connected grounded-neutral sources, the addition of ungrounded-neutral sources and loads will increase the current flow through the grounded-neutral connections.

1.8.4 Grounding-Transformer Ratings.

The electrical specifications of a grounding transformer are the following:

Voltage	The line to-line-voltage of the system
Current	The maximum neutral current
Time	The transformer is usually designed to carry rated current for a short time, such as 10 or 60 s; for high-resistance grounding, the rating may need to be continuous
Reactance	This quantity is a function of the positive-sequence short-circuit reactance of the power system, or X_1

The determination of the grounding-transformer reactance, when used to effect reactance-type grounding, is based on the following criterion. The X_0/X_1 ratio should not exceed 10, and preferably not exceed 3, in order to eliminate the possibility of transient overvoltages from a forced current zero interruption. This maximum limitation of 3 for the X_0/X_1 ratio, together with a maximum limitation of 1 for the R_0/X_1 ratio, will also satisfy the criteria for an effectively grounded system, and will permit the application of line-to-ground-voltage rated surge arresters for greater economy and protection. The ratios specified must be met at any location in the system where the reduced-rating arresters are to be applied. In a system having a grounding transformer, its reactance is the principal part of X_0 in the preceding criterion. Also, the positive-sequence reactance X_1 is equal to the reactance of the system to initial symmetrical root-mean-square three-phase short-circuit current. The value of X_1 used in these limiting ratios should be based on the subtransient reactance of rotating machines and the