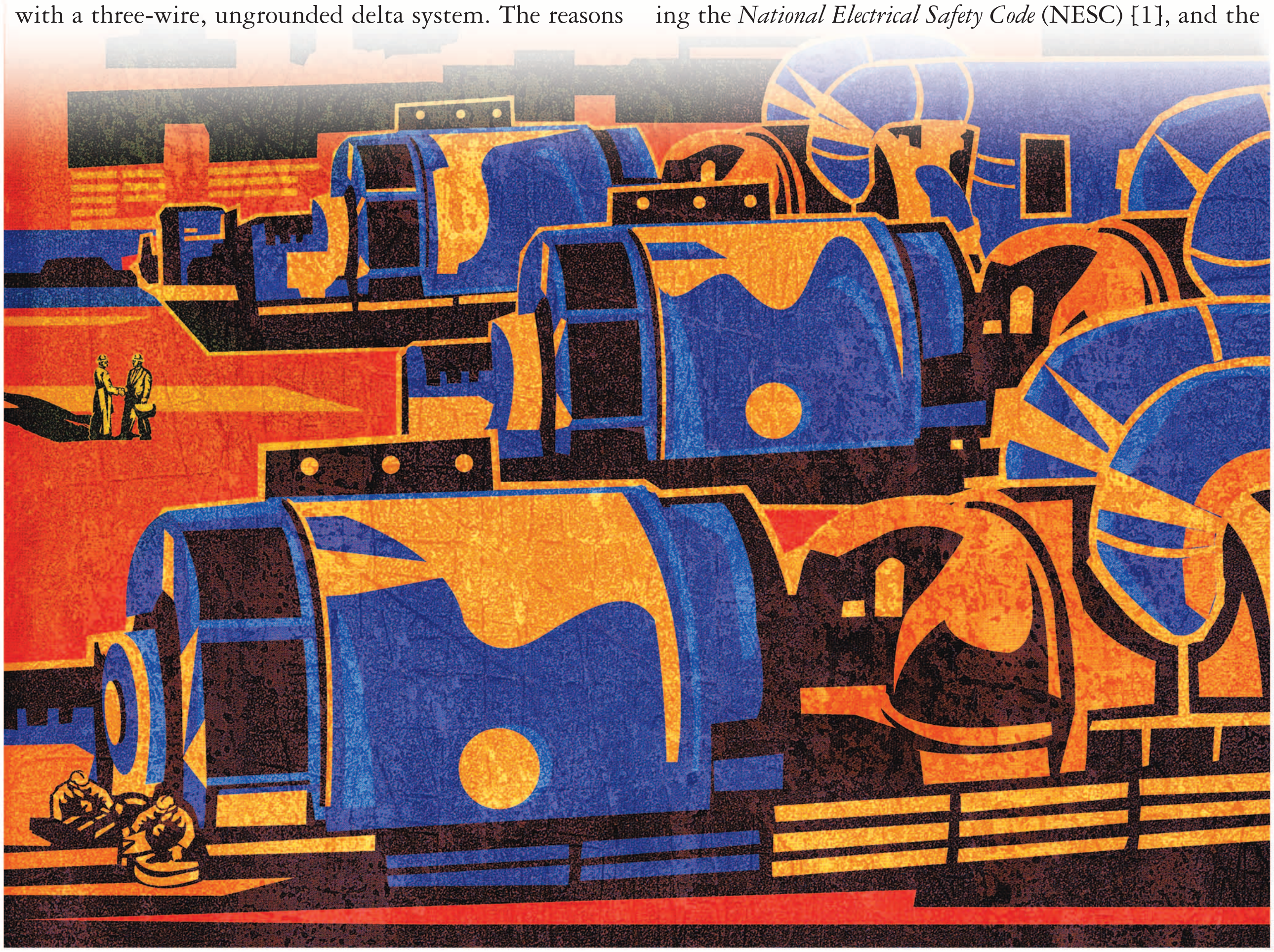
GROUNDING POWER SYSTEMS ABOVE 600 V

A practical viewpoint.

BY JOHN P. NELSON

THE THREE-PHASE, FOUR-WIRE, multigrounded distribution system has been selected by most utilities in North America as the medium-voltage distribution system of choice, even though many utilities started with a three-wire, ungrounded delta system. The reasons for the development of the three-phase, four-wire, multigrounded systems involve a combination of safety and economic considerations. The three-phase, four-wire multigrounded design has been successfully used for many years and is well documented in standards, including the *National Electrical Safety Code* (NESC) [1], and the



1077-2618/06/$20.00©2006 IEEE

National Electrical Code (NEC) [2]. Have there been problems associated with this system? Yes. Are there reasonable solutions available to minimize these problems? Absolutely! Should the use of the multigrounded system be eliminated? This article will show that the answer to the last question is absolutely not.

The earth is an electromagnetic circuit, with north and south magnetic poles and with an ionosphere made up with charged particles. During electromagnetic storms caused by sunspot activity, observations have been made showing potential gradients (stray voltages) on the earth's surface of 1–10 V/km [3]. These voltage gradients have occurred since the origin of the earth and will continue to occur in the future. Man and animals have lived with these stray voltages and associated stray currents with no apparent adverse reactions. And, if found that there were hazards associated with them, there is little that can be done about stopping it at its source, the sun. Therefore, we live in a world where stray voltages and stray currents are natural.

Next, there are many hazards associated with the generation, transmission, and distribution of electricity. The following is a list of a few of those hazards:

- contact with energized parts
- electrical arc flashes
- auto accidents involving power poles
- drowning in water associated with hydroelectric plants
- illness and deaths from the gases emitted from coal and oil-fired generation plants
- auto accidents involving trains transporting coal to electric generating stations.

The risks associated with these hazards are minimized with sound engineering, construction, and maintenance practices. The benefits of safely using electricity far outweigh the risks involved in its generation, transmission, and distribution. Rather than outlawing the use of electricity due to its inherent hazards, engineering standards and designs have been developed to minimize the hazards and to mitigate the problems to a level of acceptable risk.

Acceptable Risks

To explain the term "acceptable risk," let us consider a common everyday risk. Each year, over 50,000 lives are lost due to automobile accidents in the United States. Throughout the world, that figure is most likely higher, but few people would agree that saving those 50,000 lives is worth outlawing automobiles. Statistically speaking, every person in the United States has approximately a one in 5,000 chance of dying in an automobile accident in any given year. We consider that probability an "acceptable risk."

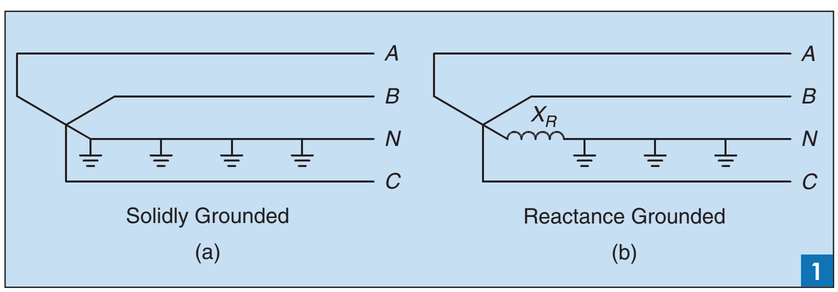
Another similar statistic is that in 2001, 491 people across the United States died in train-vehicle collisions [4]. Many more were injured at rail crossings. Using similar statistical calculations, on the average, a person has a one in 500,000 chance of being killed in a car-train collision. The number of such deaths could be drastically reduced, if not eliminated, by eliminating railroad crossings. This could be accomplished by constructing expensive overpasses at each rail crossing. Safety crossings can be installed at approximately US$180,000 each and bridges at US$4 million. In Colorado alone, there exist 1,368 rail crossings that are not equipped with any type of warning device [5]. The cost to implement better safety measures for those 1,368 rail crossings is estimated to be US$246 million to place warning signals at each of those crossings or US$5.47 billion to place bridges at all of those crossings. And Colorado only accounts for 1% of the fatalities in the United States [4]. While 19 fatalities occurred in Colorado from 1999 to present, Texas was Number 1 in the nation, with 161 deaths, and California had 122 recorded fatalities. While those numbers of fatalities are alarming, they show that there are risks to people and we accept those risks in our everyday life. There are many other examples of similar risks, including being struck by lightning, being involved in an airplane crash, and many others. The chances of being injured or killed in such an accident in any given year is part of life, will never be totally eliminated, and is considered an "acceptable risk."

System Grounding

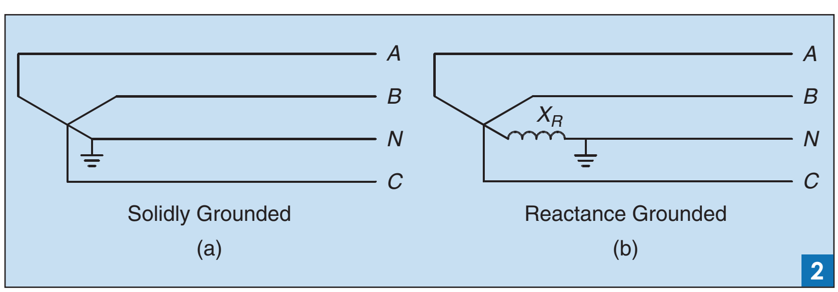
System-neutral grounding of a distribution system takes on one of several forms:

- solidly grounded
- reactance grounded
- resistance grounded
- ungrounded.

While there is always an exception, for all practical purposes, a neutral conductor is not required for the resistance grounded or ungrounded system due to the



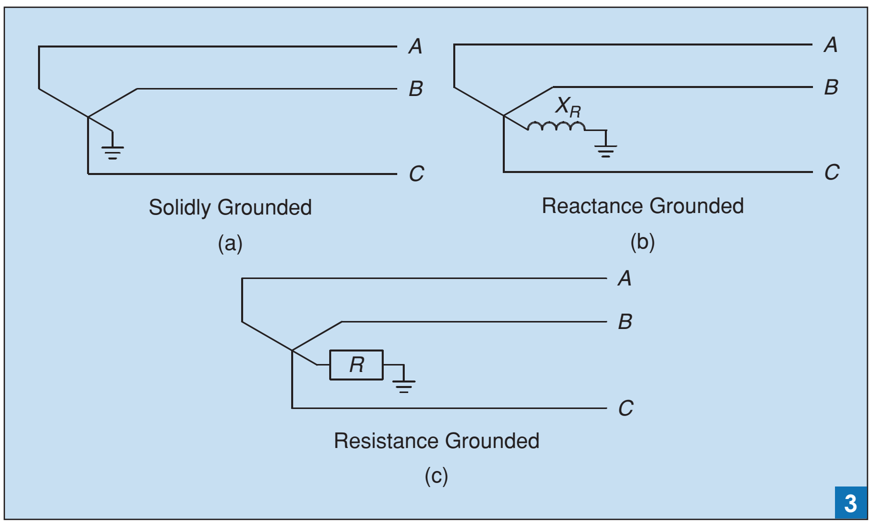
Four-wire multigrounded neutral system (solid and reactance grounded).



Four-wire single point grounded-neutral system (solid and reactance grounded).

fact that no neutral current is expected to flow. Therefore, only limited discussion of those two systems will be included. That leaves the solidly-grounded and reactance-grounded systems that will be discussed in greater detail in this article. The latter two systems can have a single-point grounded or multigrounded neutral. In general, the systems shown in Figures 1–5 are the options available for use.

Figure 1 depicts the multigrounded neutral system for the solidly grounded and reactance grounded systems commonly used by electric utilities in North America. The neutral-grounding reactor is used by some utilities to reduce the available ground-fault current while at the same time maintaining an effectively grounded system. The NESC provides a definition for an "effectively grounded system":



Three-wire, single-point grounded system without a neutral (solid, reactance, and resistance grounded).

> An effectively grounded system is intentionally connected to earth through a ground connection or connections of sufficiently low impedance and having sufficient current carrying capacity to limit the buildup of voltages to levels below that which may result in undue hazard to persons or to connected equipment [1].

There are other, more technical issues of an effectively grounded system that will be discussed later in this article.

Figure 2 is different from Figure 1 in that the system neutral is grounded only at one point. The ground connection would typically be located in the distribution substation.

Figure 3 shows the connections for a solidly grounded, reactance-grounded, and resistance-grounded three-phase, three-wire system.

Figure 4 shows a three-wire ungrounded delta system, and Figure 5 shows a three-wire ungrounded-wye system. For personnel and equipment safety, neither of these two systems is currently recommended for modern-day systems. Some still exist, but very few are currently designed and constructed as an ungrounded system.

The differences between the multigrounded systems in Figure 1 and the single-point grounded systems shown in Figure 2 may appear insignificant, but the safety and economic differences are significant, as will be explained in more detail later.

The three-phase, three-wire systems shown in Figure 3 are commonly used in an industrial power system. Industrial power systems typically have a large number of three-phase motors and have no need for neutral-connected loads. Therefore, industrial users will usually dispense with the need for the fourth-wire neutral.

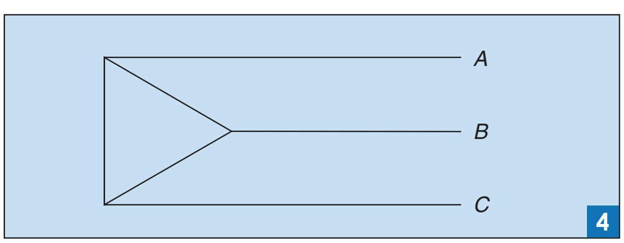
Safety and Code Considerations

The multigrounded system is referenced in both the NESC and the NEC. The NEC requires single-point grounding on low-voltage systems (600 V and below). However, the NEC allows the use of a multigrounded system for voltages above 600 V. On the other hand, the NESC is quite specific that a three-phase, four-wire system must have a multigrounded neutral. Otherwise, the required clearances may need to be increased to that of an ungrounded system. Furthermore, a single-point grounded neutral can no longer be considered effectively grounded, can have a substantial voltage present, and may need to be isolated by using additional clearances.

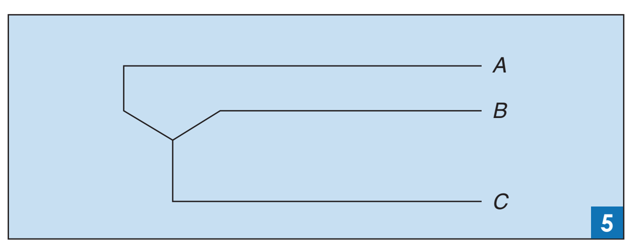
Code and safety considerations include:

A. *NESC Section 096.C: Multi-Grounded Systems:*

> The neutral, which shall be of sufficient size and ampacity for the duty involved, shall be connected to



Three-wire, ungrounded delta connected transformer.



Three-wire, ungrounded-wye connected transformer.

a made or existing electrode at each transformer location and at a sufficient number of additional points with made or existing electrodes to total not less than four grounds in each 1.6 km (1 mi) of the entire line, not including grounds at individual services.

B. *NEC Article 250 Part X Grounding of Systems and Circuits 1 kV and Over (High Voltage) Section 250.180 (B) Multiple Grounding:*

The neutral of a solidly grounded neutral system shall be permitted to be grounded at more than one point [2].

C. *250.180 (D) Multigrounded Neutral Conductor:*

- ground each transformer
- ground at 400-m intervals or less
- ground shielded cables where exposed to personnel contact

D. *Safety Concerns on Cable Shields:*

Medium- and high-voltage cables typically have cable shields (NEC requirement above 5 kV) that need to be grounded. There are several reasons for this shield: [6]

- to confine electric fields within the cable
- to obtain uniform radial distribution of the electric field
- to protect against induced voltages
- to reduce the hazard of shock.

If the shield is not grounded, the shock hazard can be increased. With the shield grounded at one point, induced voltage on the shield can be significant and create a shock hazard. Therefore, it is common practice to apply multiple grounds on the shield to keep the voltage limited to 25 V. This practice of multigrounding cable shields includes the grounding of concentric neutrals on power cables thereby extending the need for multigrounding of neutrals on the power system.

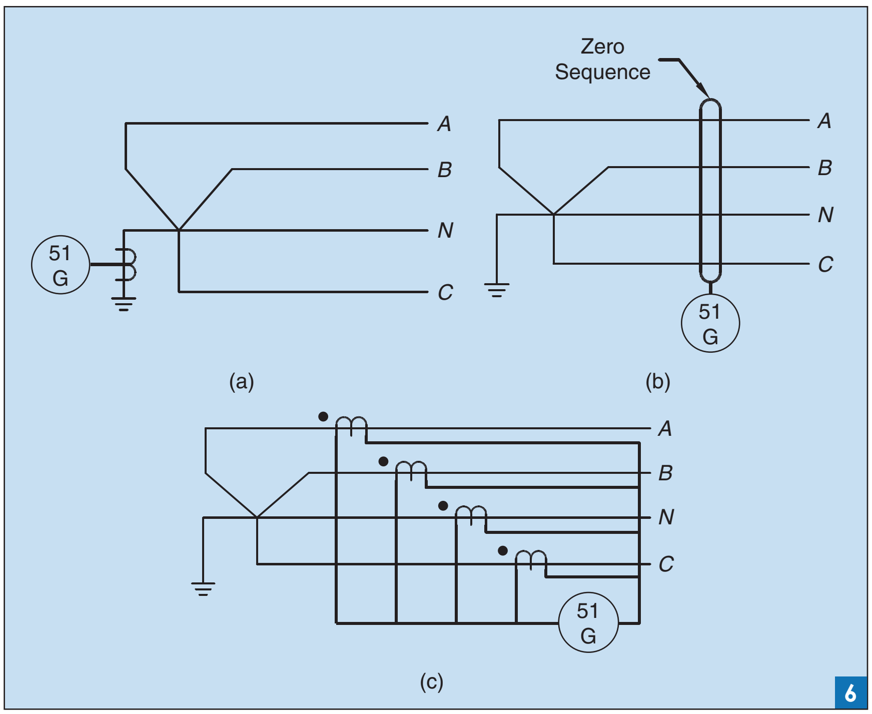
Protective Relaying Considerations

Protective relays need to sense abnormal conditions, especially those involving a ground fault. The single-point grounded system, with or without a neutral conductor, provides the easiest method for sensing ground faults. Any current flowing into the ground should be considered abnormal (excluding normal charging current). Three means of sensing ground faults are:

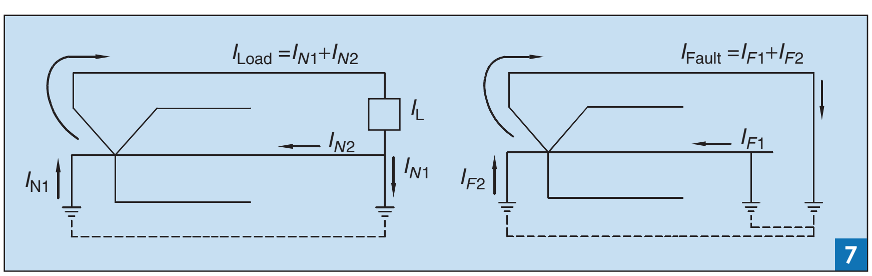
- A current transformer (CT) in the location where the neutral is grounded can be used to sense the ground fault (zero sequence) current [Figure 6(a)].
- A zero-sequence CT enclosing the three-phase and neutral conductors [Figure 6(b)].
- Four CT residue circuit (Three CT residual with neutral CT cancellation) [Figure 6(c)].

Protecting against ground faults on a multigrounded neutral system is more difficult than the single point grounded system, since both neutral and ground-fault currents must be considered. Neutral current and, likewise, ground-fault current can flow in both the neutral and the ground. So, consideration must be given to the amount of neutral current that may flow in the circuit, and the ground fault setting must be above this neutral current. This is self-explanatory from Figure 7.

While the sensing of the ground-fault current in the single-point grounded system is less complex than in the multigrounded system, the amount of ground-fault current on the single-point grounded system may be greatly limited due to the fact that all ground-fault current must



Ground current sensing. (a) Current transformer in ground. (b) Zero sequence CT including neutral. (c) Residual current with neutral cancellation.



Current distribution in multi-grounded system. (a) Neutral current flowing in neutral and ground. (b) Ground-fault current flowing in the neutral and ground.

return through the earth. This is especially true where the earth resistivity is high, the soil is frozen, or the soil is extremely dry. Therefore, the multigrounded neutral system imcreases the probability of sensing a ground fault under all conditions and, therefore, provides more and more reliable, and, thus, safer, means of isolating ground faults from the system.

Earth Resistance and Reactance

Early research by Carson and others into the development of transmission line impedances showed that the earth resistance, R_e, is frequency dependent and earth resistivity independent [7], and (1) shows this relationship.

$$R_e = 0.00296\, f \quad \Omega/\text{km}, \tag{1}$$

where R_e = earth resistance in ohms per kilometer.

However, it is interesting to note that the earth reactance is dependent on both frequency and earth resistivity, as seen in (2) and Table 1 [7].

TABLE 1. R_e AND X_e @ f = 60 HZ.

ρ Ω-m	R_e (Ω/km)	X_e (Ω/km)
1	0.178	1.273
5	0.178	1.455
10	0.178	1.533
50	0.178	1.715
100	0.178	1.793
500	0.178	1.975
1000	0.178	2.054
5000	0.178	2.236
10000	0.178	2.314

$$X_e = 0.004338\, f \log_{10}[4.6656 \times 10^6(\rho/f)]\Omega/\text{km}, \tag{2}$$

where

X_e = earth reactance in Ω/km
f = frequency in Hertz
ρ = earth resistivity in Ω-m.

Based on (1) and (2), Table 1 shows R_e and X_e for 60 Hz with various soil resistivities.

Soil resistivity varies considerably by types of soils. See Table 2 [8]. However, it is important to look at two additional aspects for soil resistivity: moisture and temperature.

Soil resistivity of the permafrost is typically in the range of 3,500–4,000 Ω-m [9]. Soil resistivity is temperature dependent, especially once the temperature falls below freezing. For example, clay may have a soil resistivity in the range as low as 15 Ω-m at 10 °C, 20 Ω-m near 0 °C and 1,000 Ω-m at −15 °C. Another example is silt in the Fairbanks, Alaska, area, which has a relatively constant soil resistivity of 300 Ω-m down to freezing to as high as 8,000 Ω-m at −15 °C [10].

The interesting aspect of the previous discussions on soil resistivity can be seen in (3), the resistance of a single ground rod [8].

$$R = \frac{\rho}{2\pi}\left(\ln\frac{4\,L}{a} - 1\right)\ \Omega, \tag{3}$$

where,

L = length of rod (m)
a = radius of rod (m)
ρ = resistivity of soil (Ω-m).

The rod resistance of a 16 mm × 3 m ground rod for varying soil resistivities (10–100,000 Ω-m) is shown in Table 3.

APPENDIX 1—SOIL GROUP SYMBOLS

The following is a list of soil group symbols that were referenced in Table 2: [8]

Symbol	Soil Description
GW	Well graded gravel, gravel-sand mixtures or no fines
GP	Poorly graded gravels, grave-sand mixtures, little or no fines
GC	Clayey gravel, poorly graded gravel, sand clay mixtures
SM	Silty sands, poorly graded sand-silt mixtures
SC	Clayey sands, poorly graded sand-clay milxtures
ML	Silty or clayey fine sands with slight plasticity
MH	Fine sandy or silty soils, elastic silts
CL	Gravely clays, sandy clays, silty clays, lean clays
CH	Inorganic clays of high plasticity

TABLE 2. TYPICAL SOIL RESISTIVITY AND GND ROD (16 MM × 3 M) RESISTANCE.

Soil Group*	Range of Resistivity (Ω-m)	Rod (16 mm × 3 m) Resistance (Ω)
GP	1–2.5 k	300–750
GW	600–1000	180–300
GC	200–400	60–120
SM	100–500	30–150
SC	50–200	15–60
ML	30–80	9–24
MH	80–300	24–90
CL	25–60	17–18
CH	10–55	3–16

(*See Appendix 1 for soil group types)

As the soil resistivity increases, so does the ground rod resistance for a particular size ground rod. With frozen ground, the resistance increases to such a point that minimal current can flow through it.

It should be noted that X_e varies from 2.050 to 3.726 for soil resistivities ranging from 1–10,000 Ω-m. This is close to a 2:1 ratio and is shown in Table 1.

Another aspect is that of temperature on the resistance of a conductor. The temperature is usually not the same as the ambient temperature due to the fact that loading results in resistive heating losses. The effect of temperature on the conductor resistance [11] is:

$$R_{t2} = R_{t1}\left(1 + \alpha_{t1}(t_2 - t_1)\right), \quad (4)$$

where

R_{t1} = the resistance at a given temperature, normally 20 °C in Ω
R_{t2} = the resistance at some other temperature in Ω
t_1 = temperature 1 in °C
t_2 = temperature 2 in °C
α_{t1} = temperature coefficient of resistance in $(°C)^{-1}$.

This equation is good for a relatively small range of temperatures. α_{t1} for aluminum at 61% conductivity is 0.00403 and 0.00393 for copper at 100% conductivity. For example, the difference in resistance for an aluminum conductor from a temperature of 20 to –50 °C is reduced by approximately 28%. (Copper is slightly less at approximately 27%.)

As it turns out, the temperature dependence of the conductor resistance is somewhat insignificant when looking at the system impedances. Normally, studies are conducted at a given temperature and the calculated impedances are sufficient for the accuracy of most system studies. Therefore, conductor temperature can most likely be excluded as being significant for determination of an effectively grounded system.

Surge Arresters

Surge arresters are applied to a power system based on the line-to-ground voltage under normal and abnormal conditions. Under normal conditions, the line-to-ground voltage is typically maintained at ±5% of the nominal value for distribution systems and ±10% of the nominal value for transmission systems. Under ground-fault conditions, the line-to-ground voltage can increase up to 1.73 p.u. on the two, unfaulted phases for a ground fault that occurs on an ungrounded and impedance-grounded system.

Application of surge arresters on a power system is dependent on the effectiveness of the system grounding. The overvoltage condition that can occur during a ground fault can be minimized by keeping the zero sequence impedance low. Therefore, optimization in sizing the surge arresters on the system is dependent on the system grounding. An effectively grounded power system allows the use of a lower rated surge arrester. The lower rated surge arrester provides better surge protection at a lower cost. An effectively grounded system can only be accomplished using a properly sized, multigrounded system neutral. With few, if any, exceptions, all other systems require the use of full line-to-line voltage-rated arresters. This increases the cost of the surge arresters while at the same time reduces the protection provided by the surge arrester. In addition, if the fourth wire neutral is not mulitgrounded, it would be good engineering practice to place surge arresters at appropriate locations on that conductor

The zero sequence self-impedance Z_{oa} of a three-phase circuit without ground wires is shown in (5):

$$Z_{oa} = R_c + R_e + j(X_e + X_c - 2X_d)\ \Omega/\text{km}, \quad (5)$$

where

R_c = phase conductor resistance in Ω/km
R_e = earth resistance in Ω/km
X_e = earth reactance in Ω/km
X_c = phase conductor self reactance in Ω/km
$X_d = 1/3(X_{d(ab)} + X_{d(bc)} + X_{d(ca)})\ \Omega/\text{km}$.

The zero sequence self impedance of one multigrounded, ground wire with earth return, Z_{og}, is shown in (6).

$$Z_{og} = 3R_a + R_e + j(X_e + 3X_a)\ \Omega/\text{km}, \quad (6)$$

where

R_a = resistance of ground wire in Ω/km
X_a = self reactance of ground wire in Ω/km.

The zero sequence self impedance of n ground wires with earth return is shown in (7):

$$Z_{og} = 3R_a/n + R_e + j\Big(X_e + 3X_a/n - \big(3(n-1)/n\big)X_d\Big)\ \Omega/\text{km}, \quad (7)$$

where $X_d = 1/(n(n-1))(\Sigma X_d$ for possible distances between all between all ground wires) Ω/km.

The zero sequence mutual impedance between one circuit and n ground wires is shown in (8):

$$Z_{oag} = R_e + j(X_e - j(X_e - 3X_d)\ \Omega/\text{km}, \quad (8)$$

where

$$X_d = (1/3n)(X_{d(ag1)} + X_{d(bg1)} + X_{d(cg1)} + \ldots + X_{d(agn)} + X_{d(bgn)} + X_{d(cgn)}\quad \Omega/\text{km}.$$

TABLE 3. ROD RESISTANCES WITH VARYING SOIL RESISTIVITY.

Soil Resistivity (Ω-m)	Rod Resistance (Ω)
10	3.35
100	33.5
1,000	335
10,000	3,350
100,000	33,500

Zero sequence impedance of one circuit and n ground wires and earth return is shown in (9):

$$Z_o = Z_{oa} - (Z_{oag})^2 / Z_{og} \ \Omega/\text{km}. \tag{9}$$

A further definition of an effectively grounded system, as previously discussed, is

> a system or portion of a system can be said to be effectively grounded when for all points on the system or specified portion thereof the ratio of zero-sequence reactance to positive sequence reactance is not greater than three and the ratio of zero-sequence resistance to positive-reactance is not greater than one for any condition of operation and for any amount of generator capacity [7].

For an effectively grounded system, both conditions of (10) and (11) must be met:

$$\frac{X_0}{X_1} \le 3, \tag{10}$$

$$\frac{R_o}{X_1} \le 3. \tag{11}$$

Table 4 shows an example of how the X_0/X_1 ratio for a typical distribution line consisting of 477 ACSR phase conductors with a multigrounded 4/0 ACSR ground wire and without a multigrounded ground wire varies with all conditions constant except for the soil resistivity. It should be noted that under all soil resistivities, the system without a multigrounded neutral does not meet the criteria of being effectively grounded.

Three-Phase, Five Wire System

A demonstration project of a five-wire distribution circuit was tried in New York state [12] with the fourth wire being turned into a multigrounded ground wire and the fifth wire was used as a "fifth-wire source-grounded neutral." The source grounded neutral conductor was insulated along the route and created some confusion to the linemen. The fifth wire needed to be treated as an energized conductor including the recommendation that surge arresters be properly located on the neutrals of the transformers. The conversion costs have been estimated at 20–40% of the installed cost of the existing overhead line, and new construction of the five-wire system has been estimated at 10–20% higher than the cost for new, four-wire construction.

TABLE 4. X_O/X_1 RATIOS WITH AND WITHOUT GROUND WIRE.

Resistivity ρ	X_O/X_1 w/gnd wire	X_O/X_1 w/o gnd wire
50	2.80	4.43
100	2.85	4.62
500	2.95	5.07
1000	2.99	5.27
5000	3.07	5.72
10000	3.11	5.91

Advantages and Disadvantages

- Under fault conditions and open neutrals, the fifth wire can rise to several thousand volts above ground—therefore it needs to be isolated and insulated. Warning signs to linemen were installed due to safety concerns.
- Balancing transformers were required where a transition was made back to the four-wire system.
- Benefit: Easier detection of high-impedance ground faults.
- Benefit: Reduction of stray voltages.

The use of the multigrounded neutral provides the following:

- Benefit of extending substation and system grounding to large area.
- Improves ground return current from a point of fault to the substation.
- Reduces the zero sequence impedance.

According to the five-wire study, the main conclusion of the five-wire demonstration project is that the five-wire system improved performance for high-impedance faults, stray voltages, and magnetic fields relative to a four wire system [12].

Effect of Capacitors and Resistive Loads on Zero-Sequence Circuits

Grounded-wye capacitor banks on the multi-grounded three-phase, four-wire system provide a path for zero sequence currents to flow. Ungrounded and delta-connected capacitors do not. The capacitance of the grounded-wye capacitor bank shows up in the zero sequence circuit as a capacitor.

Resistive three-phase loads also provide a path for zero currents to flow. These loads are normally reflected through as an equivalent set of three, single-phase transformers. These loads are normally neglected due to the fact that the amount is usually insignificant. However, it does provide a path to help maintain an effectively grounded system. By solidly grounding to the system, these three-phase grounded-wye capacitor banks and single-phase resistive loads help to maintain an effectively grounded system.

The Insulated Neutral System

It was noted earlier that the NEC requires single-point grounding of the neutral on low voltage systems (600 V and below). There are those who advocate that the use of the four-wire multigrounded systems be forbidden in favor of an insulated neutral system [13]. The rationale for this is that there have been a few instances in which both humans and animals have experienced electric shock due to stray voltages caused by the flow of neutral return current through the earth.

While the rationale for use of the insulated neutral system in low voltage applications such as residences and commercial building is supportable, there are serious issues associated with its application at higher voltages and in applications involving longer circuit length. This design is seriously limited by any neutral current flow that will increase the voltage drop and cause neutral shifts for single-phase and unbalanced, three-phase, four-wire loads. In addition, the zero-sequence impedances will be of such magnitude that full line-to-line rated surge arresters will be required. The use of the single point grounded system would essentially dictate the use of delta primary windings and line-to-line connected single-phase transformers. The price of such a system would be unreasonable for most new applications, and the cost of replacing existing three-phase, four-wire systems would be totally prohibitive.

Another problem with the single-point grounded system is that a break in the neutral could cause a neutral shift that may result in unacceptably high and low single-phase voltages. This is similar to the reason that utility companies ground the neutral of secondary services and the NEC requires a grounding conductor on the neutral of a service entrance. The grounding conductor will help maintain neutral stability.

It is this author's opinion that, while there may be rare instances of problematical stray voltages associated with multi-grounded distribution systems, the risks are reasonable compared with the costs and consequences associated with eliminating that practice in favor of the insulated neutral system for medium voltage distribution.

Single Conductor Line with Earth Return

The ultimate reliance on earth grounding occurs on the single conductor line with earth return. Figures 8 and 9 show a single conductor line with earth return for a 19-kV, single-phase system in South Australia.

The Australian system is an example of a present day, operational single conductor circuit with earth return. Is such a system reasonable and practical today? The answer is yes, and such a system is being considered today on an Alaskan project where electrical costs are a prime consideration for whether or not remote villages receive electricity [14]. A single-wire, ground return circuit will require a waiver from the Alaska legislature or the U.S. Department of Labor since it does not comply with the NESC. However, the author does not believe that the single-conductor, earth return circuit should be considered and firmly believes that a multigrounded neutral be considered on all single- and three-phase, four-wire circuits.

Step and Touch Potentials

The introduction of stray current into the earth will invariably create a voltage unless the impedance to "true" ground is zero. This resulting voltage is commonly referred to as a "stray" voltage. And, the stray voltage can be harmful under certain conditions. However, as previously mentioned, stray voltages cannot be eliminated.

Four legged animals are more susceptible to problems associated with stray voltages than humans. That is due to the physiological difference between a two-legged person and a four-legged animal. The stray voltage on an animal is directly across the body and heart where it is only between the two legs of a human. This is exactly why the allowable step voltage for a person in an electrical substation is considerably higher than the touch voltage [15]. See (12) and (13), which show the allowable step and touch voltages, respectively. It is evident from (12) that a person can withstand a greater step potential than touch potential.

$$V_{\text{step}} = (1{,}000 + 6\rho_s)0.157(t_s)^{-1/2}\ V, \quad (12)$$

$$V_{\text{touch}} = (1{,}000 + 1.5\rho_s)0.157(t_s)^{-1/2}\ V, \quad (13)$$

where

ρ_s = surface resistivity in Ω-m,
t_s = duration of shock current in s
(V_{step} and V_{touch} are for a 70-kg person. For a 50-kg person, the constant 0.157 should be changed to 0.116 to account for the lighter weight person.)

The step-and-touch potential calculations, along with the properly designed substation within an electrical substation, is but one simple example of how the utility industry limits ground voltages due to ground potential rises within an electrical substation. In addition, another important aspect of the multigrounded system is the fact that substation grounding is improved with the use of a multigrounded distribution system.

8

Single-phase service in South Australia with earth return.

9

A single-conductor 19-kV circuit with earth return.

Examples of Stray Voltages Problems and Solutions

The following are several examples of personal experiences of the author on the impacts of stray voltages.

Mount Evans Elk Herd

One of the more unfortunate examples on the impact of stray voltages on animals occurred in the late 1990s in Mount Evans, Colorado. A herd of approximately 50 elk was found dead. The apparent cause was the stray voltage in the ground as a result of a lightning stroke to the earth. The high stray current in the ground as a result of that lightning stroke created a sufficient voltage gradient on the ground that electrocuted the elk. Unfortunately, there is no solution to prevent a similar occurrence in the future.

Woman in Shower

A second example involved a woman noticing a "tingling" of electricity when she showered. An investigation revealed an electrical voltage was present between the shower drain and the shower knobs. The fact that the woman was in her wet bare feet with wet hands contributed to the sensitivity of noticing the voltage difference. The cause of the problem was found to be stray voltages produced by an overhead distribution line. The voltage difference was between the well and the septic system. The solution was to bond the drain and water pipes together.

Computer Failure

Another example involved a customer complaint regarding computer modem and computer failures. The utility found that the failures occurred coincidentally with power disturbances (ground faults) on one of the main feeders. An investigation showed that the telephone, water and power grounds were isolated. Proper bonding eliminated further problems with that customer.

Swimming Pool

A municipal utility was notified by a customer who had recently constructed a swimming pool that the swimmers were receiving a tingling sensation when entering and exiting the pool. The utility had an underground, single-phase distribution line serving the area. It was determined that the bare concentric neutral was corroded. The utility replaced the cable with a jacketed concentric neutral. The problem was eliminated.

Baseball Diamond

Baseball players (at the same municipal utility with the swimming pool incident) with metallic cleats were getting shocked while playing baseball. As it turns out, the soil was extremely corrosive and it is not unusual for copper to corrode and disappear. Similar to the swimming pool problem above, the utility found the copper concentric neutral totally corroded. The utility replaced the cable with a jacketed concentric neutral and again the problem was solved.

Conclusions

The multigrounded neutral system for power systems above 600 V is a reasonable and safe design. It presents many factors that improve safety over a single-point, neutral-grounded system. The multigrounded neutral system provides the following benefits:

- safety is enhanced to utility personnel and the general public with the multigrounded system when compared with the single point grounded neutral system
- the zero sequence impedance is lower for a multi-grounded system than the single-point grounded neutral system
- lightning-arrester sizes can be optimized using a multi-grounded system. A single-point grounded neutral system will most likely require higher voltage rated arresters.
- freezing and arctic conditions have an adverse impact on the zero sequence impedance. A multi-grounded system neutral will still lower the zero sequence impedance over a single point ground. In fact, without the multi-grounded system, it is more probable that insufficient fault current will flow to properly operate the ground fault protection.
- dry conditions have an adverse impact on the zero sequence impedance similar to that of the arctic conditions
- the cost of equipment for the multigrounded system is lower.

Problems occur and will continue to occur on all power systems. Three-phase, three-wire; three-phase, four-wire multigrounded; three-phase, four-wire single-point grounded and other systems should all be considered acceptable and reasonable. When problems occur, reasonable solutions exist. That is no less true for three-phase, four-wire, multigrounded power systems.

References

[1] *National Electrical Safety Code,* ANSI/IEEE C2-2002.
[2] National Electrical Code, NFPA 70, 2002.
[3] J.R. Eaton, R.P. Merritt, and E.F. Rice, "Electrical power engineering in an arctic environment," *The Northern Engineer*, vol. 21, no. 1.
[4] J. Leib, "Train-car crashes on the rise," *Denver Post*, p. 1B, Nov. 7, 2002.
[5] J. Lieb, G. Merritt, and Bortnick, "42 percent of rail crossings unmarked," *Denver Post*, pp. 1B, 3B, Nov. 17, 2002.
[6] "Engineering data for copper and aluminum conductor electrical cables," Bulletin EHB-98, The Okonite Company, Ramsey, NJ, 1998, pp. 16–18.
[7] *Electrical Transmission and Distribution Reference Book*, Westinghouse Electric, Pittsburgh, PA, 1964.
[8] *Recommended Practice for Grounding of Industrial and Commercial Power Systems* (The IEEE Green Book), ANSI/IEEE 142-1991.
[9] R.T. Beck and Luke Yu, "Design considerations for grounding systems," *IEEE Trans. Ind. Applicat.*, vol. 24, pp. 1096–1100, Nov./Dec. 1988.
[10] D.R. Frietag and McFadden Terry, *Introduction to Cold Regions Engineering.* New York: ASCE Press, 1997, pp. 71–715.
[11] D.G. Fink and J.M. Carroll, *Standard Handbook for Electrical Engineers.* New York: McGraw-Hill, 1968, pp. 4.5–4.11.
[12] T.A. Short, J.R. Stewart, D.R. Smith, J. O'Brien, and K. Hampton, "Five-wire distribution system demonstration project," *IEEE Trans. Power Delivery*, vol. 17, pp. 649–654, Apr. 2002.
[13] D.W. Zipse, "Earthing—grounding methods: A primer," in *IEEE-IAS-PCIC-01-2 Conf. Rec.*, 2001, pp. 11–30.
[14] J. Gay, *Anchorage Daily News*, Sep. 15, 2002.
[15] *IEEE Guide for Safety in AC Substation Grounding*, ANSI/IEEE 80-1986.

John P. Nelson (jnelson@neiengineerina.com) is with NEI Electric Power Engineering, Inc, in Arvada, Colorado. Nelson is a Fellow of the IEEE. This article first appeared in its original form at the 2003 IEEE/IAS Petroleum and Chemical Industry Technical Committee Conference.