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Grounding of Industrial Power Systems

**Editorially Revised
September, 1960**

**A Report of the
Industrial Power Systems Committee**



**PUBLISHED BY
THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, Inc.
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PREFACE

The subjects covered by this report are divided into four parts corresponding to the four chapters.

Chapter I covers the problems of system grounding; that is, connection of the neutral, the corner-of-the-delta or mid-tap of one phase to ground. This chapter discusses the pros and cons of grounded versus ungrounded systems. If it is decided to ground, 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.

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

Chapter III deals with the problems of static — how it is generated, what processes may produce static, how it is measured, and what should be done to prevent its generation or to drain the static charges to earth to prevent sparking. It also covers the methods of protecting structures against the effects of lightning. It is not a treatise on the application of lightning arresters but, because the system for protecting structures against lightning consists entirely of conductors to earth, it is considered within the scope of this report to discuss the general aspects of the problem.

Chapter IV 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 direct or through an impedance between transformer or generator neutrals and the building grounding system which is described in Chapter II. The grounding system described in Chapter II in turn is connected to earth through the system of ground rods and water pipes described in Chapter IV.

The protective systems discussed for static and lightning protection in Chapter III would likewise be connected to the ground rods and water pipe system as outlined in Chapter IV.

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This publication was prepared by the Industrial Grounding Subcommittee of the AIEE Committee on Industrial Power Systems. The members of the Subcommittee were:

D. L. BEEMAN, *Chairman*
General Electric Co.
Schenectady, N. Y.

D. M. ALLISON
Westinghouse Elec. Corp.
Tulsa, Oklahoma

H. H. ANGEL
Chairman, Working Group, Chapter II
Bethlehem Steel Co.
Bethlehem, Pa.

J. E. ARBERRY
Pittsburgh Plate Glass Co.
Pittsburgh, Pa.

K. M. BAUSCH
Bechtel Corporation
San Francisco, Calif.

A. J. BISSON
Consolidated Edison Co. of N. Y.
New York, N. Y.

L. J. CARPENTER
General Electric Co.
Schenectady, N. Y.

M. A. LELAND
Chairman, Working Group, Chapter IV
Burndy Engineering Co., Inc.
Norwalk, Conn.

F. R. LONGLEY
Western Massachusetts Elec. Co.
Springfield, Mass.

C. C. SAUNDERS
Chairman, Working Group, Chapter III
E. I. duPont de Nemours & Co.
Wilmington, Delaware

J. M. SCHMIDT
General Electric Co.
Schenectady, N. Y.

H. E. SPRINGER
Rayonier, Inc.
Port Angeles, Wash.

H. M. STEWART
Humble Oil & Refining Co.
Baytown, Texas

T. O. SWEATT
Wearn, Vreeland, Carlson & Sweatt, Inc.
New York, N. Y.

H. B. THACKER
Chairman, Working Group, Chapter I
Westinghouse Electric Corp.
East Pittsburgh, Pa.

B. F. THOMAS, JR.
N. A. Lougee & Co.
New York, N. Y.

CHAPTER I

SYSTEM GROUNDING

The question of whether or not to ground a power system is one which must be faced sometime by most engineers charged with planning industrial distribution. A decision in favor of a grounded system leads then to the question of how to ground.

It is the intent of this chapter to assist the planning engineer to answer 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,¹ and for the grounding of transmission systems,² particularly those operated at 23 kilovolts and higher, have been summarized in other guides.³ The practices set forth in those guides are applicable to industrial power systems in 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 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.

DEFINITIONS

Ungrounded system means a system without an intentional connection to ground except through potential indicating or measuring devices. 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 1.1 (a) shows an ungrounded system with voltage relations for balanced phase-to-ground capacitances.

A **grounded system** is one in which at least one conductor or point (usually the neutral point of transformer or generator windings) is intentionally grounded, either solidly or through a current-limiting device. Various degrees of grounding are used from "solid" or "effective" to the high-reactance grounding obtained from a small grounding transformer used only to secure enough ground current for relaying.

¹ Numbers refer to numbered references in bibliography at end of this chapter.

Figures 1.1 (b) and 1.1 (c) show two points at which a system may be grounded; and the corresponding voltage relationships.

The term "solidly grounded", though commonly used, is somewhat confusing since a transformer may have its neutral "solidly" connected to ground and yet 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 more positively and logically define grounding as to degree, the term "effectively grounded" has come into use. The term solidly grounded will therefore be used in this report only with reference to a solid metallic connection from system neutral to ground, i.e. with no impedance intentionally added in the grounding circuit.

Section 32-1.05 of AIEE Standard No. 32, May 1947,⁴ defines **effective grounding** as follows: "A system or portion of a system may be said to be effectively grounded when for all points on the system or specified portion thereof the ratio of zero-sequence reactance to positive-sequence reactance is not greater than three and the ratio of zero-sequence resistance to positive-sequence reactance is not greater than one for any condition of operation and for any amount of connected generator capacity."

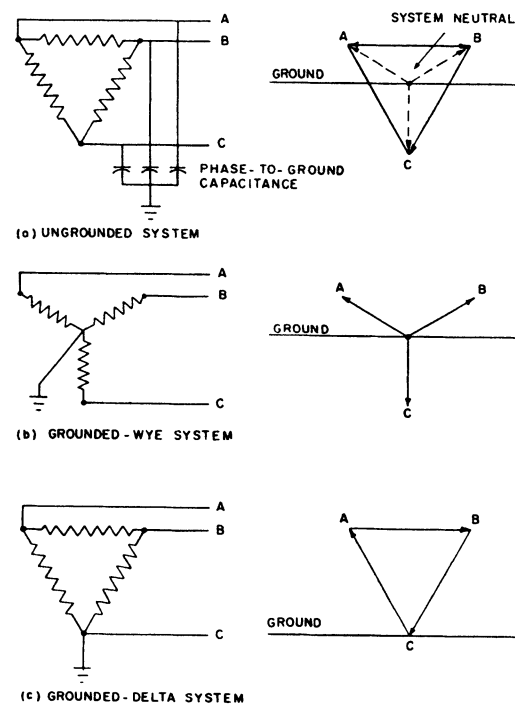


Figure 1.1
Diagram showing voltages to ground under steady-state conditions for (a) ungrounded system, (b) grounded-wye system, (c) grounded delta system.

FACTORS INFLUENCING CHOICE OF GROUNDED OR UNGROUNDED SYSTEM

Service Continuity

For many years most 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 set up so that circuit protective devices will remove a faulty circuit from the system regardless of the type of fault. A phase-to-ground fault results in the immediate isolation of the faulted circuit with the attendant outage of the loads on that circuit. However, experience has shown,⁵ in a number of systems, that greater service continuity is obtained with grounded neutral than with ungrounded neutral systems.

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 dropped. If the second fault is on a different feeder, both feeders will be dropped.

The longer a ground is allowed to remain on an ungrounded system, the greater is the likelihood of a second ground occurring on another phase resulting in an outage. The advantage 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 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 such that grounds 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 best operation of the ungrounded system.

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

Location of Faults

On an ungrounded system a ground fault does not open the circuit. Some means of detecting the presence of a ground 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 the removal from service of one feeder at a time until the ground detector indicates the faulted

feeder has been removed from the system. Should it happen that the same phase of two different feeders become 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 use of various types of locating apparatus.⁶ For example, an interrupted direct voltage or superimposed audio signals may be applied to the feeder bus and the tracing current detected in the grounded feeders. Some operators have reported success with locating apparatus used without de-energizing system feeders. This, of course, has the advantage of permitting location of grounds without waiting for light load periods on the system.

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

Safety

Many of the hazards to personnel and property existing in some industrial electric systems are the result of poor or non-existent grounding of electric equipment and metallic structures. While the subject of Equipment Grounding is treated in Chapter II, 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.

Effectively grounding a low-voltage (600 volts or less) distribution system may result in less likelihood of accidents to personnel than leaving the system supposedly ungrounded. If all circuits were treated with the same caution there might be slightly less hazard of shock on the ungrounded system in some cases. However, the impression that one phase of an ungrounded system can be safely contacted may lead to carelessness in handling the circuit when energized. The subconscious knowledge that a circuit is grounded generally will result in greater care on the part of the workman.

During the period a ground fault remains on one phase of an ungrounded system, personnel contacting one of the other phases and ground are subjected to full line-to-line voltage instead of the line-to-neutral voltage that would be experienced at any time on the grounded system.

Other hazards of shock and fire may result from inadequate grounding of equipment in either grounded or ungrounded systems. Accidental grounds 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 would 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 shock to personnel from such a condition should they bridge all or part of the high impedance ground path, for example, contacting the frame of the faulty machine. This hazard is particularly bad because there are more possible victims than in the case of persons familiar with electric systems working on a circuit.

Abnormal Voltage Hazards

The possible overvoltages on the ungrounded system may cause more frequent failure 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 system places a sustained overvoltage 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 tend to reduce the life of the insulation.

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

Power System Overvoltages⁷

Some of the more common sources of overvoltage on a power system are: (a) lightning, (b) switching surges, (c) static, (d) contact with higher-voltage system, (e) line-to-ground faults, (f) resonant conditions, (g) restriking ground faults.

Lightning⁸ (See Chapter III)

Most industrial systems are effectively shielded against direct lightning strokes. Many circuits are either underground in ducts or are within grounded metal conduits or raceways. Even open-wire circuits are often shielded by adjacent metallic structures and buildings. Lightning arresters applied at the incoming service limit the surge voltages within the plant resulting from strokes to the exposed service lines. Other arrester 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, lightning arresters may be required on the low side of the transformer to protect plant equipment from surges passed by the high-side arresters and reflected through the transformer.

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 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 current-limiting fuses must be carefully applied because of this overvoltage problem.

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, reducing the possibility of excessive voltage stress on the phase-to-ground insulation of a particular phase.

Static (See Chapter III)

Build-up 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 build-up.

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 a transformer. If the low-voltage system is ungrounded the high voltage will remain on the low-voltage system causing breakdown of insulation possibly at several points. An effectively-grounded low-voltage system, though resulting in high values of fault current for this condition, will hold the system neutral close to ground potential and greatly reduce the overvoltages to ground on the low-voltage system.

Line-to-Ground Faults

A common source of sustained overvoltage on an ungrounded system is caused by one phase of a three-phase system becoming grounded. In this case the insulation of the other phases is subjected to 73 percent above normal voltage. A grounded-neutral system would not have this overvoltage. The cumulative effect of higher than normal voltage stresses may somewhat reduce insulation life.

Resonant Conditions

Ungrounded systems 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 where tuned inductive-capacitive circuits are used such as for operation of welders. For example, if the welder is equipped with a series capacitor for power factor improvement, the voltage across the capacitor and across the transformer winding are each many times the supply line-to-line voltage. A ground fault on the connecting lead between the capacitor and the welder transformer imposes this high voltage on the line-to-ground insulation of every piece of electric equipment connected to these lines. A grounded neutral system would prevent this overvoltage by holding the phases to their approximate normal voltage to ground.

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 six times normal line-to-line voltage. 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 or be the result of an intermittent contact between line and ground. 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 arcs where the pressure may increase after each conduction period. Neutral grounding is effective in reducing transient voltage build-up from such intermittent ground faults by reducing neutral displacement from ground potential and reducing destructive effectiveness of any high-frequency voltage oscillations following each arc initiation or restrike.

Cost

Grounded neutral systems may cost at most only a few percent more than ungrounded neutral systems, depending upon system voltage and whether it is an existing or new system that is to be grounded. Equipment for 208Y/120-volt systems almost universally provides for system neutral grounding and, therefore, does not involve any extra cost. Wye-connected unit substations for grounding 480-volt systems are standard but cost from nothing more to about six percent more than delta-connected substations. 2400-volt wye-connected transformers for system neutral grounding of these systems can be obtained at a slight cost premium over 2400-volt delta transformers. In addition there is the cost of the resistor or other grounding impedance if used.

For system voltage of 4.16 and 13.8 kilovolts, wye-connected transformers are standard and, therefore, there is no price penalty, transformer-wise, for ground-

ing these systems. The cost of grounding resistor or impedance, however, does represent an extra cost of the grounded neutral system.

Grounding existing systems may be very expensive because it may be necessary to add grounding transformers and their protective equipment, grounding impedance if required, and a third current transformer in all circuits to obtain ground-fault relaying on all three phases.

There should be three overcurrent elements in the protective devices in a grounded neutral system. This may require more expensive motor control devices in rare cases, but the present practice is to provide three overcurrent elements in all low-voltage air circuit breakers. Usually it is not necessary to carry the neutral wire along with the three-phase circuits unless the circuits supply single-phase loads connected from line-to-neutral as in 208Y/120-volt circuits supplying 120-volt lighting load. Therefore, there is no additional circuit cost to charge against the grounded-neutral arrangement. The additional costs of grounded-neutral transformers and controls with three overcurrent elements may seem significant when compared with the cost of the devices, but when additional costs are considered as a fraction of the total system cost they are generally very small.

Trends in Application of System Grounding

The basic reasons for system grounding are threefold: First, to limit the difference of electric potential between all uninsulated conducting objects in a local area; second, to provide for isolation of faulty equipment and circuits when a fault occurs; and third, to limit overvoltages appearing on the system under various conditions.

The basic reasons for the selection of ungrounded-neutral systems is that such systems, particularly at 480 and 2400 volts, are slightly less expensive and many operators feel that the ungrounded neutral system possesses a service continuity advantage because the first ground fault may not cause a trip-out of a circuit or motor. It will be noted that there is today a divided opinion among operators as to the relative service continuity of grounded and ungrounded-neutral systems. Many operators feel that a grounded system gives them better overall service continuity than they have obtained from 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 suitable for neutral grounding.

In new installations these transformers offer the advantage that they can be operated ungrounded if desired but possess an available neutral for easy addition of a grounding circuit at a later date.

METHODS OF SYSTEM GROUNDING

Grounding the System Neutral

Most grounded systems employ some method of grounding the system neutral at one or more points. These methods are referred to as (1) solid grounding, (2) resistance grounding, (3) reactance grounding, and (4) 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.

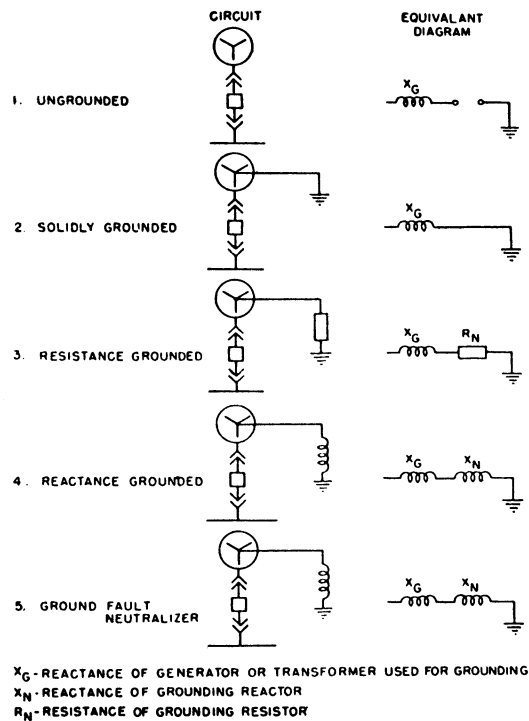


Figure 1.2
System neutral circuit and equivalent diagrams for ungrounded and various types of grounded neutral systems.

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 cannot be considered as providing a zero impedance neutral circuit.

If the reactance of the generator or transformer is too great, 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 fault 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 reactance, "effective grounding" of a system is defined on page 5.

In most generators, solid grounding, i.e., 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, in cases where effective grounding of a system is indicated, most generators should be grounded through a reactor having a low ohmic value, which will limit generator phase-current during single line-to-ground faults to a value no greater than three-phase fault current. In the case of three-phase, four-wire systems, limitation of ground-fault currents to 100 percent of the three-phase fault current is usually practical without interfering with normal four-wire operation.

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

Resistance Grounding

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

A system properly grounded by resistance is not subject to destructive transient overvoltages. For resistance-grounded systems at 15 kilovolts and below, such overvoltages will not ordinarily be of a serious nature, unless the resistance is so high as to limit the ground-fault current to a small fraction of one percent of the system three-phase fault current (less than the system charging current). This much ground current (usually well below 50 amperes) is far less than is normally used with resistance grounding.

Systems grounded through resistors generally require lightning arresters suitable for use on ungrounded-neutral circuits, i.e., with a voltage rating at least equal to line-to-line voltage.

The reasons for limiting the current by resistance grounding are as follows:

- (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 momentary line voltage dip occasioned by occurrence and clearing of a ground fault.

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 which may flow in a reactance-grounded system is a function of the neutral reactance, the magnitude of 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 percent of the three-phase fault current to prevent serious transient overvoltages. This is considerably higher than the minimum fault current desirable in a resistance-grounded system and, therefore, reactance grounding is usually not considered an alternative of resistance grounding.

In practice, reactance grounding is generally used only in the case cited under "Solid Grounding", in which a generator neutral is to be connected directly to ground. 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.

Ground-Fault Neutralizer⁹

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 degrees 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, as 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 recovery voltage on the faulted phase is very low. Hence, the arc is extinguished without restriking and flashovers in the presence of self-healing dielectrics like air, are quenched without removing the faulted line section from service.

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 kilovolts, consisting largely of overhead trans-

mission lines. This method is a second choice to resistor grounding, which provides ground relaying to disconnect the faulted circuit. 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 are not extinguished by the use of the ground-fault neutralizer.

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 scheme is to use a ground-fault neutralizer in the neutral to limit the ground-fault current and to reduce switching surges to safe values. A resistor is arranged to be connected in parallel with the neutralizer when it is desired to pass enough ground-fault current to cause relays to give a signal or trip the breaker of the faulty feeder. 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 the resistor only were used. Such a scheme is expensive and is only used in very special cases.

Care should 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 readjust the neutral reactance by changing the neutralizer tap.

Grounding at Points Other Than System Neutral

In some cases low-voltage systems, (600 volts 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.

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 or one "corner-of-the-delta" has sometimes been done as a means of obtaining a grounded system. Advantages are: (1) may be less costly for existing delta systems; (2) possibility of slightly better protection with two-element motor starters when located in the two ungrounded phases. With properly connected control circuits, grounds in the control circuit will not start the motor and will not prevent stopping the motor by pushing the pushbutton. Disadvantages are: (1) inability to supply dual voltage service for lighting and power load; (2) necessity of positive identification of grounded phase throughout the system to avoid connecting meters, instruments and relays in the grounded phase; (3) line-to-ground voltage is higher than in neutral-grounded system. Because of its limitations this type of grounding has not been widely used in industrial systems.

One Phase of A Delta System Grounded at the Mid-Point

Where existing systems at 600 volts and below are supplied by three single-phase transformers with mid-taps available, it is possible to gain some of the advantages of neutral grounding by grounding the mid-tap of one phase. The distribution of voltage stress among the phases remains somewhat unbalanced (50 percent overvoltage to ground on one phase conductor). The system is frequently found in electric utility service at 240 volts to supply 240/120 volts single-phase three-wire, and 240 volts three-phase three-wire simultaneously.

SELECTION AND DESIGN OF SYSTEM GROUNDING ARRANGEMENTS

Obtaining the System Neutral

The best way to obtain the system neutral for grounding purposes 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 volts. On new systems, 208Y/120 or 480Y/277-volt transformers may be used to good advantage instead of 240 volts. For 2400-volt or 4800-volt systems, special 2400 wye- or 4800 wye-connected source transformers may be purchased or grounding transformers used.

Grounding Transformers

System neutrals may not be available, particularly in many old systems 600 volts or less and many existing 2400-, 4800- and 6900-volt systems. When it is desired to ground existing delta connected systems, grounding transformers may be used to obtain the neutral. Grounding transformers may be either of the zig-zag or wye-delta type. The type of grounding transformer most commonly used is a three-phase, zigzag transformer with no secondary winding. The internal connection of this transformer is illustrated in Figure 1.3. The impedance of the transformer to three-phase currents is high so that, when there is no fault on the systems, only a small magnetizing current flows in the transformer winding. The transformer impedance to ground current, however, is low so that it allows high ground current to flow. The transformer divides the ground current into three equal components; these currents are in phase with each other and flow in the three windings

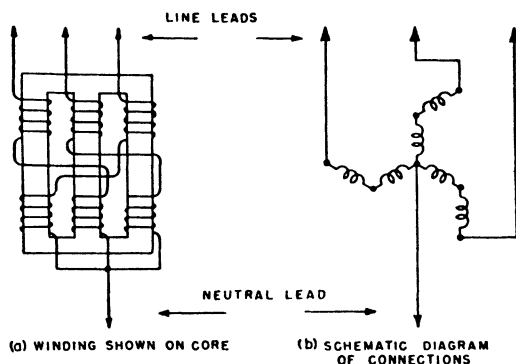


Figure 1.3
Diagram showing windings of core and schematic diagram of connections of a 3-phase zigzag grounding transformer.

of the grounding transformer. The method of winding is seen from Figure 1.3 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 transformer can also be utilized as a grounding transformer. The delta connection must be closed to provide a path for the zero-sequence current, but the delta can be designed for any convenient voltage level. It may or may not be used to serve other loads. The wye winding must be of the same voltage rating as the circuit which is to be grounded. Caution should be exercised in applying single-phase transformer units of a rating such that the transformer voltage rating when applied line-to-neutral is not equal to or greater than the system line-to-line voltage. The reason for this is that transformer reactance varies inversely as the square of the voltage applied. The connections of the transformer are shown in Figure 1.4.

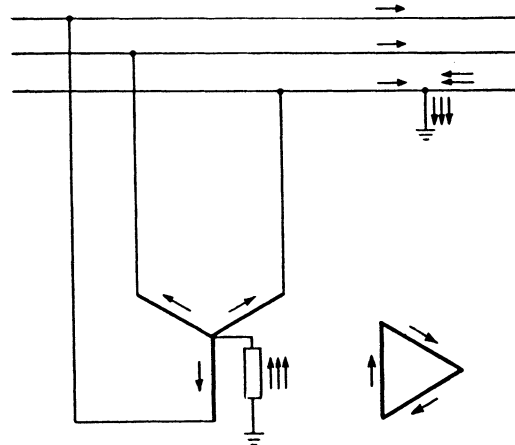


Figure 1.4
Vectors representing flow of current in wye-delta transformer used as grounding transformer. Line-to-ground fault shown.

The short-time kva rating of a grounding transformer is equal to rated line-to-neutral voltage times rated neutral current. A grounding transformer, is designed to carry its rated current for a limited time only such as 10 seconds or one minute. Hence, it is much smaller in size than an ordinary three-phase transformer of the same rated kva.

A grounding transformer should be connected to the system in such a manner that the system will always be grounded. Figure 1.5(a) shows a grounding transformer with an individual line breaker for connection directly to the main bus of the system. Figure 1.5(b) shows a means of connecting a grounding transformer to a system without an individual line breaker. In this case, the grounding transformer is connected between the main transformer bank and its breaker. If grounding transformers are connected

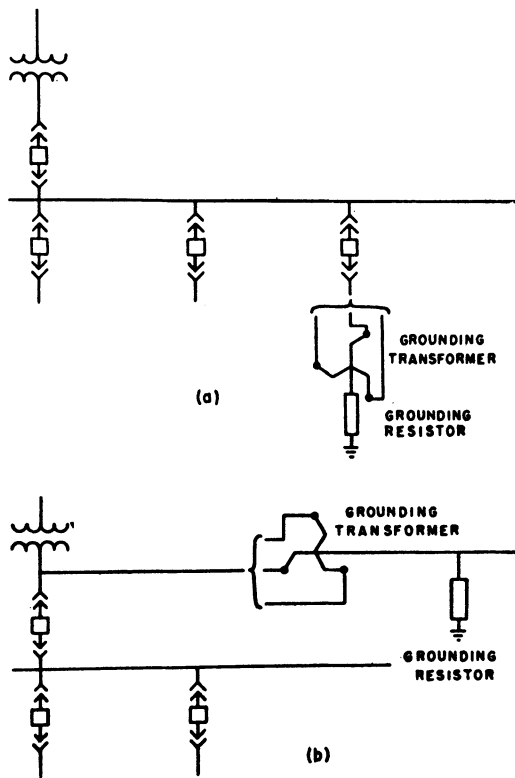


Figure 1.5
Methods of connecting grounding transformers to a delta-connected or ungrounded power system to form a neutral for system grounding

as shown in Figure 1.5(b), there should be one grounding transformer for each delta-connected bank supplying power to the system; or enough 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.

Suggested Grounding Methods **Low-Voltage Systems (600 volts and below)**

Low-voltage systems are practically always effectively grounded. One reason for this is that no expense is necessary for reactors. Another reason is that low-voltage switchgear almost universally uses direct series trip devices. Such devices demand high current magnitudes. For these reasons, effective grounding is used on systems rated 600 volts and below. For such systems, it is especially important to provide low-resistance return paths for ground-fault currents in the plant equipment ground system. Damage from high fault current magnitude is minimized because low-voltage circuit breakers are extremely fast in operation.

Medium-Voltage Systems (2.4 kv to 15 kv)

Medium-voltage systems are usually resistance grounded. In this range of system voltages, limiting ground-fault current is highly desirable in the usual industrial power system. Connection of rotating machines directly at these voltages is common, hence

resistance grounding is used to reduce the damage which may result due to a ground fault in the machine windings.

In the case of small systems supplied by generators, reactance grounding (to produce not less than 25 percent of three-phase fault currents) may be used in the interest of economy and because ground-fault currents are not too large. If the system is small and supplied by transformers, they may have their neutrals grounded solidly for the same reason.

In medium-voltage systems, when ground-fault protection is desired, it is provided by using standard overcurrent relays. Positive tripping can be accomplished with low magnitudes of fault current. For this reason resistance grounding is used except for those cases where the size of the system is so small that the maximum available fault current is not too high to be objectionable.

At the present time, it is most common practice to operate 2.4-kilovolt systems without the system neutral grounded. More and more operators however are applying system neutral grounding to 2.4-kilovolt systems. The conventional method is to provide sufficient ground-fault current to enable selective relaying through the application of residual or ground relays.

Some operators feel that it is desirable to ground the 2.4-kilovolt system neutral but that the ground-fault current should be of a very small magnitude, just enough to stabilize the neutral to prevent severe transient overvoltages upon the occurrence of re-striking grounds. This does not cause a load shutdown due to a ground fault while, at the same time, eliminating the same types of transient overvoltage hazard. It however does not eliminate all types of overvoltages. The specific value of ground-fault current that should be permitted to flow has not been well established but some industrial experience indicates that this value should be greater than the line charging current. The high-resistance grounding practice could be employed with the circuits as shown in Figure 1.5. The only difference in the various methods of resistance grounding is the amount of ground-fault current that flows. Where selective ground relaying is required, considerably higher values of ground-fault current are required.

High-Voltage Systems (above 15 kilovolts)

Systems above 15 kilovolts are nearly always effectively grounded, because these are usually transmission circuits with open lines in which, in most cases, grounded-neutral service lightning arresters are desirable for better overvoltage protection and lower cost. In addition, rotating equipment is seldom connected directly to these systems; hence, limiting ground-fault currents, to prevent burning of laminations, is a less important factor than in medium voltage systems. In addition, voltages above 15 kilovolts 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 high.