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IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems

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Abstract: The problems of system grounding, that is, connection to ground of neutral, of the corner of the delta, or of the midtap of one phase, are covered. 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. 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 is addressed. The fundamentals of making the interconnection or ground-conductor system between electric equipment and the ground rods, water pipes, etc. are outlined. 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—are treated. Methods of protecting structures against the effects of lightning are also covered. Obtaining a low-resistance connection to the earth, use of ground rods, connections to water pipes, etc. is discussed. A separate chapter on sensitive electronic equipment is included.
Keywords: System grounding, equipment grounding, static and lightning protection grounding, connection to earth, and sensitive electronic equipment grounding.

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IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems

Chapter 1

System Grounding

1.1 Introduction

Grounding of an electrical system is a decision that must be faced sometime by most engineers charged with planning or modifying electrical distribution. Grounding in some form is generally recommended, although there are certain exceptions. Several methods and criteria exist for system grounding; each has its own purpose.

It is the intention of this section to assist the engineer in making decisions on the subject by presenting basic reasons for grounding or not grounding and by reviewing general practices and methods of system grounding.

The practices set forth herein are primarily applicable to industrial power systems that distribute and utilize power at medium or low voltage, usually within a smaller geographical area than is covered by a utility.

Where distances or power levels may dictate circuitry and equipment similar to a utility, consideration of utility practices is warranted. However, restrictions of the National Electrical Code (NEC) (ANSI/NFPA 70–1990) [1],[1] particular needs of service, and the experience and training of the workforce should also be considered.

Where an industrial power system includes power-generating equipment, the reasons for grounding these components may be the same as those for grounding similar components of public utility systems. The methods of grounding would generally be similar under like conditions of service. However, in the industrial setting, conditions of service may be altered by:

1) Location within the power system
2) Individual generator characteristics
3) Manufacturing process requirements

[1]The numbers in brackets correspond to those of the references in 1.12.

All of these may affect grounding decisions.

The NEC [1], sponsored by the National Fire Protection Association, contains regulations pertaining to system and equipment grounding applicable to industrial, commercial, and special occupancy facilities. These 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

The varieties of system grounding and definitions of related terminology follow. The definitions of additional terms may be found in IEEE Std 100-1988 [2] and the NEC [1].

effectively grounded: 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.

grounded system: A system 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.

grounded: Connected to earth or to some extended conducting body that serves instead of the earth, whether the connection is intentional or accidental.

high resistance grounded: A grounded system with a purposely inserted resistance that limits ground-fault current such that the current can flow for an extended period without exacerbating damage. This level of current is commonly thought to be 10 A or less. High-resistance grounded systems are designed to meet the criterion of $R_O \leq X_{CO}$ to limit the transient overvoltages due to arcing ground faults. X_{CO} is the distributed per-phase capacitive reactance to ground of the system, and R_O is the per-phase zero-sequence resistance of the system.

low resistance grounded: A resistance-grounded system in which the purposely inserted resistance has lower ohmic value than would meet the high-resistance grounding criteria. The resistance is selected to provide the desired relaying current.

per-phase charging current: (I_{CO}). The current (V_{LN}/X_{CO}) that passes through one phase of the system to charge the distributed capacitance per phase to ground of the system, $V_{L\text{-}N}$ is the line-to-neutral voltage and X_{CO} is the per-phase distributed capacitive reactance of the system.

R_0: The per-phase zero-sequence resistance of the system.

reactance grounded: Grounded through impedance, the principal element of which is inductive reactance.

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

resonance: The enhancement of the response of a physical system (electrical system or circuit) to a periodic excitation when the excitation frequency *(f)* is equal to a natural frequency of the system. In a series circuit consisting of resistance *(R)*, inductance *(L)*, and capacitance *(C)*, when *L* and *C* parameters are such that the resultant reactance becomes zero and the current reaches maximum, then the circuit is in series resonance. This happens when

$$\omega L = \frac{1}{\omega C} \text{ or } f = \frac{1}{2\pi\sqrt{LC}}$$

Similarly, in a parallel circuit consisting of *R*, *L*, and *C*, the admittance is the lowest when $1/X_1 = 1/X_c$, and the circuit is in parallel resonance. This happens when

$$\omega L = \frac{1}{\omega C} \text{ or } f = \frac{1}{2\pi\sqrt{LC}}$$

R_n: The value of the resistance connected from the neutral to the ground of a resistance-grounded system. For high-resistance grounded systems where R_N is a major component of R_o, the relationship $R_0=3R_N$ applies.

solidly grounded: Connected directly through an adequate ground connection in which no impedance has been intentionally inserted.

static charge: The electricity generated when two dissimilar substances come into contact. Conveyor belts are active producers of static electricity.

switching surge: A transient wave of overvoltage in an electric circuit caused by the operation of a switching device interrupting load current or fault current.

system: A grounding system consists of all interconnected grounding connections in a specific power system and is defined by its isolation from adjacent; grounding systems. The isolation is provided by transformer primary and secondary windings that are coupled only by magnetic means. Thus, the system boundary is defined by the lack of a physical connection that is either metallic or through a significantly high impedance. Fig 1 illustrates the limits and boundaries of grounding systems.

system charging current: The total distributed capacitive charging current ($3V_{\mathrm{LN}}/X_{CO}$) of a three-phase system.

three-phase four-wire system: A system of alternating current supply comprising four conductors, three of which are connected as in a three-phase three-wire system, the fourth being connected to the neutral point of the supply or midpoint of one-phase in case of delta-connected transformer secondary, which may be grounded.

three-phase three-wire system: A system of alternating current supply comprising three conductors, between successive pairs of which are maintained alternating differences of potential successively displaced in phase by one third of a period.

transient overvoltage: The temporary overvoltage of short duration associated with the operation of the switching device, a fault, a lightning stroke, or during arcing ground faults on the ungrounded system.

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

1.3 Purposes of System Grounding

System grounding, or the intentional connection of a phase or neutral conductor to earth, is for the purpose of controlling the voltage to earth, or ground, within predictable limits. It also provides for a flow of current that will allow detection of an unwanted connection between system conductors and ground and which may instigate operation of automatic devices to remove the source of voltage from conductors with such undesired connections to ground. The NEC [1], prescribes certain system grounding connections that must be made to be in compliance with the code. The control of voltage to ground limits the voltage stress on the insulation of conductors so that insulation performance can more readily be predicted. The control of voltage also allows reduction of shock hazard to persons who might come in contact with live conductors.

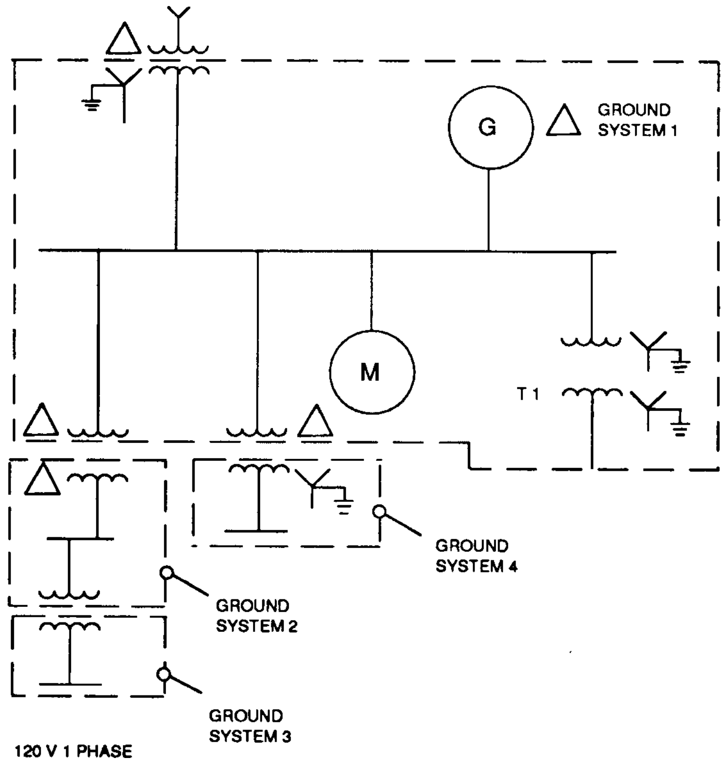


Figure 1—Grounding Systems

1.4 Methods of System Neutral Grounding

1.4.1 Introduction

Most grounded systems employ some method of grounding the system neutral at one or more points. These methods can be divided into two general categories: Solid grounding and impedance grounding. Impedance grounding may be further divided into several subcategories: Reactance grounding, resistance grounding and ground-fault-neutralizer grounding. Fig 2 shows examples of these methods of 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 the system source impedance.

Many of the concepts involved in defining system-grounding types and levels are best explained in terms of symmetrical components or equivalent circuits. The reader who is not familiar with these analytical methods is referred to Chapter 2 of Beeman [10] and to Chapter 3 of the *IEEE Brown Book* [5] for guidance.

Molded-case circuit-breaker interrupting capabilities can be affected by the method of grounding. If other than effective grounding is used, circuit breakers should be reevaluated for the application.

1.4.2 Ungrounded Systems (No Intentional Grounding)

Electrical power systems which are operated with no intentional ground connection to the system conductors are generally described as ungrounded. In reality, these systems are grounded through the system capacitance to ground.

In most systems, this is an extremely high impedance, and the resulting system relationships to ground are weak and easily distorted.

Two principal advantages are attributed to ungrounded systems. The first is operational: The first ground fault on a system causes only a small ground current to flow, so the system may be operated with a ground fault present, improving system continuity. The second is economic: No expenditures are required for grounding equipment or grounded system conductors.

Numerous advantages are attributed to grounded systems, including greater safety, freedom from excessive system overvoltages that can occur on ungrounded systems during arcing, resonant or near-resonant ground faults, and easier detection and location of ground faults when they do occur.

Resonant effects can occur when the ground fault path includes an inductive reactance approximately equal to the system capacitive reactance to ground. Beeman [10], pp. 281–285, discusses this phenomenon in depth. For an extensive discussion of the advantages of grounded systems, see pp 345–348 of Beeman [10]. Also, Article 250–5 of [1] requires certain systems to be grounded. Grounded systems are now the predominant choice.

When an ungrounded system is chosen, a ground detection scheme may be applied to the system. This scheme frequently takes the form of three voltage transformers with their primary windings connected in wye and with the primary neutral grounded. The secondary windings of the voltage transformers are usually connected in broken delta, with a voltage relay connected in the open corner and used to operate an indication or alarm circuit. Loading resistors may be required either in the primary neutral circuit or in the secondary circuit to avoid ferroresonance.

1.4.3 Resistance Grounding

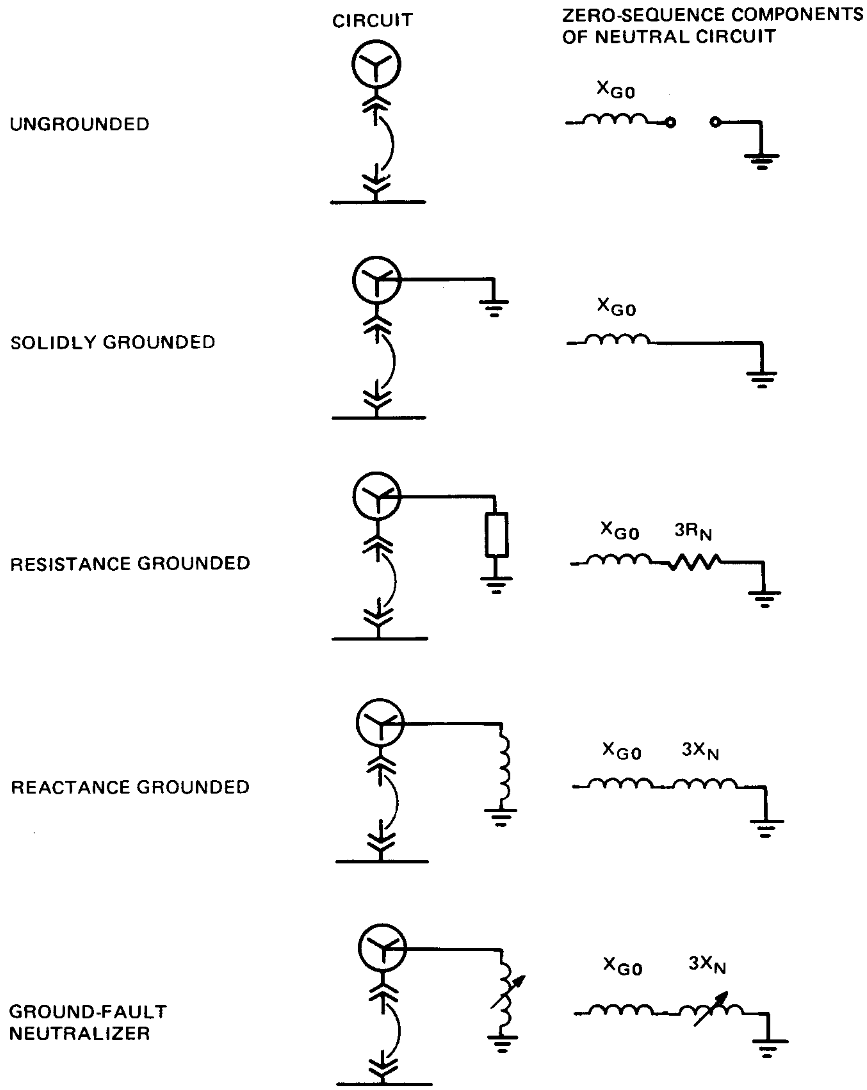
In resistance grounding, the neutral is connected to ground through one or more resistors. In this method, with the resistor values normally used, and except for transient overvoltages, the line-to-ground voltages that exist during a line-to-ground fault are nearly the same as those for an ungrounded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

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).

Resistance grounding may be either of two classes, high resistance or low resistance, distinguished by the magnitude of ground-fault current permitted to flow. Although there are no recognized standards for the levels of ground-fault current that define these two classes, in practice there is a clear difference. High-resistance grounding typically uses ground-fault current levels of 10 A or less, although some specialized systems at voltages in the 15 kV class may have higher ground-fault current levels. Low-resistance grounding typically uses ground-fault current levels of at least 100 A, with currents in the 200–1000 A range being more usual.



X_{GO} = Zero-sequence reactance of generator or transformer
X_N = Reactance of grounding reactor
R_N = Resistance of grounding resistor

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

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 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. Metal oxide surge arrester ratings must be chosen so that neither the maximum continuous operating voltage capability nor the one-second temporary overvoltage capability is exceeded under system ground fault conditions.

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 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 most generators, solid grounding, that is, grounding without external impedance, may permit the maximum ground-fault current from the generator to exceed the maximum three-phase fault current that the generator can deliver and for which its windings are braced. Consequently, neutral-grounded generators should be grounded through a low-value reactor that 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. In practice, reactance grounding is generally used only in this case and to ground substation transformers with similar characteristics.

1.4.5 Ground-Fault Neutralizer (Resonant Grounding)

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. The reactance is tuned to the system charging current so that the resulting ground fault current is resistive and of a low magnitude. This current is in phase with the line-to-neutral voltage, so that current zero and voltage zero occur simultaneously. If the ground fault is in air, such as an insulator flashover, it may be self-extinguishing. This method of grounding is used primarily on systems above 15 kV, consisting largely of overhead transmission or distribution lines. Since systems of such construction are rarely used in industrial or commercial power systems, the ground-fault neutralizer finds little application in these systems. For further information on the use of ground-fault neutralizers, see Reference [9].

1.4.6 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 system zero-sequence circuit is too great with respect to the system positive-sequence reactance, the objectives sought in grounding, principally freedom from transient overvoltages, may not be achieved. This is rarely a problem in typical industrial and commercial power systems. The zero-sequence impedance of most generators used in these systems is much lower than the positive-sequence impedance of these generators. The zero-sequence impedance of a delta-wye transformer will not exceed the transformer's positive-sequence impedance. There are, however, conditions under which relatively high zero-sequence impedance may occur.

One of these conditions is a power system fed by several generators and/or transformers in parallel. If the neutral of only one source is grounded, it is possible for the zero-sequence impedance of the grounded source to exceed the effective positive-sequence impedance of the several sources in parallel.

Another such condition may occur where power is distributed to remote facilities by an overhead line without a metallic ground return path. In this case, the return path for ground-fault current is through the earth, and, even though both the neutral of the source and the nonconducting parts at the load may be grounded with well-made electrodes, the ground return path includes the impedance of both of these ground electrodes. This impedance may be significant. Another significant source of zero sequence impedance is the large line-to-ground spacing of the overhead line.

To ensure the benefits of solid grounding, 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. Effectively grounded systems will have a line-to-ground short circuit current of at least 60% of the three-phase short-circuit value. In terms of resistance and 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 Thevenin equivalent positive-sequence reactance of the complete system including the subtransient reactance of all rotating machines.

Application of surge arresters for grounded-neutral service requires that the system be effectively grounded.

1.4.7 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 V 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.

System neutrals may not be available, particularly 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.

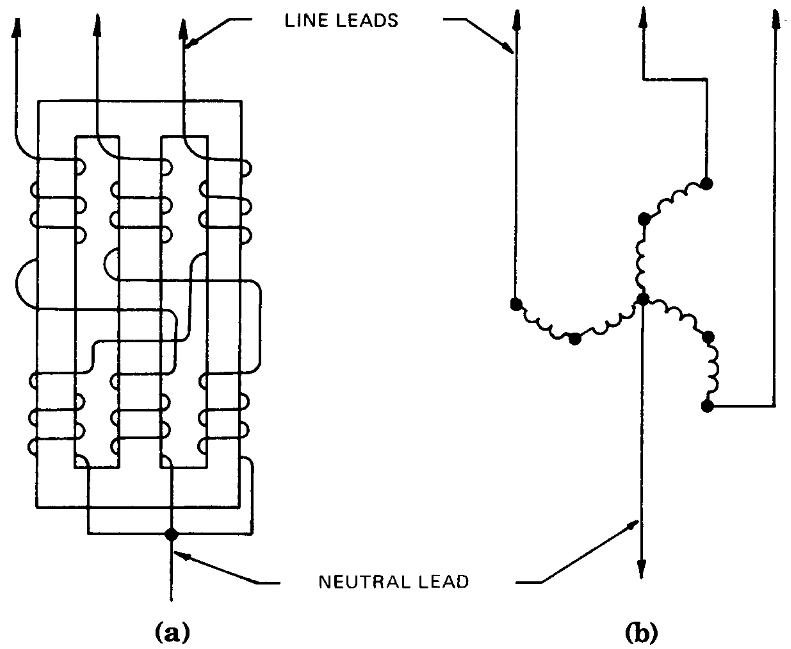


Figure 3—(a) Core Windings
(b) Connections of Three-Phase Zigzag Grounding Transformer

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 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 that 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 three-phase grounding transformer or bank, in kVA, is equal to the rated line-to-neutral voltage in kilovolts times the rated neutral current [18]. 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.

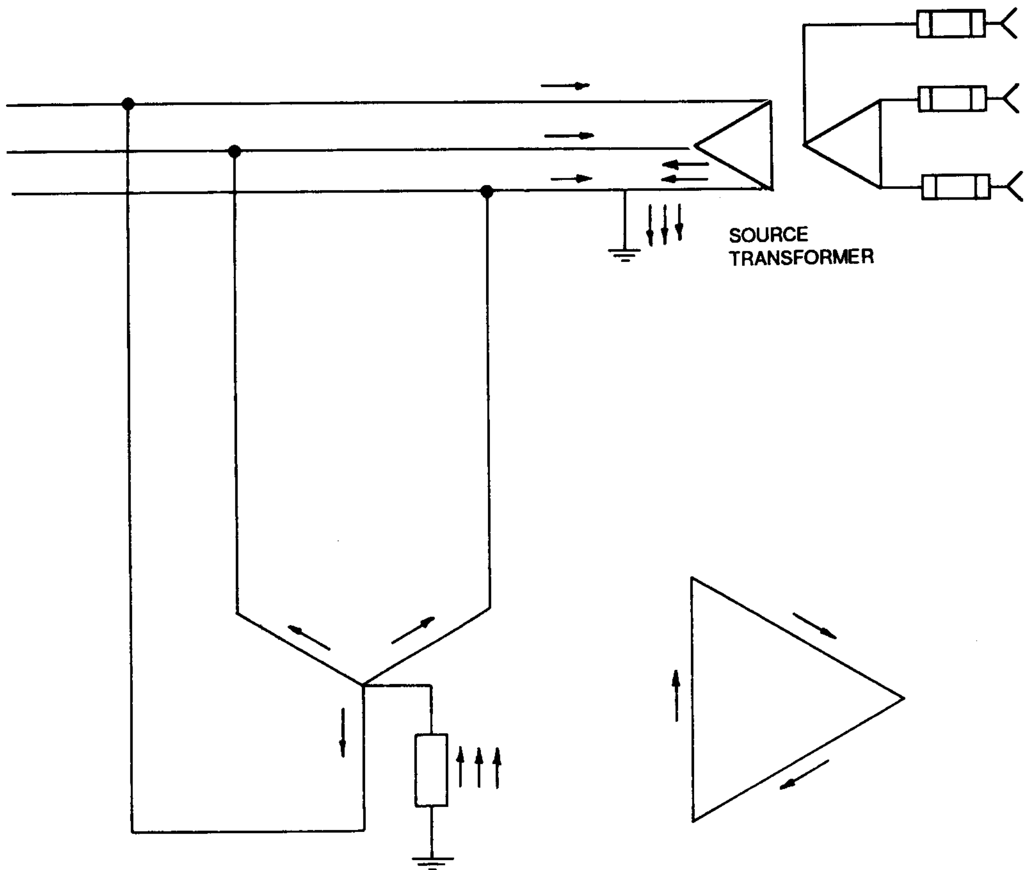


Figure 4—Vectors Representing Current Flow in Wye-Delta Transformer Used as Grounding Transformer with Line-to Ground Fault

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 inadvertently 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 grounding 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 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 to obtain a grounded electrical system. This is done where exiting delta transformer connections do not provide access to the system neutral. Two systems are in general use.

1.5.1 Corner-of-the-Delta Systems

Low-voltage systems, which in the past have been nearly all supplied from transformers with delta-connected secondaries, have been ungrounded. Grounding of one-phase corner-of-the-delta grounding has sometimes been used as a means of obtaining a grounded system. The advantages are the following:

1) It is the least costly method of converting an ungrounded delta system to a grounded system. This method was adapted by one very large industrial company in 1935 for their older plants. No problems have been reported and it is still in use. The first costs of a new transformer are approximately the same for either a delta or a wye secondary connection.
2) Although motor overload protection, theoretically, is needed only in the two phases that are not grounded, the NEC Table 430–37 states that for three-phase systems, three overloads are required, one in each phase. The advantage in the past of having only two overloads is no longer viable.
3) With properly connected control circuits, ground faults in the control circuit will neither start the motor nor prevent stopping the motor by means of the stop push button.
4) There is a high probability of sustaining arcing for 480 V or higher, phase-to-phase, single-phase circuit extension, without escalation to a three-phase fault.
5) The corner-grounded system will effectively control transient and overvoltages; however, a maximum of 1.73 times the normal phase-to-neutral voltage can exist between two conductors and the ground.
6) A fault from phase to ground is easily detected and found.

The disadvantages are the following:

1) An inability to supply dual-voltage service for lighting and power loads.
2) The necessity of positive identification of the grounded phase throughout the system to avoid connecting meters, fuses, 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.

1.5.2 One Phase of a Delta System Grounded at Midpoint

In some areas where the utility had a large single-phase 120/240 V load and a small three-phase 240 V load, they have supplied a large single-phase 120/240 transformer and one or two smaller 240 V transformers. In other cases where three single-phase transformers are connected in delta, the midpoint, if available, is grounded. With this method it is possible to gain some of the advantages of neutral grounding by grounding the midpoint of one phase. This method does not provide all the advantages of a system neutral grounding and is not recommended for voltages over 240 V. The advantages are the following:

1) The first costs are approximately the same as a solidly grounded system.
2) Fast tripping for phase-to-ground faults.
3) Mid-phase grounding effectively controls, to safe levels, the over-voltages.

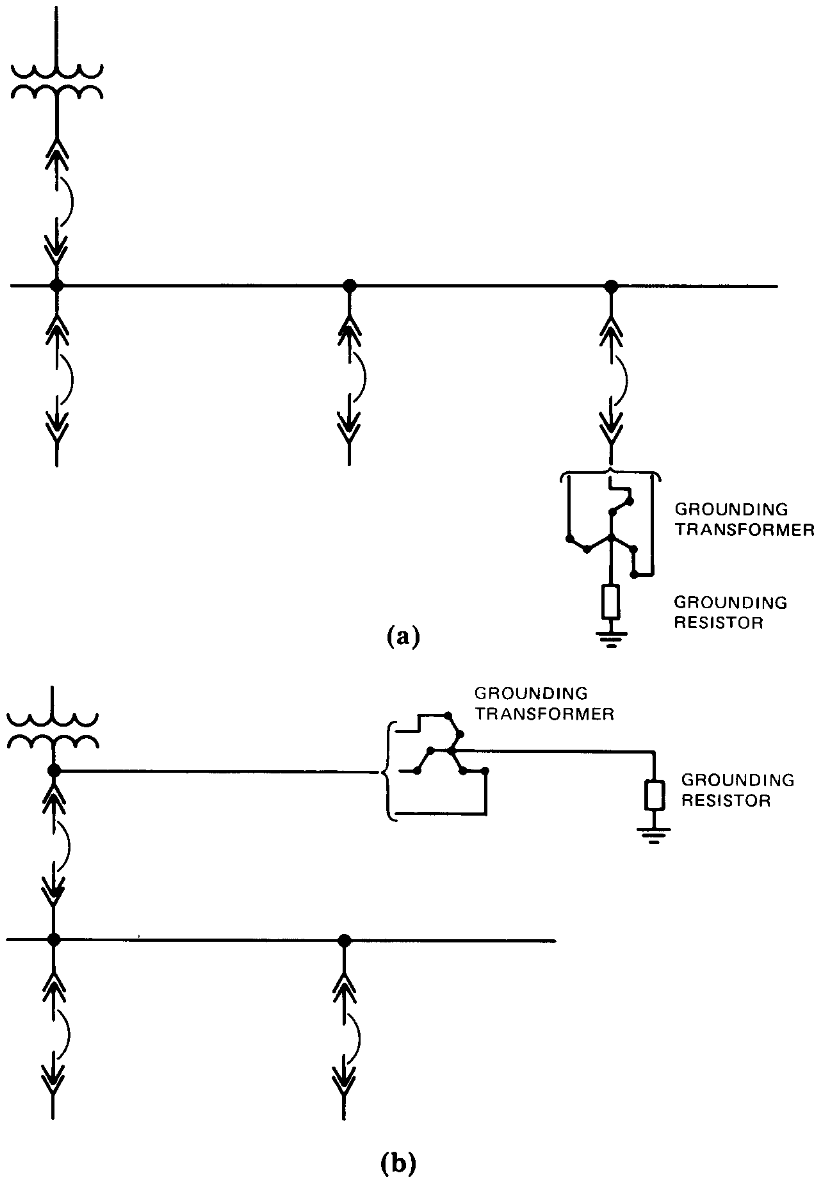


Figure 5—Methods of Connecting Grounding Transformer to a Delta-Connected or Ungrounded Power System to Form Neutral for System Grounding

The disadvantages are the following:

1) The shock hazard of the high phase leg to ground is 1.73 times the voltage from the other two phases.
2) There must be positive identification of the conductor with the highest voltage to ground to avoid connecting 120 V loads to that conductor.
3) Serious flash hazard from a phase-to-ground fault can exist because of the high fault levels.
4) The cost of maintenance is somewhat above the neutral grounded system due to the sustained higher voltage and insulation stress on one phase.
5) Grounding of one phase of a delta system at the midpoint of that phase for three-phase systems with phase-to-phase voltages over 240 V has little application.

1.6 Location of System Grounding Points

1.6.1 Selection

Each system as described in 1.2 of this chapter is defined by "its isolation from adjacent grounding systems. The isolation is provided by transformer primary and secondary windings." The new system created by each transformer or generator requires the establishment of a new system ground.

The selection of a system grounding point is influenced by whether the transformer or generator windings are connected "wye" or "delta" "Delta-wye" or "wye-delta" transformers effectively block the flow of zero-sequence current between systems. Although the wye connection is generally more conducive to system grounding because of the availability of a neutral connection, that fact alone should not be the sole criteria for the location of the system ground point.

The system ground point should always be at the power source. An archaic concept of grounding at the load or at other points in the system because of the availability of a convenient grounding point is not recommended because of the problems caused by multiple ground paths and because of the danger that the system could be left ungrounded and therefore unsafe. The National Electrical Code recognizes this danger and prohibits system grounding at any place except the source and/or service equipment.

As previously described in 1.4.6 of this chapter, grounding of other than neutrals may be accomplished with the use of zigzag grounding transformers or grounded wye primary-delta secondary grounding transformer banks connected directly to the phase bus.

1.6.2 Single Power Source

When a 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 (Fig 6). Provision of a switch or circuit breaker to open the neutral circuit is not recommended. It is not desirable to operate the system ungrounded by having the ground connection open while the generator or transformer is in service.

In the event that some means of disconnecting the ground connection is required for measurement, testing, or repair, a disconnecting link should be used and only opened when the system is de-energized.

1.6.3 Multiple Power Sources

For installation with multiple power sources (i.e., generators or power transformers) interconnected that are or can be operated in parallel, the system ground can be accomplished in one of two ways:

1) Each source grounded, with or without impedance (Fig 7).
2) Each source neutral connected to a common neutral bus, which is the grounded, with or without impedance (Fig 8).

For Solidly Grounded Systems with multiple sources where all sources must be solidly grounded, it is always acceptable to separately ground each power source as shown in Fig 7(a). Levels of fault current are determined by the number and available fault current of each interconnected source. Where sources are in close proximity, Common Ground Point connection [Fig 8(a) will allow for selective relaying to identify and isolate only the faulted source.

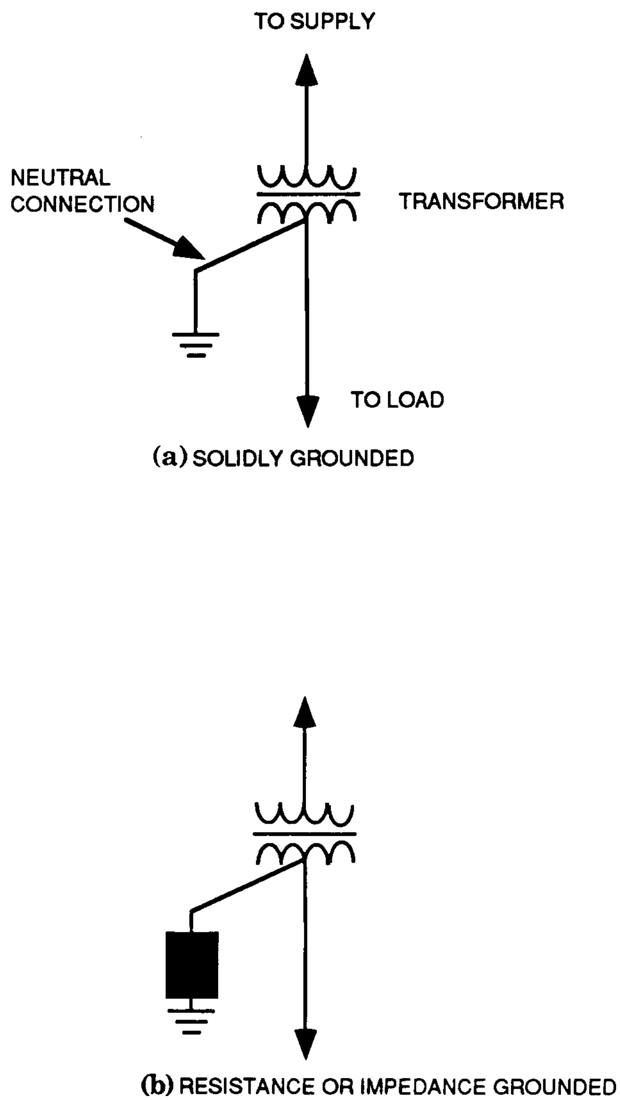
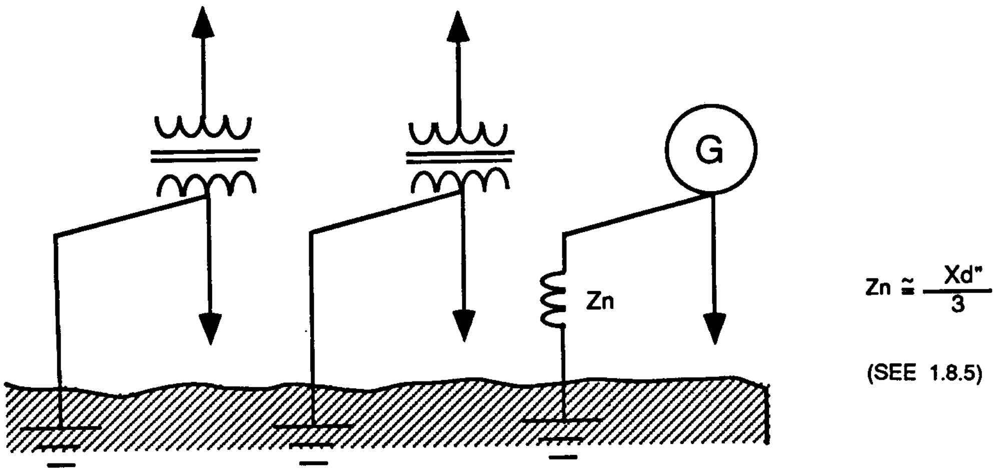
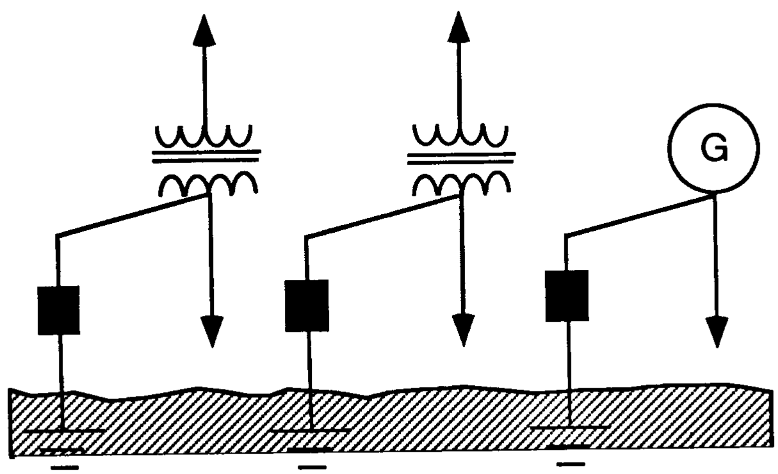


Figure 6—Grounding for Systems with One Source of Power



(a) SOLIDLY GROUNDED



(b) R OR Z GROUNDED

Figure 7—Grounding for Systems with Multiple Power Sources (Method 1)

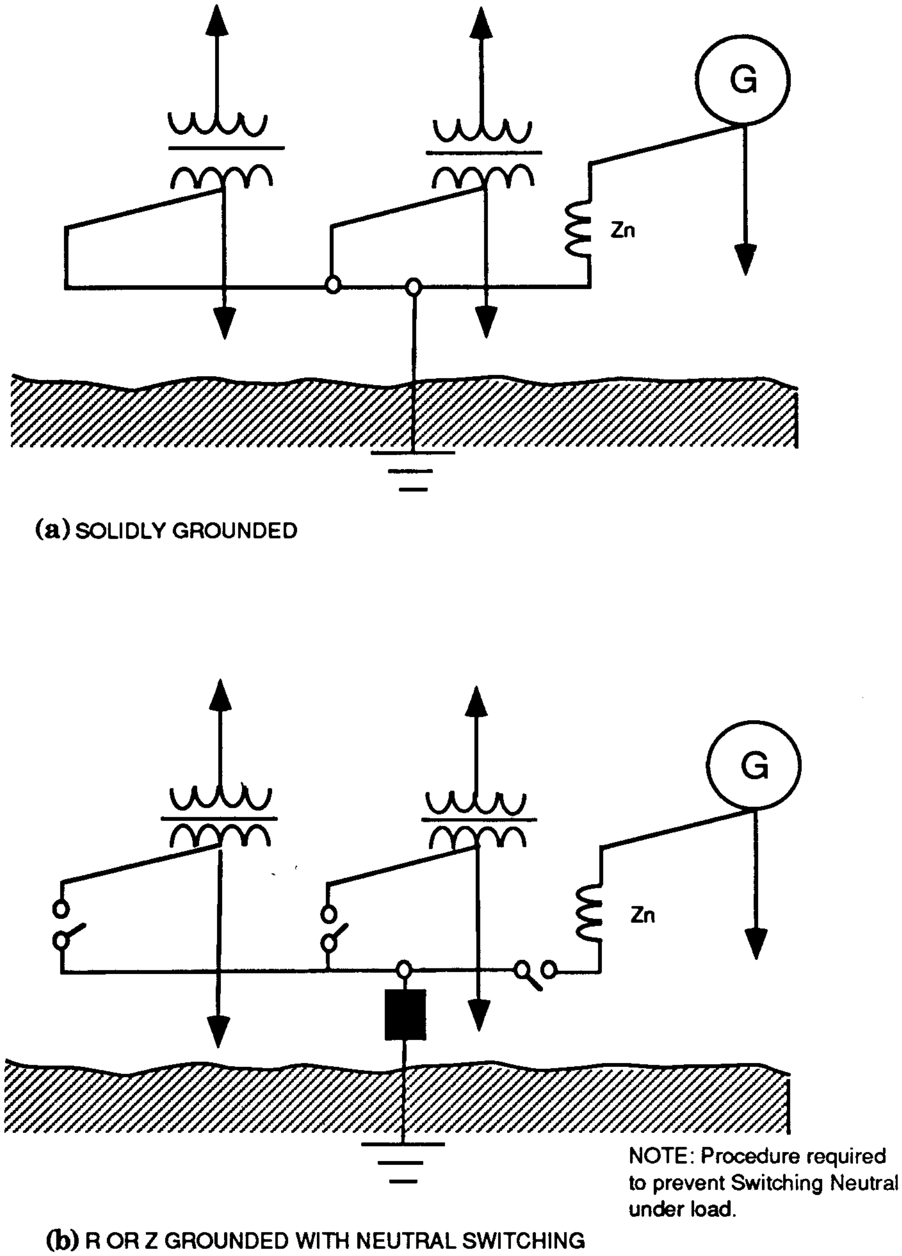


Figure 8—Grounding for Systems with Multiple Power Sources (Method 2)

If the power sources are not in close proximity, Common Ground Point is not recommended. The impedance in the neutral bus connection may become large enough to prevent effectively grounding the neutral of the source at the remote location. The interconnect may inadvertently become open, allowing the transformer to operate ungrounded.

For Impedance Grounded Systems it is always acceptable to separately connect each neutral to ground through individual impedances [Fig 7(b)]. Each impedance rating should allow sufficient current to satisfy the criteria for the grounding system being used.

Individual neutral switching devices (automatic or manual) are not recommended, since incorrect operation may allow a power source to operate ungrounded.

System relaying is more complex when such impedance grounding is used, because of multiple grounding points. Capability of detecting a ground fault at any point in the system requires sensing at each ground point in addition to any normal feeder protection. The fault current sensed by the feeder is variable, depending on the number of sources that are grounded at the time of the fault.

When individual impedances are used, circulation of third-harmonic currents between paralleled generators is not a problem since the impedance limits the circulating current to negligible values. When total ground-fault currents with several individual impedances would exceed about 1000–4000 A, a Common Ground Point and single impedance to limit the fault current should be considered [Fig 8(b)]. The advantage of this connection is that the maximum fault current is known and selective relaying can be used to open tie breakers and selectively isolate the faulted bus.

The primary purpose of neutral disconnecting devices in impedance grounded systems is to isolate the generator or transformer neutral from the neutral bus when the source is taken out of service, because the neutral bus is energized during ground faults. A generator or transformer disconnected from the power bus, but with an unbroken connection of its neutral to a neutral bus, would have all of its terminals elevated with respect to ground during a ground fault. Disconnecting devices should be 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.

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. Generators that are designed to suppress zero sequence harmonics, usually by the use of a two-thirds pitch winding, will have negligible circulating currents when operated in parallel; therefore, it is often found practical to operate these types of generators with the neutral disconnect device closed. This simplifies the operating procedure and increases assurance that the system will be grounded at all times, because interlocking methods can be used.

It is sometimes desirable to operate with only one generator neutral disconnecting device closed at a time to eliminate any circulating harmonic or zero-sequence currents. In addition, this method provides control over the maximum ground fault current and simplifies ground relaying. When the generator whose neutral is grounded is to be shut down, another generator is grounded by means of its neutral disconnecting device before the main and neutral disconnecting device of the first one are opened. This method has some inherent safety considerations that must be recognized and addressed in order to ensure continual safe operation. The procedures required to permit only one disconnecting device to be closed with multiple sources generally do not permit the use of conventional interlocking methods to ensure that at least one neutral disconnecting device will be closed. Therefore, this method should only be used where strict supervision of operating procedures is assured.

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.

1.6.4 Creation of Stray Currents and Potentials

If a current-carrying conductor, even though nominally at ground potential, is connected to earth at more than one location, part of the load current will flow through the earth because it is then in parallel with the grounded conductor. Since there is impedance in both the conductor and the earth, a voltage drop will occur both along the earth and the conductor. Most of the voltage drop in the earth will occur in the vicinity of the point of connection to earth, as explained in Chapter 4. Because of this nonlinear voltage drop in the earth, most of the earth will be at a different potential than the grounded conductor due to the load current flowing from this conductor to earth.

An equipment grounding conductor connected to the same electrode as the grounded load conductor will also have a potential difference from most of the earth due to the potential drop caused by the load current. In most instances the potential difference will be too low to present a shock hazard to persons or affect operation of conventional electrical load equipment. However, in many instances it has been of sufficient level to be detected by livestock, either by coming in contact with noncurrent carrying enclosures to which an equipment grounding conductor is connected, or where sufficient difference in potential exists between the earth contacts of the different hoofs. Although potential levels may not be life threatening to the livestock, it has been reported that as little as 0.5 V rms can affect milk production [17].

Section 250-24 of the NEC [1] has required that the grounded circuit conductor (neutral) of a single system must be connected to a different grounding electrode each time it enters a separate building. Where there is a multibuilding facility, as is common on farms, there will be load currents flowing in the earth due to these multiple groundings.

Section 250-24 has been modified by exceptions so that these multiple groundings are no longer universally required. Exception No. 2 will waive a neutral grounding at other than the service entrance from the utility if a separate equipment grounding conductor is run to each building and grounded and bonded at each building as specified in the code. Since no load current would be flowing into these grounding electrodes, the equipment grounding conductor should be at earth potential.

Another possible source of multigrounding of a neutral would be the use of the neutral for grounding of the frames of cooking ranges or clothes dryers as allowed in Article 250–61, Exception 1. If the appliance frame also has a separate connection to earth, the multigrounding of the neutral will be achieved. This practice should be avoided in the vicinity of the barns, and even at other locations on farms.

There is another condition of multigrounding, since the utility will ground the neutral at the supply transformer and it must be grounded again at the service entrance. Since the equipment grounding conductor has its origin at the service entrance ground, it will have a potential to earth as a function of the voltage drop created by load current in the earth in parallel with the service drop neutral current. The magnitude of this potential will be affected by the size and length of the service drop neutral, the magnitude of the neutral current, and the resistance to earth of the service entrance grounding electrode as well as other connections to earth of the equipment grounding conductor. These factors are all subject to some control.

It is recommended that sources of stray currents on the premises that can be created by grounding of the neutral at other than the service entrance should be eliminated. Do not ground the neutral except at the service entrance. Make regular checks of electrical circuits and equipment to assure that unintentional grounding of either line or neutral has not occurred due to insulation failures. It is also recommended that voltages caused by current in the service drop neutral be minimized by balancing loads to minimize neutral current. All loads creating irregular currents, such as motors, should not be connected line-to-neutral.

There is a remaining source of circulating current when the utility distribution circuit includes a multi-grounded neutral. The grounding of the supply-transformer secondary neutral has often been made common with the grounding of the primary neutral. It has been established that there may be a potential difference between this primary neutral and earth and that there may be primary load current flowing through the ground (see [26], [27], [24], and [17]). This will be affected by the neutral current, the location on the distribution feeder, and the effectiveness of the various ground electrodes.

Neutral-to-ground voltages injected into the user system from the utility primary neutral cannot be eliminated by system grounding techniques on the premises, although some reduction may be achieved if the service entrance ground is made extremely effective and is located at some distance from livestock facilities. There are active systems to counteract equipment-to-ground voltages produced by utility injections [17]. Also, used are so-called equipotential ground planes, which bring earth surface voltages to the same value as that of equipment [17]. Both of these are out of the scope of system grounding, but are mentioned for reader reference.

1.6.5 Grounding Locations Specified by the NEC [1]

The following are system locations of grounding connections that appear to be required or permitted for the more common power system groundings by the NEC [1]). This is not intended to be a complete listing of code requirements, and the current edition of the NEC should be consulted for details or recent changes as well as to determine whether grounding is required or prohibited. The purpose is to call attention to location requirements but not to interpret the requirements, since that is the province of the cognizant enforcing authorities.

On service-supplied systems of 50 to 1000 V, system grounding when required or elected should be made at the service entrance, between the load end of the service drop or lateral and the neutral landing point, and, if supplied from a transformer external to the building, also at one point external to the building. If a grounded conductor extends past the service entrance switch, it should have no further grounds on this extension except as noted by the various exceptions in the code to this requirement ([1], Sec. 250-23[a]), such as mentioned below.

Where dual services feed to a double-ended bus, a single ground at the center point of the neutral bus is allowed to replace those listed above ([1], Sec. 250-23[a], Exception 4).

If more than one building is fed from a single service there should be a system grounding connection made at the entrance to each building. However, if an equipment grounding conductor is run with the load conductors, this ground connection can be eliminated so as to avoid elevating noncurrent- carrying enclosures above ground potential due to load drop in the neutral conductor ([1], Sec. 250-23[a], Exception 2; Sec. 250-24[a], Exception 2; Sec. 547-8, Exception 1).

For circuits of 240 V or less, the code allows the grounded conductor to be used for grounding the frames of ranges, ovens, or clothes dryers ([1], Sec. 250-23[a], Exception 3). It does not prohibit simultaneous grounding by the equipment grounding conductor or to an effectively grounded water pipe, so that such connections could ground the neutral downstream of the service switch. This standard does not recommend that the grounded circuit conductor be connected to these appliance frames even if allowed by the code. It is recommended that the appliance frames be grounded by connection of an equipment grounding conductor.

Grounding connections should not be located or connected so as to cause objectionable currents in grounding conductors or grounding paths ([1], Sec. 250-21[a]).

Separately derived circuits, if required or elected to have a system ground, should be grounded between the source and the first disconnecting device. System grounding connections downstream of the disconnecting device have the same rules as for service-supplied circuits.

The point of grounding for systems shall be the neutral or common conductor where one exists, otherwise the point shall be a phase conductor ([1], Sec. 250-25).

On systems over 1000 V, a transformer-derived neutral may also be used as the attachment point for a system ground. This method is not mentioned for effective grounding of low-voltage systems.

High-voltage systems may also have multiple neutral grounds where the conductors are overhead outdoors, or where they are directly buried with a bare neutral conductor.

1.6.6 Avoiding Common-Mode Noise

When all of the conductors of a signal or power system have an identical potential difference with respect to another reference, this potential is known as a common-mode voltage or signal. If such voltage or signal is undesirable, it is usually called noise. The other references are usually the equipment enclosure or the ground, both of which may be at the same potential. Electronic equipment may often exhibit a susceptibility to common-mode noise between the incoming power conductors and ground, which may affect either digital or analog signals.

Common-mode noise on a power source occurs when a potential difference exists between the ground to which the power source is referenced and the ground to which the power-consuming equipment is referenced. There is often a capacitive or resistive coupling between the equipment's circuitry and its enclosure. The potential difference can be created when there is a current flow in the equipment grounding conductor, or the earth, between the equipment enclosure and the power source grounding.

The earth has many stray currents, resulting in small potential differences between points. These currents may be other than power frequencies, and even if power frequencies, may contain transients or bursts due to switching or other aberrations. Therefore, if the equipment cabinet is connected to earth at its location, any potential occurring between there and the power system grounding point can be coupled into the circuitry.

The equipment enclosure can be maintained at the same potential as the power system ground if the equipment grounding conductor is of low impedance and has no connection to earth except at the grounding point of the source transformer, the so-called "single point ground." This is allowed by the NEC 1], Sec. 250-74, Exception 4, and is referred to as an IG, or isolated ground outlet. Sec. 1.6.4 in this chapter illustrates why the neutral must be grounded only at the source transformer. The earth potential difference between the source grounding point and the equipment must not be sufficient to develop a shock hazard to persons standing within reach, and must not present the possibility of resistively or capacitively coupling this potential into the equipment enclosure at a magnitude sufficient to create a noise problem. Normally, meeting all these criteria is possible only if the equipment is physically and electrically close to the source transformer.

Connection of the equipment ground to earth with an electrode that is physically separate from all other power system and structural grounding electrodes and is not bonded to any of these other grounding electrodes, will inevitably produce common mode noise, since it is not referenced to the power source ground. The magnitude of this common mode potential can be destructive to the equipment and hazardous to personnel, since a power system fault can raise the power system or structure several hundred or thousand volts above other earth references. This grounding method is in violation of the NEC, Article 250 [1].

For greater detail on the grounding of sensitive equipment, refer to Chapter 5 of this standard and to P1100 [7].

1.6.7 Limiting Transferred Earth Potentials

The term *transferred earth potentials* refers to the voltage-to-earth of grounding systems that will appear on conductors as a result of the source system grounding electrode being above normal earth potential. The larger voltages are usually developed by ground fault currents returning to their source through earth. A common example is a ground fault of a conductor, which is supplying a substation transformer primary, to the station ground grid that is used for grounding of the transformer secondary neutral. If this grounding grid is not connected to the high-voltage source system ground, there can be a significant voltage rise above earth as the fault current flows into the earth. Low-voltage conductors leaving the area where the ground or grounding electrode voltage has been affected will have that voltage added to their normal line-to-ground voltage. The total voltage may exceed the insulating rating of the conductors or the equipment to which they are connected.

Control and telephone circuits running into areas where the grounding electrode or mat is subject to significant voltage rise are particularly vulnerable. High voltage appearing on such circuits is more likely to be a hazard to personnel and to exceed insulating ratings. Such conductors should not interconnect between two areas whose ground-mat potential is not held equal unless special protection or isolation is applied to the low voltage circuits. Another hazard can be created when portable or mobile equipment can be subjected to a transferred voltage rise. This is specifically treated in 1.11 as well as in Article 250–154 of the NEC [1].

Transferred potentials will be reduced if the resistance to earth or impedance between grounding grids is held to minimum. Isolation between low-voltage equipments at locations having unequal ground potentials can be accomplished by use of devices rejecting common-mode voltages. Such devices include isolation transformers, neutralizing reactors, or optical links [25].

Within most industrial distribution systems, compliance with the NEC requirements for equipment grounding conductors and the running of the grounding conductor to the service entrance panel serve to limit such potentials to safe limits. If there are areas that are interconnected by three-wire overhead lines only, bonding provisions should be made before interconnecting low-voltage circuits between the two areas.

Low-voltage potential differences can be created by the flow of load or other small currents through ground or grounding conductors. These can be quite troublesome to livestock, which is discussed in 1.6.4. It can also be troublesome to sensitive electronic equipment, particularly if the equipment is sensitive to common mode voltages on the power supply conductors or common-mode voltages on communication lines that may run between locations with different earth potentials. Existing NEC grounding requirements designed to prevent the flow of load currents through grounding paths are often not adequate because of the sensitivity to very low levels and because the voltages can be caused by other phenomena. These problems are further discussed in Chapter 5 and in P1100 [7].

Further information is available in Reference [25].

1.7 [Reserved for Future Use]

1.8 Grounding of Industrial Generators

1.8.1 Discussion of Generator Characteristics

Generators have several characteristics that are significantly different from transformers, the other common source of power. As compared to the transformer, the generator has little ability to withstand the heating effects or mechanical forces of short circuits. The generator may be required by standards to withstand a less than 10-per-unit short circuit, and the imposition of higher currents is defined as unusual service by the National Electrical Manufacturers Association (NEMA) M-G 1 [8], whereas a transformer may be required to withstand a 25-per-unit current. The generator may be capable of withstanding less than 25% of the heating effect of this current as compared to the transformer. If the current is unbalanced, this capability may be reduced to less than 10% of the transformer capability (see [8] and [23]).

Unlike the transformer, the three sequence reactances of a generator are not equal. The zero-sequence reactance has the lowest value, and the positive sequence reactance varies as a function of time. Thus, a generator will usually have higher initial ground-fault current than a three-phase fault current if the generator has a solidly grounded neutral. According to NEMA, the generator is required to withstand only the three-phase current level unless it is otherwise specified (see Reference 8). Also, NEMA states that the negative sequence current thermal withstand limit is a product of time in seconds and the square of per-unit negative sequence current (I_2^2t) equaling 40 [18]. With a solidly grounded neutral, the steady-state ground-fault current will be about eight times that of the full-load current when the steady-state three-phase fault current is three times the full-load current, but because of the negative sequence content of the ground-fault current, the generator has less thermal withstand capability than it would for a three-phase fault.

A generator can develop a significant third-harmonic voltage when loaded. A solidly grounded neutral and lack of external impedance to third harmonic current will allow flow of this third-harmonic current, whose value may approach rated current. If the winding is designed with a two-thirds pitch, this third-harmonic voltage will be suppressed [12] but the zero-sequence impedance will be lowered, increasing the ground-fault current.

The physical limitations imposed by generator construction result in less available insulation thicknesses, with a resulting reduction in voltage-impulse withstand as compared to nonrotating electrical equipment. Thus, special attention should be given to limiting voltage to ground by the grounding of generator neutrals.

Internal ground faults in solidly grounded generators can produce large fault currents. These currents can damage the laminated core, adding significantly to the time and cost of repair. Such currents persist until the generator voltage decays, since they are not capable of being interrupted by the generator circuit breaker [21]. Both magnitude and duration of these currents should be limited whenever possible.

NOTE — One per unit is equal to generator-rated current.

1.8.2 Single Unparalleled Generator

This configuration may offer the most options for grounding. The distribution system may be particularly designed for flexibility in applying grounding by having only three-wire loads connected directly to the generator or even having only a single transformer connected to the generator (unit bank). Thus the design may employ high-resistance grounding to minimize damage from internal ground faults, or low-resistance grounding if needed to operate selective ground relays. In either case the ground-current level should be substantially less than the phase-current fault levels.

The generator may also be applied to a four-wire load without transformation. If the generator is rated for solidly grounded service, the neutral may be connected directly to the grounded circuit conductor. If a standard generator is used, a reactor should be connected between neutral and the grounded circuit conductor so as to limit the momentary ground fault current to no more than the momentary three-phase fault current (see [10] and [8]). When $3i_0 = i''_d$ the value of this neutral reactor, X_N, should be

$$X_N = 1/3\ (2X''_d - X_2 - X_2) \tag{1}$$

where

$3i_0$	= The ground fault current = $3/(X''_d+X_2+X_0+3X_n)$
i''_d	= The three phase subtransient fault current = $1/X''_d$
X''_d	= The generator subtransient reactance
X_2	= The generator negative sequence reactance
X_0	= The generator zero sequence reactance

Note that a resistor should not be used for this purpose, since its impedance is in quadrature with the machine reactance and thus would require a much larger value of resistance than reactance. This resistance would incur large losses from the flow of either fault or load current. The zero-sequence load current would also produce an objectionable voltage drop, since the load is primarily resistive.

On the other hand, the neutral reactor will cause little voltage drop to be produced by in-phase zero-sequence load current. The total zero-sequence current will be a small value because the generator has limited unbalanced current capacity. The continuous negative-sequence current capability of generators covered in ANSI C50 standards is 8% or 10%. Salient-pole industrial generators may have slightly higher capacity. The use of the reactor between the generator neutral and the neutral circuit conductor does not affect the NEC [1] requirement that the neutral circuit conductor be solidly grounded.

If generators are solidly grounded, the system's circuit breaker duty must be calculated at the higher ground fault duty.

If the wye side of a delta-wye transformer is connected to a generator that is configured for four-wire service, the generator should be designed with a two-thirds pitch winding. This transformer will act as a short circuit to third-harmonic currents, and without cancellation of third-harmonic voltage, the resultant current may adversely affect ground-fault relaying and generator capacity.

1.8.3 Paralleled Generators in Isolated System

This section covers only those generators that are paralleled to other generators on the same bus. Generators paralleled through transformers would be considered as paralleled to a separate source.

The considerations are similar to 1.8.1 except for the possible circulation of third-harmonic current between solidly grounded generators if any of the generators do not have two-thirds pitch windings. If generators are of identical design, there will be no significant circulation of third-harmonic current while the generators are being operated at identical power and reactive current outputs. If the generators are not of identical design, there will be a third-harmonic circulating current. If identical generators are operated with unequal loading, there will be a third harmonic circulating current. If these currents are not limited by neutral impedance, they may have levels that adversely affect ground relaying or generator thermal capacity. Generators with two-thirds pitch windings have the minimum impedance to the flow of third harmonic currents generated elsewhere due to their low zero-sequence impedance.

High-resistance grounding of the generators will adequately limit these harmonic currents. Thus, it is attractive to use high-resistance grounding on the generators even if there are load feeders directly connected to the generator bus, and to use low-resistance bus grounding to provide selective relaying on the load feeders. Low-resistance grounding of the generators at values not exceeding 25% of generator rating will normally suppress third-harmonic current to adequate values even with dissimilar generators, but the variable ground fault current available with multiple generators may pose a relay-coordination problem.

Where multiple generators are solidly grounded but have switches in the neutral, there has sometimes been the practice of grounding only one of the several generators in parallel to limit ground-fault current duty or circulating third-harmonic current. This will increase the fault-current duty in the grounded generator above that for which it would customarily be rated. A chart showing this difference appears in the *Westinghouse Transmission and Distribution Reference Book* [18]. The ability to switch neutrals appears to invite operational errors that could affect integrity of grounding, allowing overvoltage on four-wire loads, which would result in failure to meet criteria for effective grounding or acceptable reactive grounding and thus would possibly violate the NEC.

1.8.4 Generators as Unparalleled Alternate Sources

This category covers emergency and standby generators that are connected to the loads by transfer switches, which precludes paralleling with the normal source. With three-wire systems the generators would be considered a separately derived source, since there would be no continuous connection through a system neutral. Generator grounding practices would be guided by 1.8.2 and 1.8.3.

Where four-wire systems are involved, it has been shown in IEEE Std 446-1987 [6], Chapter 7, that objectionable currents can flow if a three-pole transfer switch is used. Whether or not the neutral is grounded at the generator as well as at the normal service, ground-fault relaying errors can occur. The NEC does not require neutral grounding at a generator when it has a common neutral with the grounded utility service neutral conductor per Article 250-5(d) and its fine-print note. However, this connection scheme will not allow any repair or testing of the normal system, which involves disconnection from ground of the neutral conductor to the generator if the generator is operating. There is the hazard that workers performing such repair or tests may not be aware that the generator is operating. The use of a four-pole transfer switch can eliminate these problems and is recommended. This will allow generator grounding practices to be in accordance with 1.8.2 and 1.8.3.

1.8.5 Generators Paralleled with Other Sources

This category describes generators connected to transformers that are, or can be, connected to other power sources. While the primary consideration is the generator grounding, decisions can be affected by the necessity of providing the desired grounding on the other side of the transformer while other generating sources may be disconnected.

The use of a delta-wye transformer with the wye facing the generator offers the advantage of providing neutral grounding, solid or impedance, to the generator-fed bus when the generator is not connected. It has the disadvantage of not offering grounding to the system connected to the delta side of the transformer. It presents a hazard if both the transformer and generator neutrals are solidly grounded [23]. The wye winding with a delta primary is a short circuit to any third-harmonic current produced by the generator. The ground-fault duty on the bus will be greater than the arithmetical sum of the ground-fault currents supplied by the transformer and generator when each is connected to the bus independently. The ground-fault current in the generator will exceed that which would occur when the generator is not paralleled. The fault currents must be calculated using symmetrical component techniques as shown in [23] rather than simply using the sum of the admittances of the transformer and generator sources. A generator rated for grounded service not otherwise specified is normally rated for the ground fault current flowing when not paralleled.

A generator neutral reactor can be used to limit the generator-fault duty to an acceptable value as calculated per [23] but may not limit any generated third-harmonic current to an acceptable value. Thus, suppression of third harmonic may be necessary to facilitate adequate ground-fault relaying.

If the delta of the delta wye transformer is connected to the generator bus, neutral grounding is available for the system on the other side of the transformer. However, the generator bus will be ungrounded until such time as the generator is connected. Independent bus grounding will require some form of grounding bank and will produce either effective or impedance grounding. If the grounding bank is connected to the transformer terminals, generator grounding will be dictated by the nature of any load connected to the bus. If the grounding bank is connected to the bus, the generator may be high-resistance grounded.

A wye-wye transformer as shown in Fig 24 can provide grounding to the side opposite the source, whichever side may have the source connected. The disadvantage is that the zero-sequence current must be provided by the source, so that the system grounding required on the other side of the transformer will dictate the type of generator grounding. If a delta tertiary is added to the transformer, this tertiary will supply the zero-sequence current so that the generator can be grounded without regard to system grounding requirements on the other side of the transformer.

The methods of grounding are also described in [3], which covers generator ground-fault protection as well. It should be noted that this standard was developed primarily for utility generators and does not contain some of the considerations for industrial applications.

1.9 System Grounding for Uninterruptible Power Systems[2]

1.9.1 General

As with any electrical system, correct grounding procedures are essential to the overall safety and operation of an Uninterruptible Power System (UPS). In particular, personnel safety, equipment protection, and sensitive electronic system performance can all be jeopardized by incorrect or ineffective grounding systems. The grounding of the UPS is very important when such systems supply power to critical computer loads.

To illustrate the recommended practices, several schemes are presented, based on various source and load configurations, for properly grounding the on-line UPS. These schemes do not cover every possible configuration but only present some basic guidelines; UPS systems, particularly new designs, may have configurations that require different grounding schemes. The NEC and applicable local codes must be followed as interpreted by the local enforcement authorities.

In the grounding schemes presented, the grounded conductor is part of the current-carrying circuit. The term *grounded conductor* refers to that leg of the circuit (usually the neutral) that is intentionally connected to ground. The grounding conductor is not part of the current-carrying circuit. The term *grounding conductor* refers to the conductor(s) that connect(s) all exposed metal parts of a device to ground; primarily for safety, secondarily for performance.

1.9.2 Significant NEC requirements

1) Separately Derived Source—Article 250–5(d) of the NEC defines a separately-derived source:
   A premises wiring system whose power is derived from generator, transformer, or converter windings and has no direct electrical connection, including a solidly-connected grounded circuit conductor, to supply conductors originating in another (grounded) system …
2) NEC Ground Requirement — It is a requirement of the NEC [1] that the grounded circuit conductor (normally the neutral) of a separately derived source be bonded at its source to the equipment safety grounding conductor and to a local grounding electrode conductor that is connected to the nearest effectively grounded: (1) building steel, (2) metal water pipe, and (3) other man-made grounding electrode (connection to earth).

[2]The material in this section is adapted from *Technical/Application News* [23]. It is used with the permission of the Liebert Corporation.

3) Specific NEC Provision—The NEC prohibits connecting the grounded circuit conductor (neutral) to the grounding conductor at more than one point. If the neutral were connected to the grounding conductor at more than one point, some of the normal neutral current would be allowed to flow in the grounding conductor circuit between the points of connection. Besides being a safety hazard, this practice defeats ground-fault protection schemes [29].
4) UPS Classification—The most common UPS module has a wye-connected inverter output and often requires the bypass input to be fed from a wye-connected source. The inverter portion of the UPS module is a separately derived source, in that the input to the rectifier/charger is electrically isolated from the inverter output. However, because the bypass input neutral is directly connected to the inverter output neutral, the UPS as a system may or may not be considered a separately derived system, depending on the particular arrangement for the bypass input neutral. Since this configuration of UPS encounters the most severe grounding problems, it will be used in the sample grounding schemes.

1.9.3 Grounding Schemes

1.9.3.1 Configuration 1

Single UPS Module, Nonisolated Bypass, Grounded Wye-Service. In this arrangement (Fig 9), a grounded-wye service is connected to both the main input and bypass (reserve) input of a single UPS module, and the Power Distribution Center does not contain an isolation transformer. The neutral, which is bonded to the grounding conductor at the service entrance equipment, is brought into the UPS module.

1.9.3.1.1 *Grounded/Grounding Conductor Arrangement.*

Since the UPS module output neutral is solidly connected to the bypass input (service entrance) neutral, the UPS module is not considered a separately derived system according to the NEC. In this system, (1) the UPS neutral should not be bonded to the equipment grounding conductor, and (2) no local grounding electrode conductor should be installed to the UPS module.

1.9.3.1.2 *Features/Performance.*

While this arrangement may be typical for 208 V input/208 V output UPS systems, it does not provide any isolation or common mode noise attenuation for sensitive loads. It appears that ground-fault current from the inverter may adversely affect the service entrance ground fault relay as shown in IEEE Std 446-1987 [6], Chapter 7, for emergency generators. Actually, the inverter will not supply ground-fault current since the static switch will transfer because of the fault-depressed voltage.

1.9.3.2 Configuration 2

Single UPS Module, Isolated Bypass. In this configuration (Fig 10), a bypass transformer is used to feed the bypass input of the UPS module. The bypass transformer and UPS module together constitute a separately derived system, since there is no direct electrical connection between the input (service entrance) circuit conductors and the output circuit conductors.

1.9.3.2.1 *Grounded/Grounding Conductor Arrangement.*

Since this configuration is considered a separately derived source, the neutral of the UPS module should be bonded to the equipment grounding conductor, and a local grounding electrode module should be installed, per NEC [1], 250-26. (In this particular system, the bonding of the neutral to the grounding conductor could be done at either the bypass transformer or at the UPS module. The UPS module is chosen for the point of bonding because it is in the normal power flow and is electrically closer to the load.) The bypass transformer is used in the bypass input to provide isolation and to step down the voltage if required (for example, in a 480 V input/208 V output configuration).

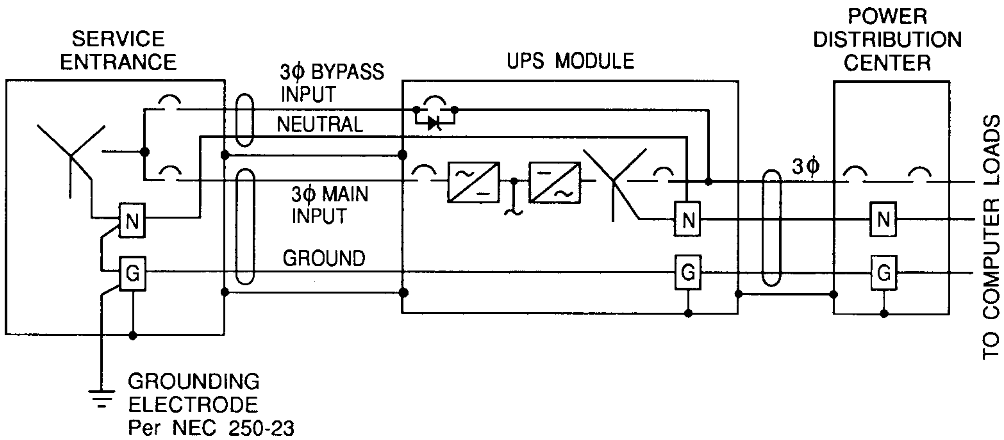


Figure 9—Configuration 1

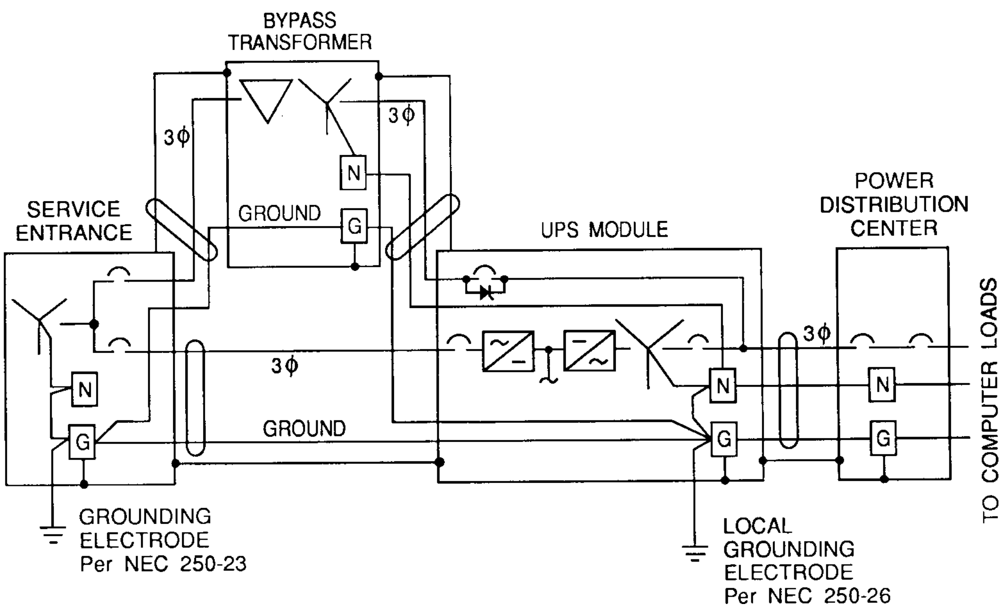


Figure 10—Configuration 2

1.9.3.2.2 *Features/Performance.*

With this arrangement, isolation from the input is achieved, and common-mode noise attenuation can be obtained for the sensitive loads if the UPS and bypass transformer are located electrically close (recommendation is 50 ft (15.2 m) or less) to the Power Distribution Center and the sensitive loads.

1.9.3.3 Configuration 3

Single UPS Module, Nonisolated Bypass, Isolated Distribution Center. In Configuration 3 (Fig 11, the UPS module main input and bypass input are connected to a grounded wye service in the same manner as Configuration 1.

1.9.3.3.1 *Ground/Grounding Conductor Arrangement.*

As explained in Configuration 1, the UPS module is not considered to be a separately derived source, since the neutral is bonded to the grounding conductor at the service entrance equipment and is solidly connected to the UPS module output neutral. Therefore, the UPS neutral would not be bonded to the equipment grounding conductor in the UPS module. However, the Power Distribution Center is provided with an isolation transformer and is considered a separately derived source. Therefore, the Power Distribution Center neutral should be bonded to the equipment grounding conductor and should be connected to a local grounding electrode in compliance with the NEC [1], 250–26.

1.9.3.3.2 *Features/Performance.*

This arrangement can be applied to 208 V input/208 V output UPS modules, as well as to 480 V input/480 V output UPS modules. (The voltage stepdown to 208 V occurs in the Power Distribution Center.) The common-mode noise attenuation of this arrangement is better than Configuration I or Configuration 2, since the isolation (common-mode rejection) occurs as close to the load as is practical. Using this configuration, the UPS module can be located remotely from the Power Distribution Center without compromising the common-mode noise performance. Also, by using 480 V input/480 V output UPS modules, smaller and less costly power feeders can be used and less voltage drop (as a percent of nominal) can be obtained. This is the preferred arrangement when using UPS modules and Power Distribution Centers.

1.9.3.4 Configuration 4

Single UPS Module, 3-Wire Bypass, Isolated Distribution Center, Grounded-Wye Service. Configuration 4 is similar to Configuration 3 except that the service entrance neutral is not included in the bypass input power feed.

1.9.3.4.1 *Grounded/Grounding Conductor Arrangement.*

In this configuration, the neutral of the service entrance equipment is not brought into the UPS module. The UPS module is, therefore, considered a separately derived source. As such, the neutral should be bonded to the equipment grounding conductor, and a local grounding electrode conductor should be installed in accordance with the NEC [1], 250-26. Since the Power Distribution Center contains an isolation transformer, it also is a separately derived source. This neutral should also be bonded to the equipment grounding conductor and to a local grounding electrode.

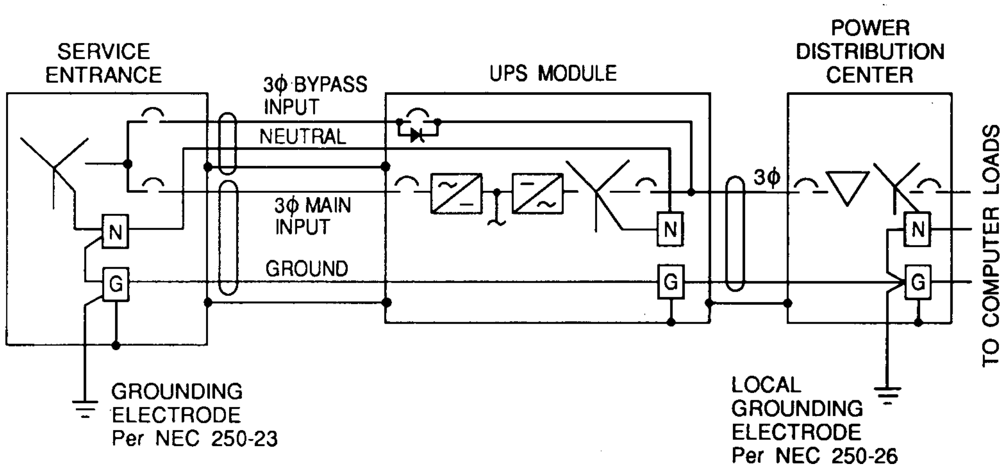


Figure 11—Configuration 3

1.9.3.4.2 *Features/Performance.*

The scheme shown in Fig 12 serves as an alternative to the scheme shown in Fig 11 when no neutral is available for the bypass input, provided that (1) the main input and bypass input are fed from the same source, (2) the source is a solidly grounded wye source, and (3) no neutral is required for the UPS load.

With some UPS systems, the neutral should be included with the bypass input, even if not required for the output, because the neutral is used for sensing and monitoring of the bypass input.

As in Configuration 3, since the Power Distribution Center contains an isolation transformer, isolation and common-mode noise reduction occurs when the center is located as close to the load as is practical.

1.9.3.5 Configuration 5

Single UPS Module, Isolated Bypass, Delta-Connected Source (Fig 13). Configuration 5 is similar to Configuration 2, with the exception that the input power source (service entrance) is delta connected. Most UPS modules require that the bypass input be fed from a wye-connected source. Therefore, when the UPS module is used with other than a wye-connected source, the bypass input must be fed from a bypass transformer with a wye-connected secondary.

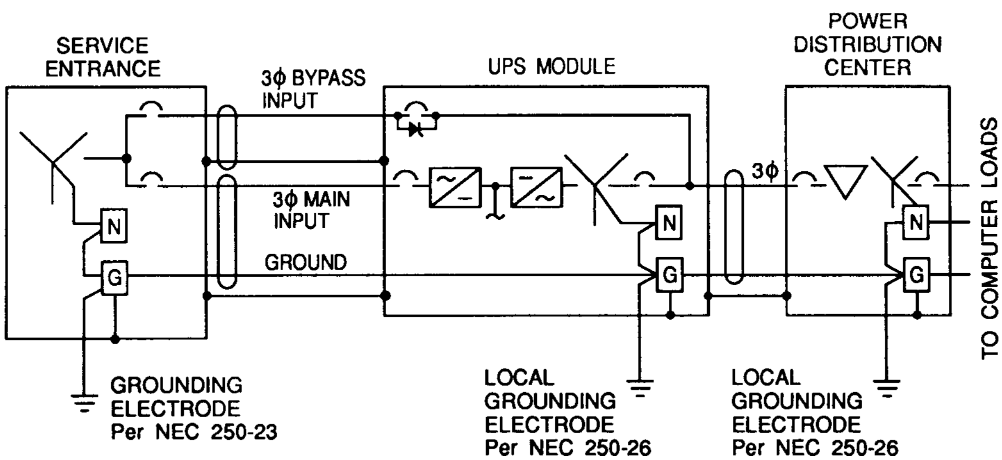


Figure 12—Configuration 4

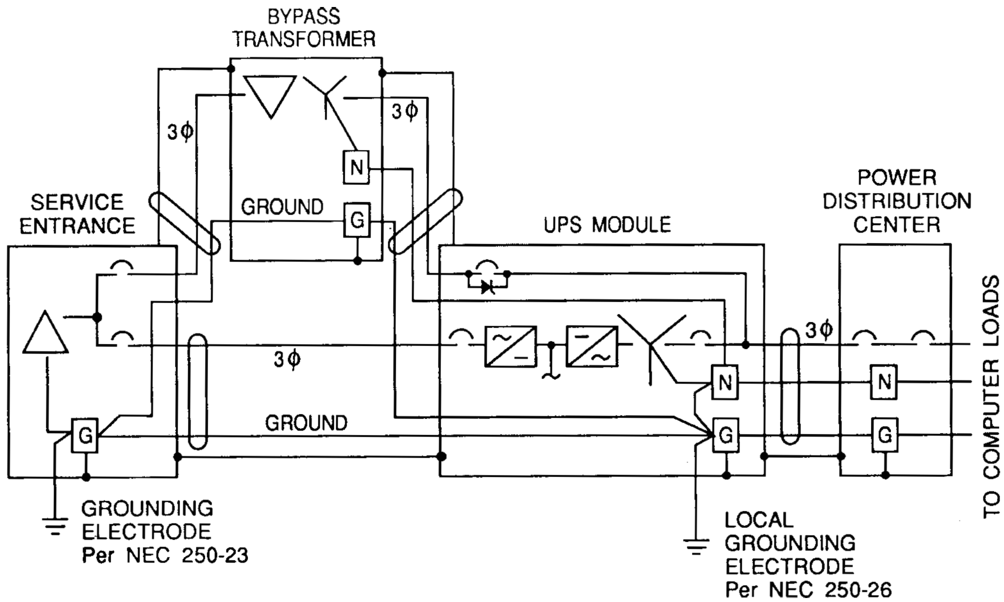


Figure 13—Configuration 5

1.9.3.5.1 *Grounded/Grounding Conductor Arrangement.*

In this configuration, as in Configuration 2, the UPS module neutral should be bonded to the equipment grounding conductor, and a local grounding electrode conductor should be installed in accordance with the NEC [1], 250–26.

1.9.3.5.2 *Features/Performance.*

With this arrangement, as in Configuration 2, isolation from the input is achieved, and common-mode noise attenuation can be obtained for the sensitive loads if the UPS and bypass transformer are located electrically close (recommended 50 ft (15.2 m) or less) to the Power Distribution Center and to the sensitive loads.

1.9.3.6 Configuration 6

Multiple-Module UPS System Example. In general, a multiple-module UPS system may be thought of as being an extension of a particular single-module system, except that the UPS "block" is now composed of more than one UPS module, and everything (including the bypass) feeds through a stand-alone static transfer switch. As an example consider Fig 14 as the multiple-module extension of the same grounding scheme shown in Fig 12.

1.9.3.6.1 *Grounded/Grounding Conductor Arrangement.*

Fig 14 illustrates one of the grounding schemes for multiple UPS modules with a stand-alone static switch. In this configuration, the bypass transformer and UPS modules I and 2 are considered to be a separately derived system, since there is no direct electrical connection between the input and output circuit conductors In order to provide a central point for bonding the UPS output neutral to the ground for the entire UPS scheme, the stand-alone static switch is utilized. (When the neutral is bonded to the grounding conductor in the stand-alone static switch, full-size neutrals must be run from the UPS modules and bypass transformer to the static switch, regardless of whether the neutral is required for the static switch loads.) The neutral-to-grounding-conductor bond and the local grounding electrode conductor should be installed in accordance with the NEC [1], 250–26.

1.9.3.6.2 *Features/Performance.*

Using the static switch to provide the central point for bonding the neutral to the grounding conductor as in this sample multiple-UPS module configuration, a UPS module could be removed from, or added to, the overall scheme without jeopardizing the integrity of the grounding system.

Depending upon the multiple-module configuration, the grounding concepts of single-model configurations 1 through 5 can be applied.

1.9.3.7 Configuration 7

Multiple-Module 415 Hz UPS System. In Configuration 7 (Fig 15), the 415 Hz UPS module main input is connected to the grounded wye service in the same manner as the previous 60 Hz UPS configurations. No bypass feed is used with 415 Hz UPS modules.

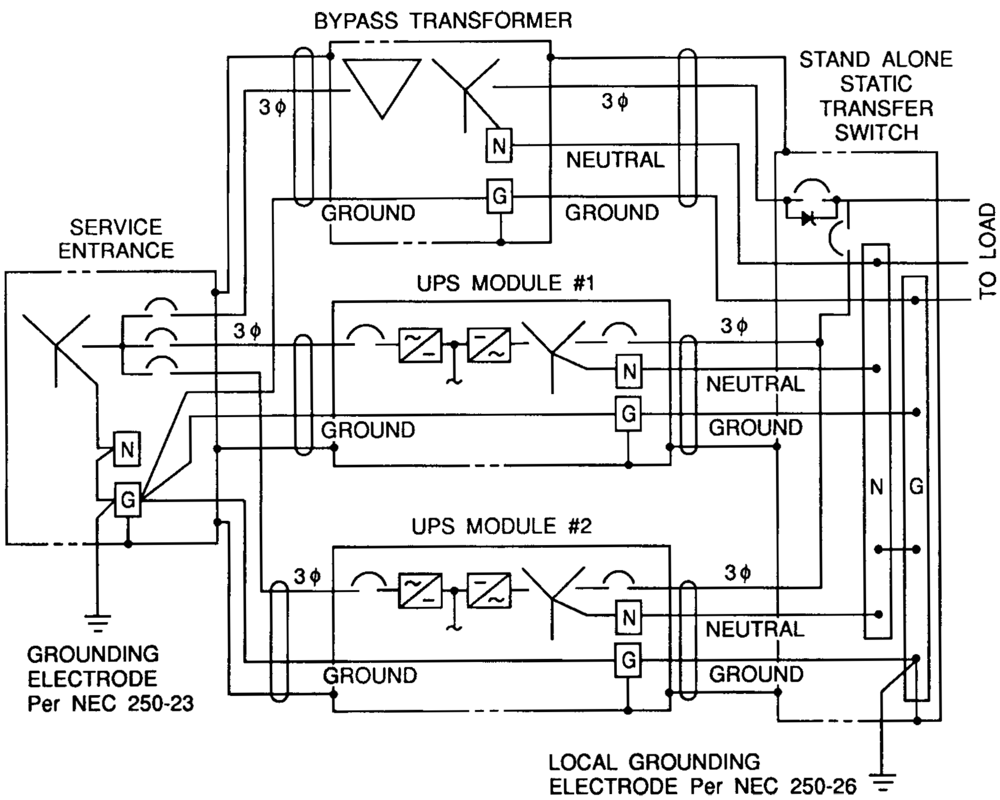


Figure 14—Configuration 6

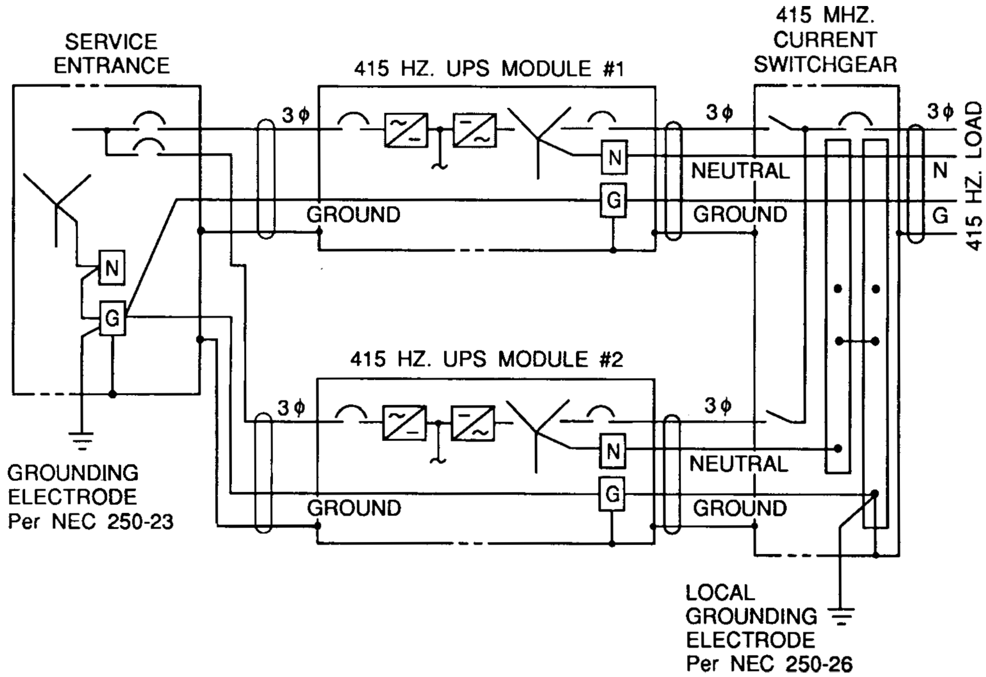


Figure 15—Configuration 7

1.9.3.7.1 *Grounded/Grounding Conductor Arrangement.*

In this configuration, there is no bypass feeder, so the neutral of the service entrance equipment is not connected to the UPS output neutral. The UPS module is, therefore, considered a separately derived source. As such, the UPS output neutral should be bonded to the equipment grounding conductor, and a local grounding electrode conductor should be installed in accordance with the NEC [1], 250-26. In this case, both UPS modules would meet the NEC requirements for a separately derived source. To provide a central point for bonding the UPS output neutral to the ground for the entire UPS system, the neutral-to-grounding-conductor bond should be made in the output switchgear. (If a single 415 Hz UPS module is used, the neutral-to-grounding-conductor bond should be made inside the UPS module.)

1.9.3.7.2 *Features/Performance.*

Using the output switchgear to provide the central point for bonding the neutral to the grounding conductor allows a UPS module to be removed or added to the parallel system without jeopardizing the integrity of the grounding scheme.

1.9.3.8 Configuration 8

Single UPS Module wit Maintenance Bypass Switchgear. In Configuration 8 (Fig 16), maintenance bypass switchgear is used to completely isolate the UPS module from the critical ac load during maintenance and off-line testing. A grounded-wye service is connected to the main input and bypass input of a single UPS module and to the maintenance bypass switchgear. If the neutral is required for the critical load, the neutral (which is bonded to the grounding conductor at the service entrance equipment) is brought into the UPS module and the maintenance bypass switchgear.

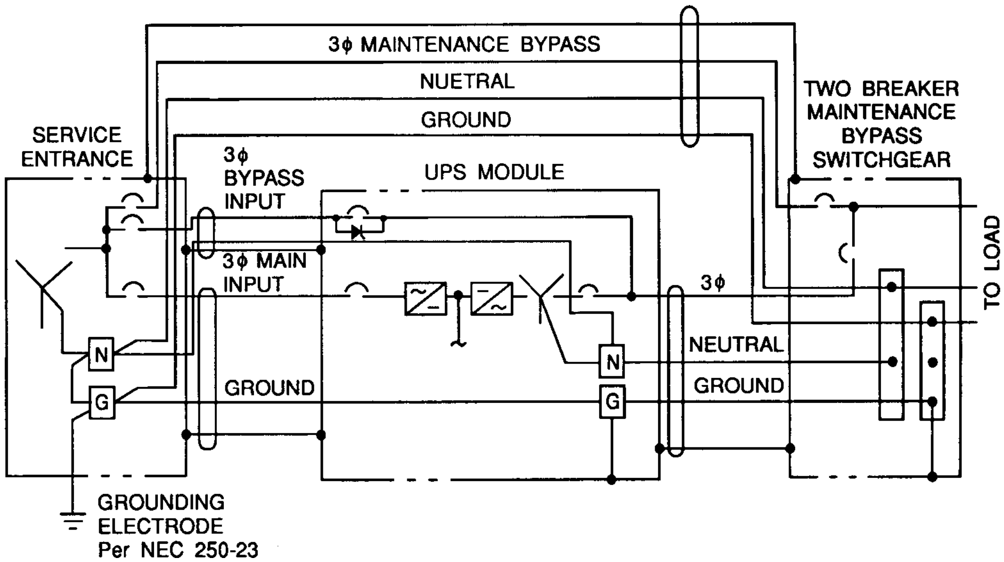


Figure 16—Configuration 8 (Four Wire)

1.9.3.8.1 *Grounded/Grounding Conductor Arrangement.*

Since the UPS output neutral and the maintenance bypass switchgear neutral are connected to the service entrance neutral, the UPS module is not considered a separately derived system according to the NEC. In this system (1) the neutrals of the UPS output and the maintenance bypass switchgear should not be bonded to the equipment grounding conductor, and (2) no local grounding electrode conductor should be installed.

1.9.3.8.2 *Features/Performance.*

This arrangement does not provide any isolation or common-mode noise attenuation for sensitive loads. If a Power Distribution Center with an isolation transformer is provided downstream from the UPS system (near the sensitive load), the common-mode noise attenuation of this arrangement would be greatly improved. Also, since the Power Distribution Center with transformer requires only a three-phase, three-wire plus ground input, the neutral conductor would not need to be connected from the service entrance to the UPS bypass and from the service entrance or the UPS output to the maintenance bypass switchgear (see Fig 17).

1.10 Multi-Voltage Systems

In any system the voltage may not be uniform throughout the system due to voltage drops caused by current flowing through system impedances. These voltage differences will normally be insignificant compared to the voltage imposed across the insulation between conductor and ground. However, the voltage can be changed significantly without creating a separate system, usually by use of an autotransformer or by connecting in series two significant reactances of opposite sign.

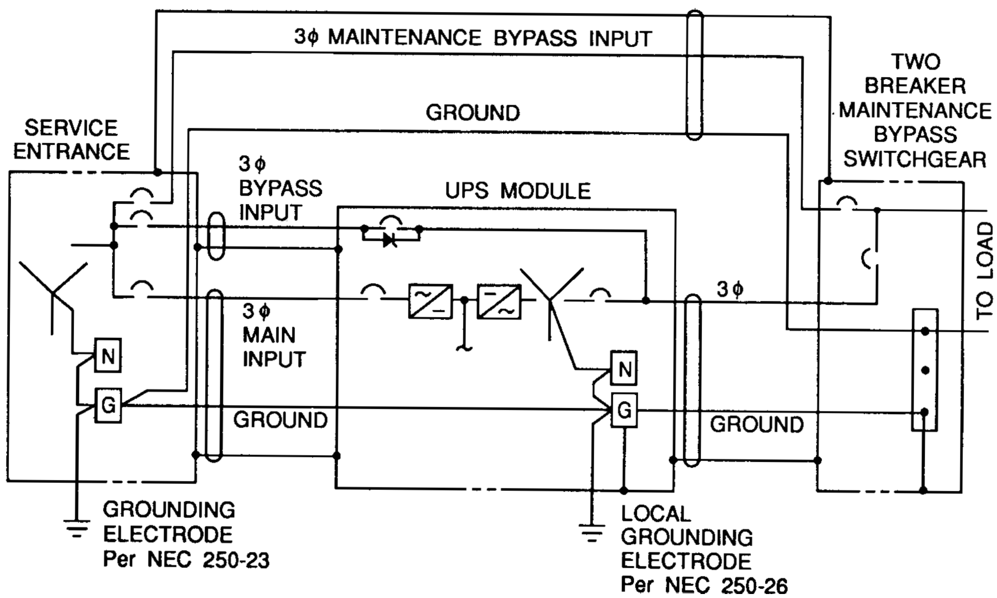


Figure 17—Configuration 8 (Three Wire)

1.10.1 Autotransformers

Occasionally autotransformers will be used to transform voltage, usually to reduce transformer cost, or perhaps to avoid creating a new grounding system. Unless the system grounding is suitable for the use of an autotransformer and the autotransformer is properly applied, its use may seriously reduce grounding and ground relaying effectiveness and expose equipment to a voltage-to-ground level higher than that for which it is designed.

The three-phase wye autotransformer with no delta tertiary has extremely high zero sequence impedance if no connection is made to its neutral. Fig 18 shows that a ground fault at *A′* will cause the source line-to-ground voltage to be imposed across the *A–A′* section of the autotransformer. Should that section of the winding be able to support this voltage, then the voltage to ground at *N*, the neutral of the autotransformer, would rise in proportion to the turns ratio of *A′–N* to *A–A′*, and *B′* and *C′* would have voltages to ground higher than B and C, the high voltage level. The secondary line-to-line voltage can also be increased.

In normal practice, winding *A–A′* would not support the full voltage, but would instead saturate, thus passing a certain amount of zero sequence current. In the process, it will create high-frequency components of voltage, at which frequency the winding can support a voltage proportional to that frequency. Thus, a very high voltage to ground could still exist at *N*.

Even if the secondary of the autotransformer is the higher voltage, it will still be overvoltaged by a secondary line-to-ground fault as shown in Chapter 6 of Beeman [10]. This reference also points out that overvoltages can also be caused by transient surges, such as from switching or lightning, being impressed across the section of winding between primary and secondary connections.

Figure 19 shows that when a source to a step-down autotransformer is impedance grounded, a ground on the source side of the autotransformer can cause the voltage from *B′* and *C′* to ground to approach the line-to-line voltage of the source. If the autotransformer steps up the voltage, the voltage to ground on the lower voltage system will lie between that shown in Fig 20 and what might be achieved in Fig 18 depending upon the relation of the grounding impedance to the exciting impedance of the autotransformer.

Figures 21 and 22 show that delta autotransformers do not offer a reduction in voltage to ground on the lower voltage system commensurate with the reduction in phase voltage, thus reducing the cost benefit of choosing the autotransformer rather than a full transformer. The open-delta version offers no reduction in maximum voltage to ground, but does result in an unbalanced voltage to ground that might be undesirable. In neither case do ground faults cause increased voltages to appear across the transformer windings, and line-to-ground voltage at either voltage will not exceed the higher line-to-line voltage. Should a full transformer be used in either case, it might be possible to reduce the class of insulation in the lower voltage system. In all the above examples there is a safety hazard due to normal perceptions of the relation of maximum voltage to the normal voltage on a circuit. For this reason, the NEC [1] has imposed restrictions as to how autotransformers can be used.

Figure 23 shows the correct configuration for using an autotransformer. There must be an effective connection between the neutral of the autotransformer and the neutral of the source transformer for flow of zero-sequence current. In an industrial installation where the NEC would apply, the connection must be made by extending the neutral of the source transformer. No ground connection must be made at the autotransformer to comply with Section 250-23 of the NEC [1]. A circuit supplied by an autotransformer would not appear to meet the criteria of a separately derived system.

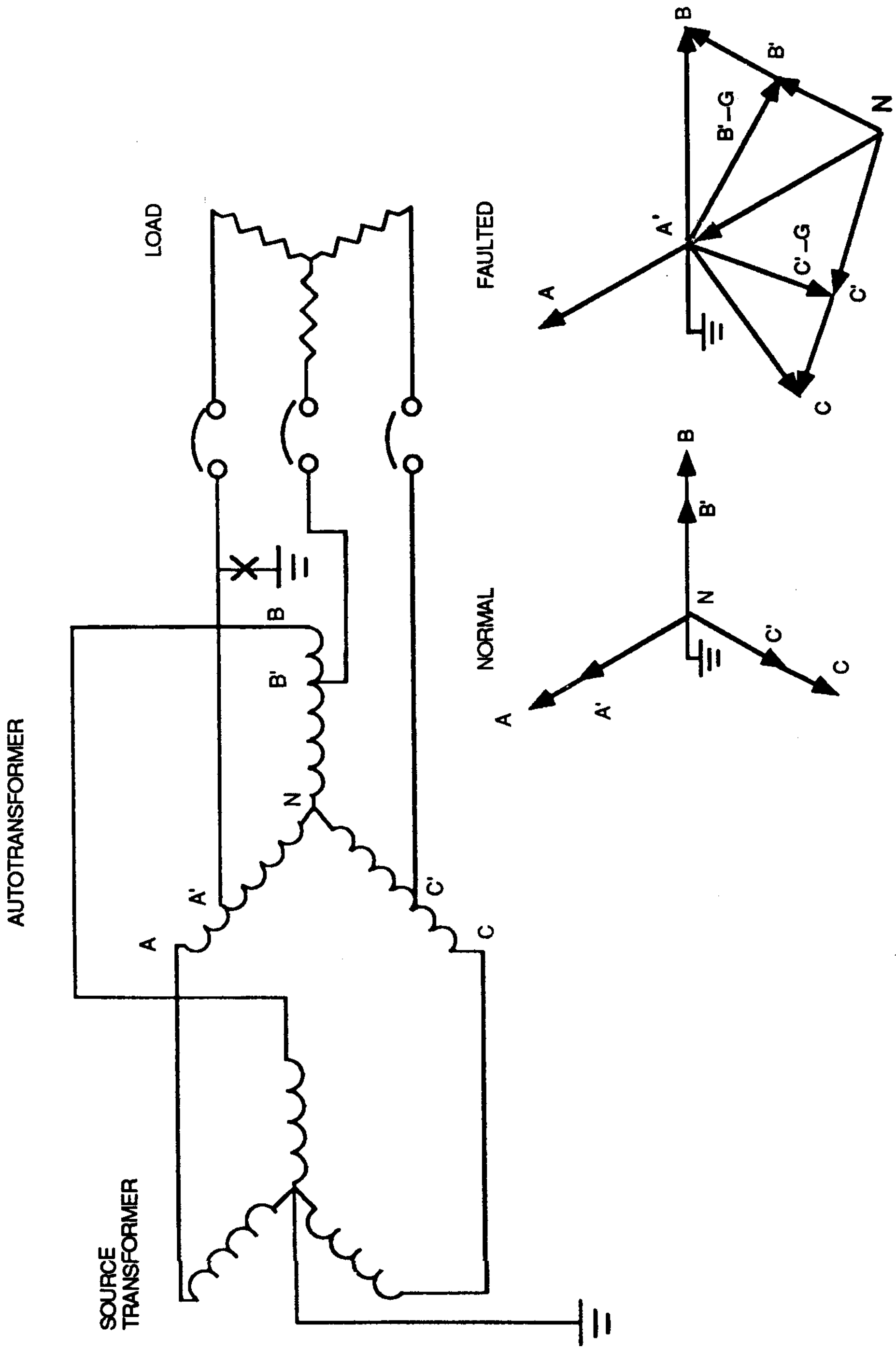


Figure 18—Ungrounded Wye Step-Down Autotransformer Normal Phasor Relations

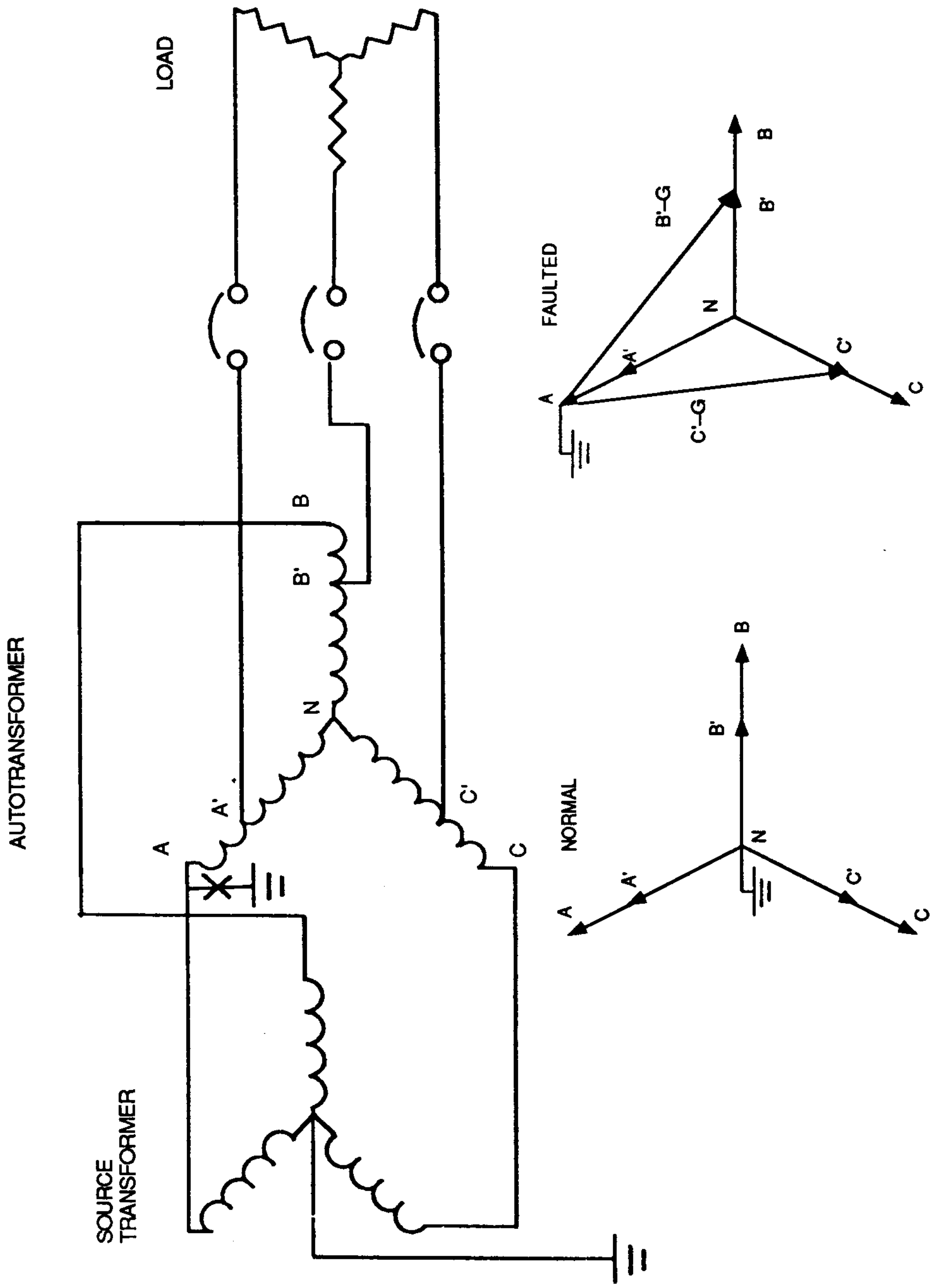


Figure 19—Ungrounded Wye Step-Down Autotransformer Phasors with Primary Ground Fault

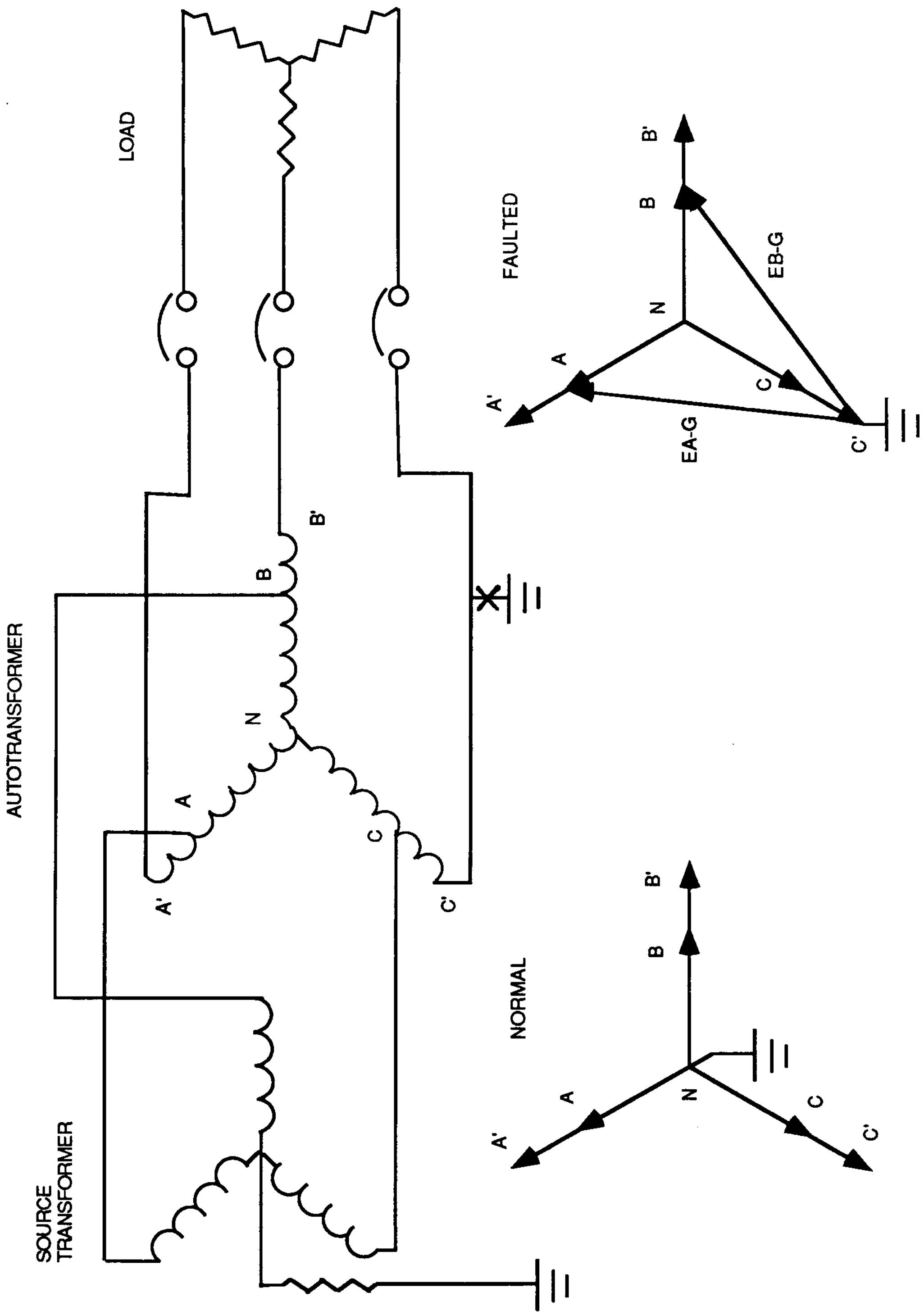


Figure 20—Ungrounded Wye Step-Up Autotransformer Normal and Fault Phasors

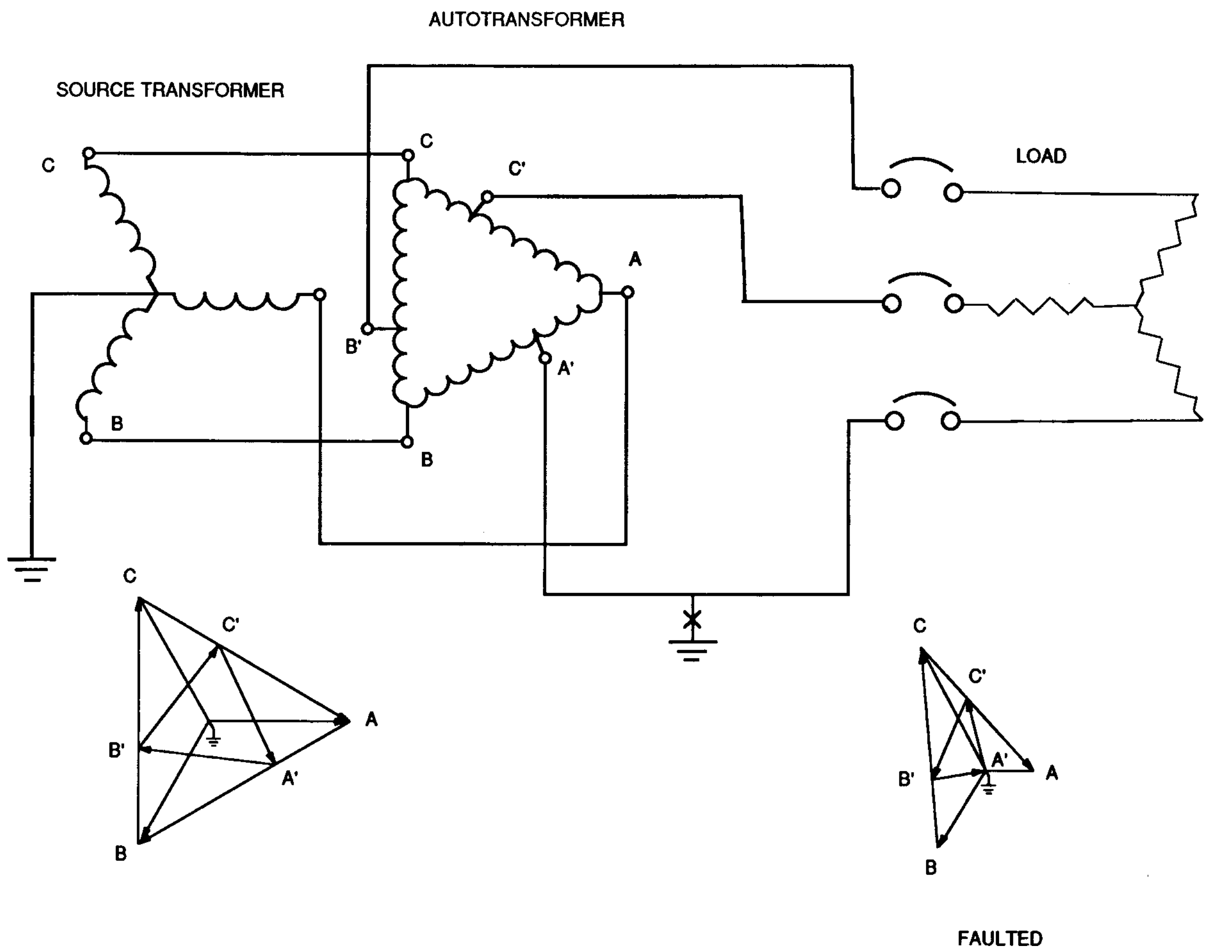


Figure 21—Delta Autotransformer

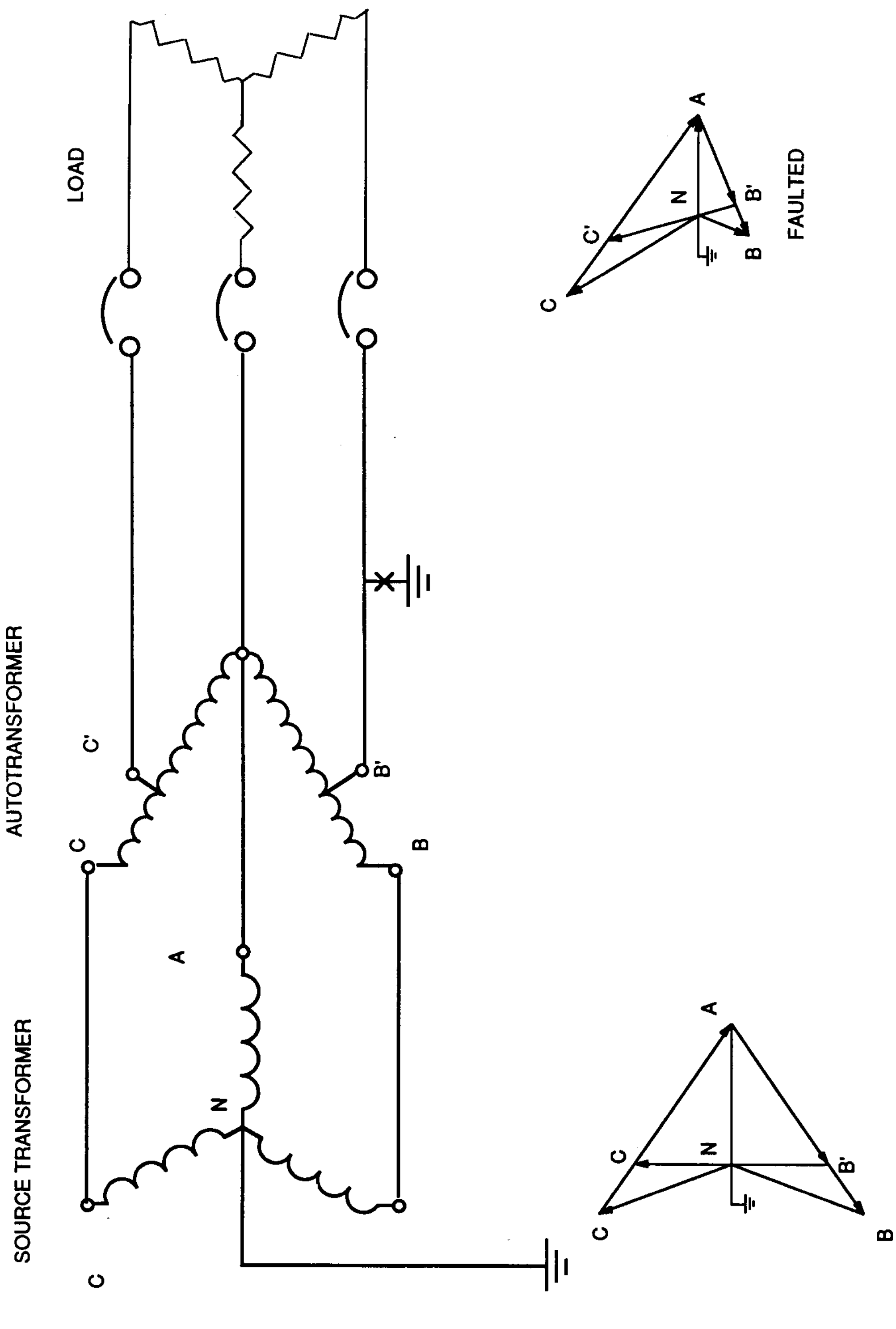


Figure 22—Open Delta Autotransformer

1.10.2 Wye-Wye Transformers

The wye-wye transformer is shown in Fig 24 with the primary and secondary neutrals interconnected and grounded. This transformer configuration is used on solidly grounded utility distribution systems, particularly underground systems, to prevent ferroresonance when the supply switches can be operated one pole at a time. The utilities ground the primary neutral point to minimize the neutral-to-earth voltage throughout the length of the distribution line and by default on underground systems using bare concentric neutral cables. They ground the secondary neutral to provide an effectively grounded low-voltage service. Note. that this multiple grounding of the primary at each transformer is not essential to prevent ferroresonance or provide secondary grounding as long as the fourth conductor is brought to the primary neutral of the transformer. The-neutral-to-transformer case and ground connection minimizes secondary neutral-to-ground voltage during a fault between primary and transformer case.

In an industrial distribution system, the physical length of the circuit will usually be short enough so that excessive neutral-to-ground voltages will not be present even if the transformer common neutral is not grounded. Section 250-23 of the NEC [1] normally prohibits grounding of the neutral on the load side of the service disconnect, but Section 250-152(2) allows multigrounding of the neutral of an outdoor overhead line or direct burial cable with bare neutral if the circuit voltage is over 1000 V.

With a continuous connection from the source neutral to the primary and secondary neutrals of the wye-wye transformer, the output of the transformer would not constitute a separately derived system as defined in Section 250-5(d) of the NEC [1]. If the neutral is grounded at the source, the output of the wye-wye transformer will be a continuation of the grounded system, though at the secondary voltage of the transformer. It is quite similar in performance to the autotransformer shown in Fig 25 except that it provides the added safety of having the only metallic connection between primary and secondary at the neutral point.

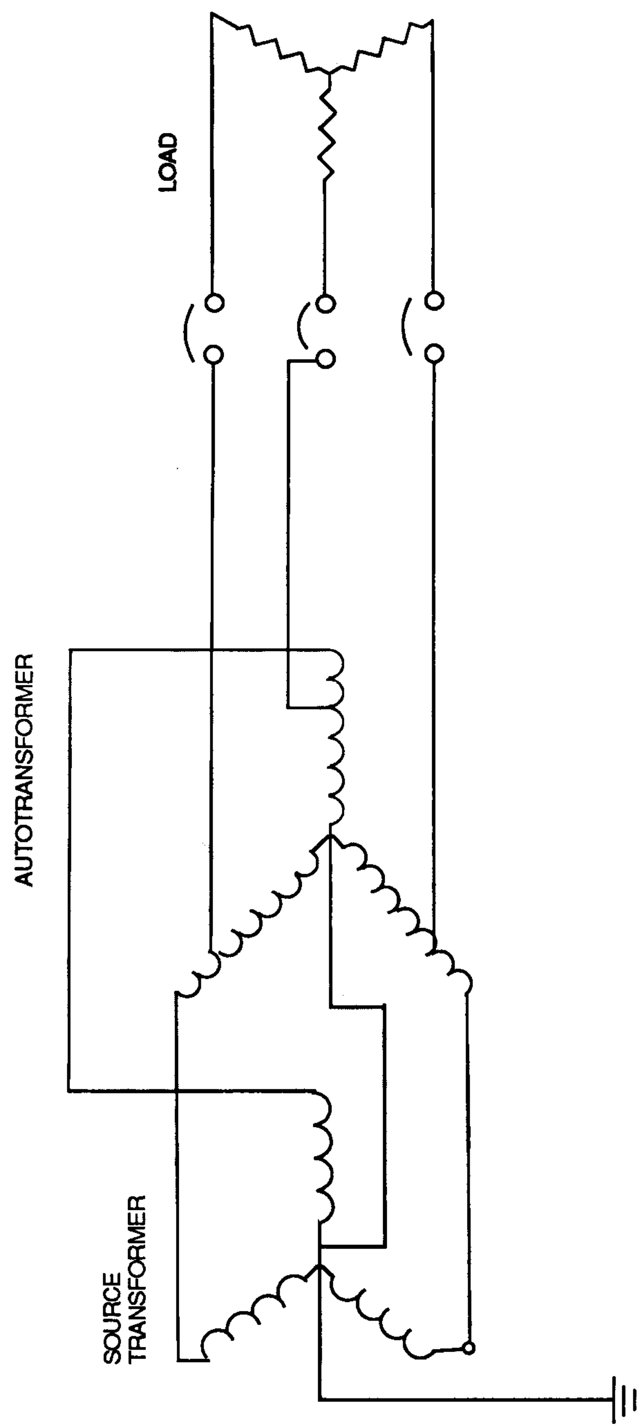


Figure 23—Wye Autotransformer Grounded Neutral Four-Wire Connection

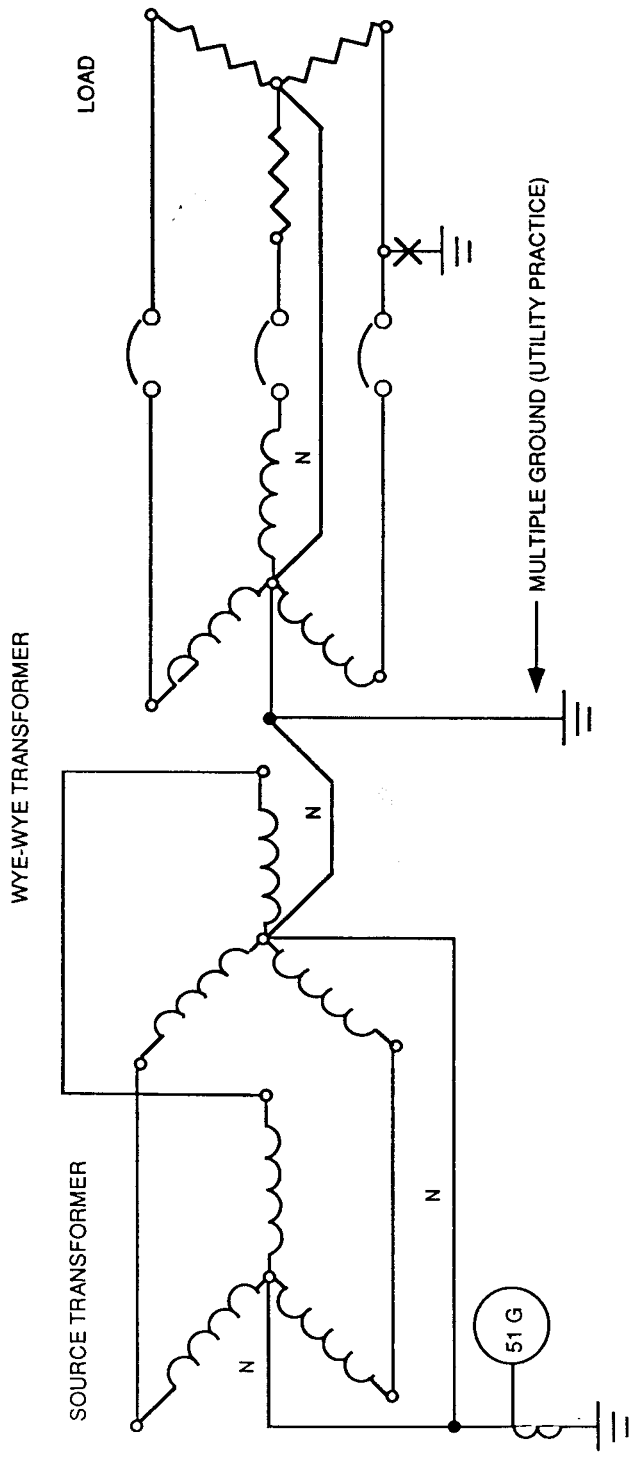


Figure 24—Grounded Wye-Grounded Wye Transformer Multigrounded Common Neutral

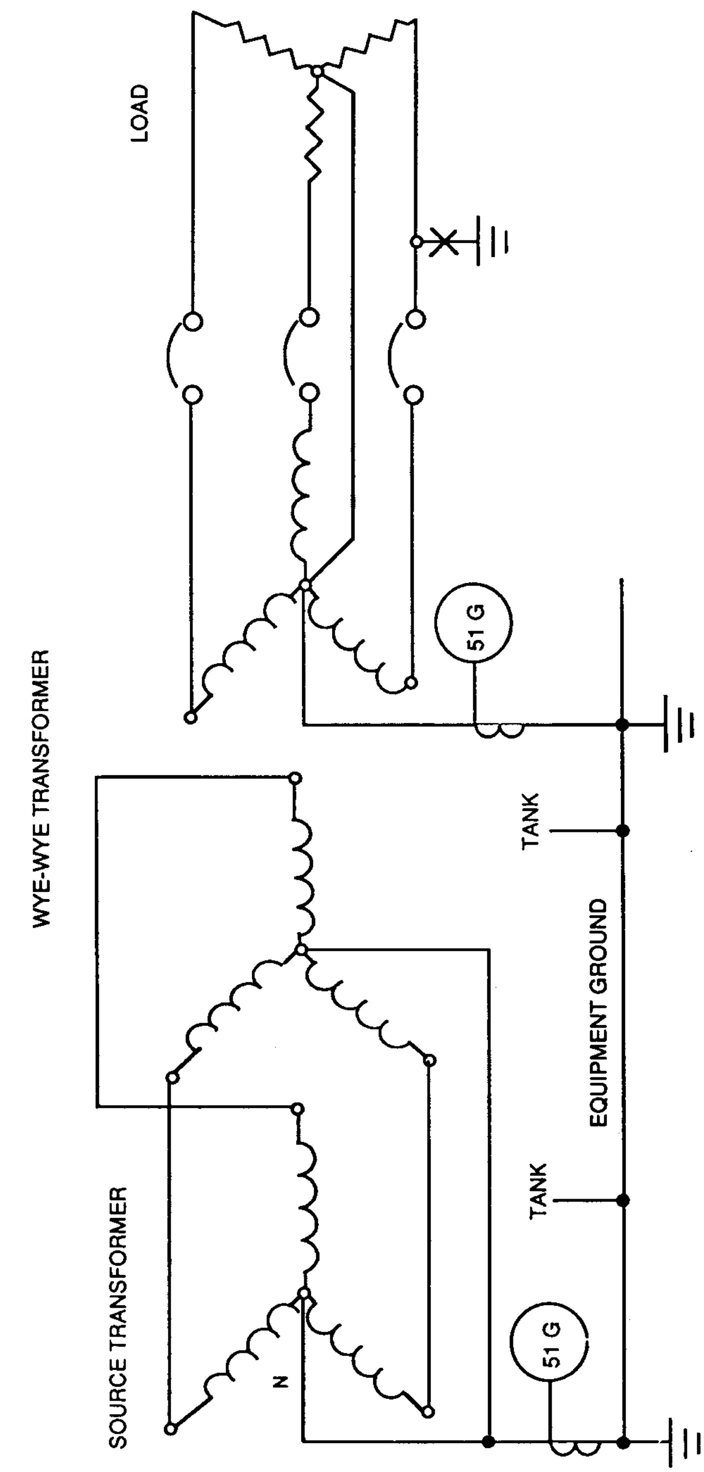


Figure 25—Grounded Wye-Grounded Wye Transformers Separately Grounded Neutrals

The circuit supplied by the wye-wye transformer shown in Fig 25 should be considered a separately derived system, since there is no direct metallic connection between primary and secondary of the transformer. Primary and secondary ground faults are separately measured and relayed. The output of the secondary will not be grounded unless a connection to earth is made from the secondary of the transformer. The secondary could be impedance grounded. Secondary neutral grounding will also require a connection from the neutral of the primary source to the primary neutral of the wye-wye transformer to supply zero-sequence current. Unlike the delta-wye transformer, the wye-wye transformer itself is not a source of zero-sequence current. Grounding can be achieved without a primary neutral connection if a phase of the secondary rather than the neutral is grounded, since no zero-sequence current is involved. The effect is then identical to corner grounding of a delta-delta transformer.

If a delta tertiary is added to a wye-wye transformer it will not be necessary to supply zero-sequence current from the primary source, since the tertiary will act as a source of zero sequence current.

Thus, the wye-wye transformer can be considered a part of a single multi-voltage system if the neutrals are interconnected or can be considered to create a separate system if they are not. The symmetry of the wye-wye allows it to provide grounding for its load-side system even though the source and load side may be interchanged at any time.

1.10.3 “Resonantly” Produced Voltages

This term is applied to the voltage that will appear at the junction between reactances of opposite sign connected in series even though the reactances may not actually be resonant at the supply frequency. The variance of the voltage with respect to the supply voltage will be a function of how close the elements are to resonance and the ratio *(Q)* of inductive reactance to the resistance.

A common instance is the use of series capacitors on low power factor loads where random switching or other variations create objectionable voltage excursions. Fig 26 represents the circuit of a spot welder whose inductance is fixed by the dimensions of the machine but whose resistive load can be varied. With full power-factor correction, the voltage rise across the capacitor will be 1.732E at 0.5 power factor and 4.9E at 0.2 power factor. With the ground fault as shown, this 4.9E across the capacitor will be impressed between the source transformer and ground. Both the transformer and its grounding impedance will be subjected to overvoltage. For this reason, such series capacitors should be used only on effectively grounded systems, which will limit the voltage rise to safe values.

A more commonly observed series reactance circuit is created when a capacitive load is connected, usually for power factor and/or voltage correction. Since these capacitors are in series with the source reactance of the power system, the voltage is caused to rise. The voltage rise caused by the normal size of power factor capacitors would not be expected to exceed 5%–10% under the worst conditions, since the system is not approaching resonance at the fundamental power frequency. This is not a different voltage class and does not present a hazard. Its discussion here is only to present a familiar example of reactances in series.

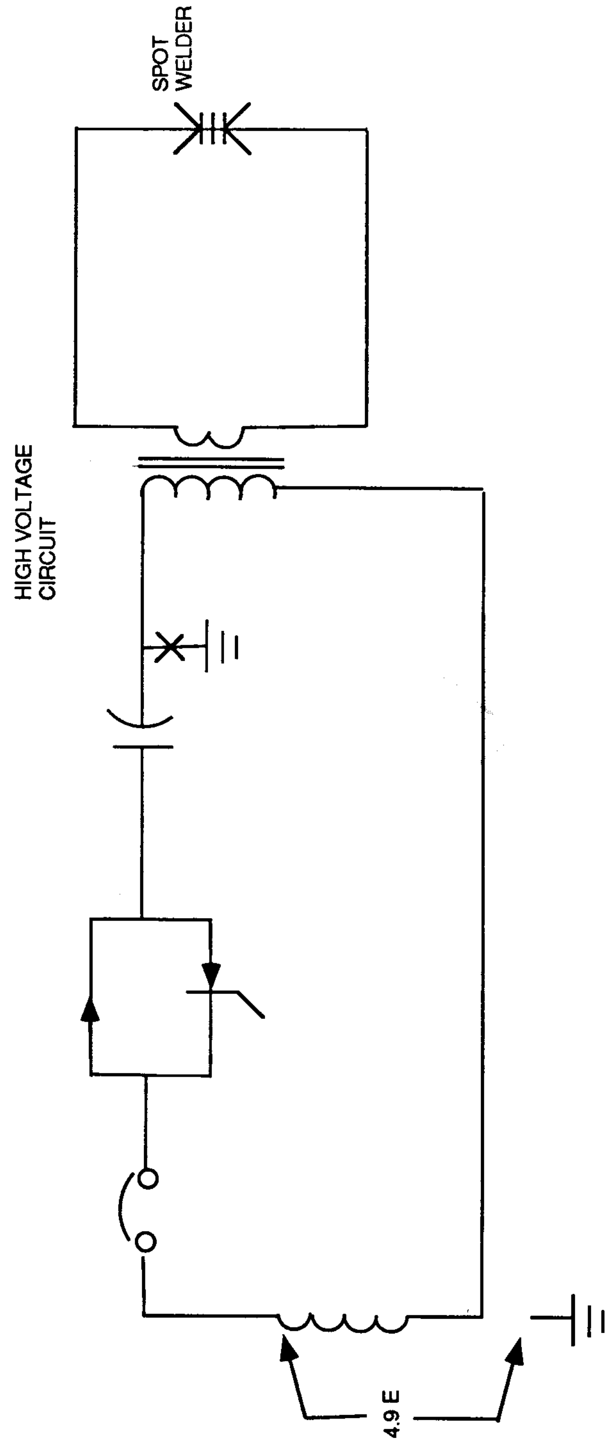


Figure 26—Series Capacitor Resistance Welder

Resonance can be achieved by the addition of power factor capacitors at multiples of the power system frequency. When there are sources of harmonics, such as nonlinear loads, the resulting harmonic voltages can be raised by a resonant condition. Such voltages would not normally reach hazardous values. A hazardous level, should it occur, would be rapidly reduced by overcurrents in the capacitors causing failures or fuse operations, thus detuning the circuit.

Impulse voltages can be amplified and extended as damped oscillations (ringing) by resonant circuits. These voltages can exceed insulation capabilities.

Resonant conditions prone to continuous oscillation due to lack of resistive loading (damping) can be triggered by switching or by system failures. The most common example is that created by single-phase switching of transformer primaries when there is no secondary load. This produces the “ferroresonant” condition where the excitation impedance of the transformer interacts with the capacitance of the primary cable.

These resonantly produced voltages are not considered as system, or useful, voltages, with the exception of the resistance welder application. Thus, they do not create multi-voltage systems, but are discussed here so that they might be avoided. With the exception of increasing the impulse capability of the insulation, the main defense against these voltages is suppression.

There are other situations where high voltages can be produced by inadvertently created resonant conditions. These are usually the result of insulation, equipment failures, or unintended circuit configurations. The voltages are more extreme if conditions at or close to resonance are achieved. When the inductive element has an iron core, the inductance can vary when the iron is saturated due to the high voltage, which at the same time causes nonsinusoidal current with resulting harmonics. This can result in arriving at a resonant condition referred to as “ferroresonance.” These are not “system voltages” as have been discussed in the preceding paragraphs, since they are unintended and may be transitory in nature.

In some cases, occurrence of these voltages can be affected or eliminated by the grounding design, but such changes in voltage also may involve choice of transformer design or performance of switching devices. A common cause of ferroresonance is the impressing of voltage across a transformer winding and a conductor capacitance to ground, the conductor having been disconnected from its normal source. If the transformer is wye connected, grounding of the neutral will usually prevent voltage being impressed across this series connection. A resonant condition produced by a grounded coil acting in series with the line-to-ground capacitance of an ungrounded system can be alleviated if the capacitance is shunted by grounding the system.

1.11 Portable Mining Equipment Supply Systems

The concept of protecting mine electrical equipment and personnel by suitable grounding has existed since electricity was first introduced into mines. As early as 1916, the U.S. Bureau of Mines recommended equipment frame grounding as a means of preventing electrical shock to miners working on or around electrical equipment [13]. Adequate grounding has been a difficult problem for the mining industry, sometimes more complex and challenging than for other industries. Hazards associated with ground faults are amplified by the portable and mobile nature of these power systems, and system and equipment grounding are interrelated. A surface-mine machine can have a substantial power demand (e.g., 18 000 hp) at potentials up to 25 kV or greater. The power demand of an underground mining machine can exceed 1100 hp at potentials up to 4160 V. The portable equipment must be designed to permit personnel to approach (and touch) apparatus structures without risk of electric shock. This section will emphasize the grounding aspects of the supply system, whereas 2.6 will cover related equipment-grounding information. Reference [22] provides extensive details about both subjects.

A simplified arrangement of a mine power system is shown in Fig 27. Sub-stations are employed to transform the incoming utility voltage to a distribution level. Mine distribution is almost always expanded radial, and overhead lines (surface mines) or cables (surface and underground mines) are used to supply switchhouses (portable switchgear) located near load concentrations. In typical underground mines, switchhouses are connected via portable cables to portable power centers, which supply lower voltage through trailing cables to the utilization equipment (e.g., continuous miners, longwalls, load-haul-dump units, etc.). In surface mines, large utilization equipment, such as shovels and draglines, are often powered at the distribution voltage, and a trailing cable completes the power circuit from the switchhouse to the machine. (As with underground mines, portable substations or power centers are used when distribution and utilization levels are different.)

The recommended grounding technique for these portable or mobile equipment applications is a safety ground system that employs resistance grounding. Fig 27 illustrates the concept (overload and short-circuit protection are not shown for clarity of the grounding systems and associated protective relaying). The substation contains two separate ground beds, maintained some distance apart. Substation surge arrestors, fencing, and equipment frames are tied to the system ground bed, typically located under the substation area. The substation transformer is either delta-wye, delta-delta, or wye-delta connected (wye-wye is not recommended), and the secondary neutral (direct or derived) is tied to the safety ground bed through the neutral grounding resistor. Each ac equipment frame in the distribution system is connected via grounding conductors to the safety ground bed. The station bed is intended to handle lightning, other transformer-primary surge conditions, and primary-system line-to-ground faults. The purpose of the safety bed is maintaining equipment frames at near earth potential, and a low bed resistance is important so dangerous potentials are not developed on machine frames. Separation between the system and safety ground beds is needed to isolate high system-ground voltage rise (a temporary rise of 5 kV or more is not unusual) from the bed. This resistance is recommended as 5.0 Ω or less (see [20] and [19]). It is not unusual to find that a much greater distance is required to provide needed separation [16]. The design of these ground beds is complex, and many variables must be examined to derive an optimum configuration (see [15] and [14]). The references cited in this paragraph should be consulted. IEEE Std 367-1987 (ANSI) [4] also contains important information about ground-bed separation in regard to the influence of a ground potential rise of a ground electrode.

At each transformation step within the distribution system, such as in a portable power center, an additional neutral point is established at the transformer secondary. The neutral is tied through a grounding resistor to the equipment frame and, thus, via the grounding conductors to the safety ground bed.

Because of the extensive use of cable distribution and the attendant capacitance from line to ground, ground-fault current limits are higher than that which was recommended for high-resistance grounding earlier in this chapter. United States practice specifies a different maximum current limit depending on the system voltage. When the system voltage is greater than 1000 V, ground current is limited so frame potentials within that system portion do not exceed 100 V during ground-fault conditions. For practical purposes (assuming a 2 Ω grounding-conductor impedance), this restricts the maximum ground-current limit to not more than 50 A; however, most substations serving mines use a 25 A ground-current limit. For power-system segments at or below 1000 V, the ground-current limit must be 25 A or less, but typical practice is 15 A (also see 2.6). Distribution and utilization (mining) equipment in surface mines is typically greater than 1000 V. Underground-mine distribution is almost always greater than 1000 V, whereas mining equipment is usually 1000 V or less.

Correct selection and coordination of protective circuitry are essential to the safety ground system. Regardless of where a ground fault occurs, ground-fault current is primarily limited by the grounding resistor, and selective coordination at each voltage level by the pickup setting alone is normally impossible. The common ground-fault relaying pickup is 40% of the ground-current limit, and time settings are relied on for multistage protection. Regulations should be consulted before selecting specific ground-fault protection schemes. (See [22] and [11].) A typical relaying arrangement is included in Fig 27 [22].

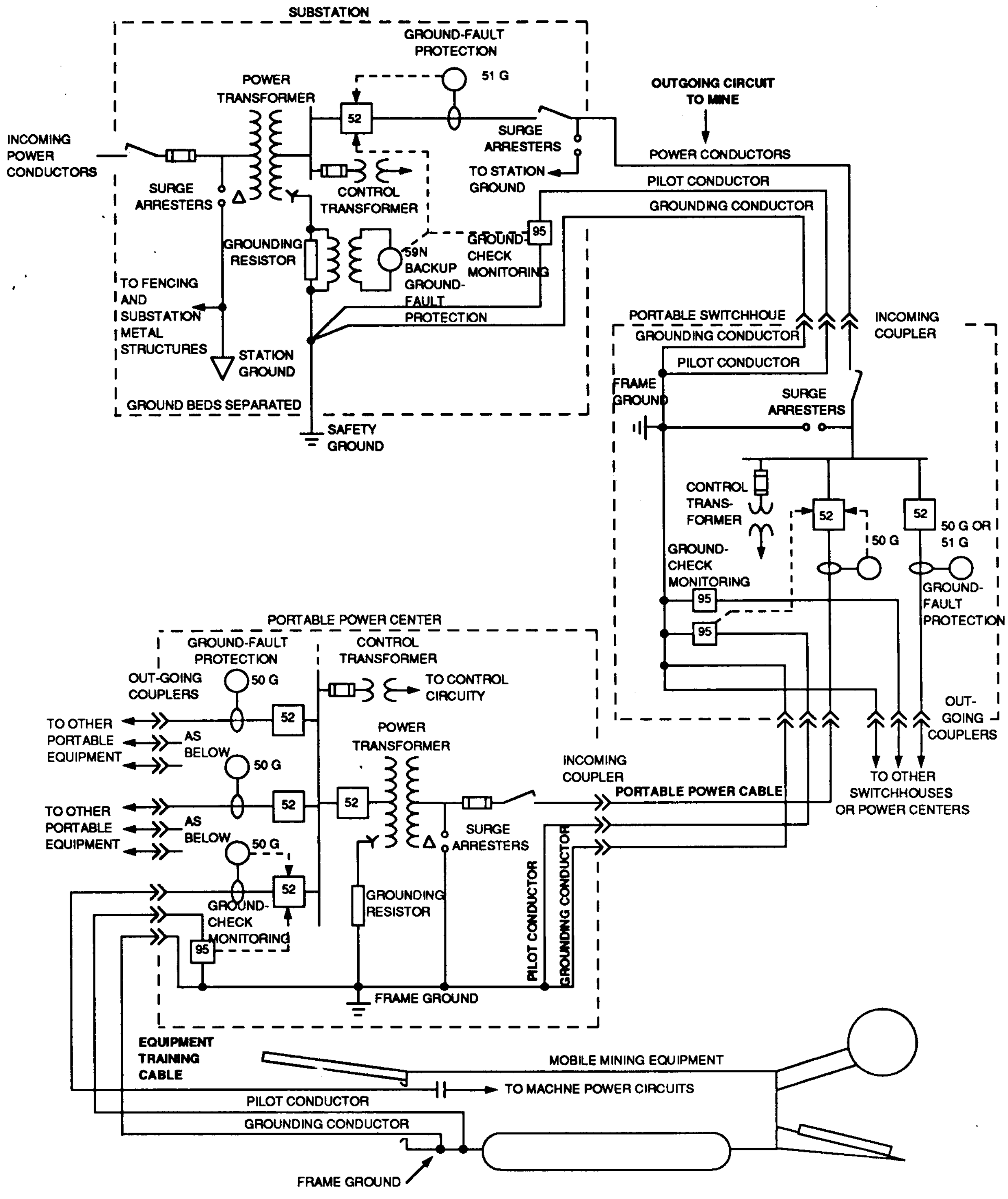


Figure 27—A Simplified Mine Power Distribution System with a Safety Grounded System (Overcurrent and Short-Circuit Protection Schemes Are Omitted for Simplicity)

Zero-sequence relaying (usually instantaneous) establishes primary ground-fault protection for the utilization circuit. Although not shown, back-up protection may also be employed (or required) here by adding a time-delayed zero-sequence relaying at the secondary of the power-center transformer or potential relaying about the grounding resistor. For the distribution system, primary ground-fault protection in the switchhouse establishes a zone of protection for each outgoing circuit; again zero-sequence relaying (instantaneous or minimum time-dial setting) is typically used. Time-delayed zero-sequence or residual relaying in the substation gives both back-up protection for downstream relaying within the distribution safety ground. United States federal regulations specify separation by distance; for example, a minimum of 25 ft (7.6 m) and a “low resistance” for each system and primary ground-fault protection for the zone between its location and the switchhouse. The potential relaying shown about the grounding resistor also provides back-up protection (both relays are sometimes required in the substation). In order for the safety ground system to be effective, grounding conductors must be continuous, and ground-check monitors (relays) are used to verify continuity. Pilot conductors are shown with each monitor, but these are not needed in instances where pilotless relays are applied. All these sensors act to trip the associated circuit interrupter and remove all power to the affected system segment.

The correct operation of the safety ground system relies on three concepts.

1) The earth cannot be used as a grounding conductor.
2) The grounding system serving portable and mobile equipment must be kept isolated.
3) Ground-fault protection must be provided on each outgoing circuit from the substation.

These criteria are sometimes difficult to achieve when other loads are being supplied from a mine substation transformer, such as preparation plants and ventilation fans. Regardless, each is particularly important when an underground mine is connected to the substation. To ensure grounding-system integrity, it is best that underground mine distribution be fed from a separate transformer secondary winding.

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