THE GROUNDING OF POWER SYSTEMS ABOVE 600 VOLTS: A PRACTICAL VIEW POINT

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Abstract **-** This paper discusses grounding practices used on electric distribution systems above 600 Volts. In particular, the paper concentrates on the three-phase four-wire, multi-grounded neutral system that is extensively used in North America. The paper addresses the benefits of the multi-grounded power system and makes comparisons with other grounding system designs including ungrounded; three-wire single-point grounded; three-phase, four-wire single point grounded neutral; and the three-phase, five-wire systems. Advantages and disadvantages of each system will be discussed. Some criticism regarding stray currents and stray voltages has been made of the multi-grounded neutrals on electric distribution systems and this will be discussed. Technical responses will be made to these comments including a discussion on reasonable solutions, alternative designs, and "acceptable risks."

Index Terms – Acceptable risk, multi-grounded system, resistance grounding, reactance grounding, single point grounded systems, solidly grounded systems, stray current and stray voltage.

I. INTRODUCTION

The three-phase, four-wire, multi-grounded 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, multi-grounded systems involve a combination of safety and economic considerations. The three-phase, four-wire multi-grounded design has been successfully used for many years and is well documented in the standards including the *National Electrical Safety Code* (NESC) [1], and the *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 multi-grounded system be eliminated? This paper will show that the answer to the last question is absolutely not.

The earth is an electro-magnetic 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 one to ten volts per kilometer. [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 good, sound engineering, construction and maintenance practices. The benefits of safely using electricity far out weigh the risks involved in the generation, transmission and distribution of electricity. 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.

II. ACCEPTABLE RISKS

To explain the term "acceptable risk," let us consider a common every day 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 many times that number, but few people would agree saving those 50,000 lives is worth the outlawing of the automobile. 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 rail 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 $180,000 each and bridges at $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 $246 million to place warning signals at each of those crossings or $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 No. 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 every day 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.”

III. 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 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 paper. The latter two systems can have a single point grounded or multi-grounded neutral. In general, the systems shown in Figs 1-5 are the options available for use.

Fig 1 depicts the multi-grounded neutral system for the solidly grounded and reactance grounded systems commonly used by the 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 still maintaining an effectively grounded system. The NESC provides a definition for an “effectively grounded system:” *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 which will be discussed later in this paper.

Fig 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.

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

Fig 4 shows a three-wire ungrounded delta system and Fig 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 presently designed and constructed as an ungrounded system.

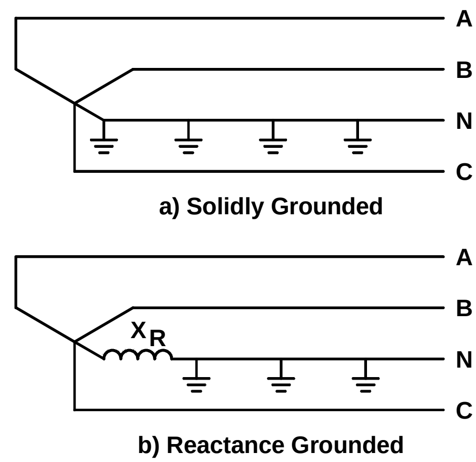

FIGURE 1
Four-wire multi-grounded neutral system (Solid and Reactance Grounded)

The differences between the multi-grounded systems in Fig 1 and the single point grounded systems shown in Fig 2 may appear insignificant, but the differences are significant as will be explained in more detail later. But suffice to say at this point, the differences involve both safety and economics.

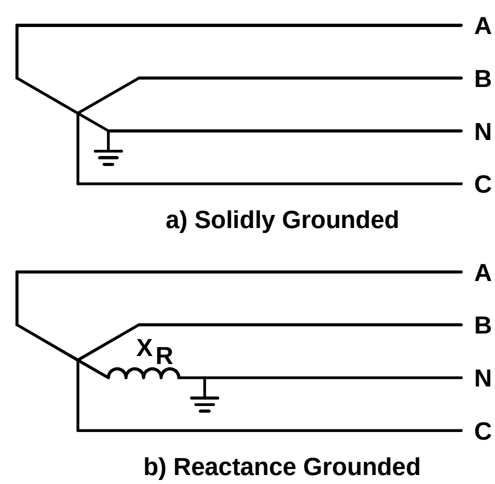

FIGURE 2
Four-wire single point grounded-neutral system (Solid and Reactance Grounded)

The three-phase, three-wire systems shown in Fig 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, the industrial users will usually dispense with the need for the fourth-wire neutral.

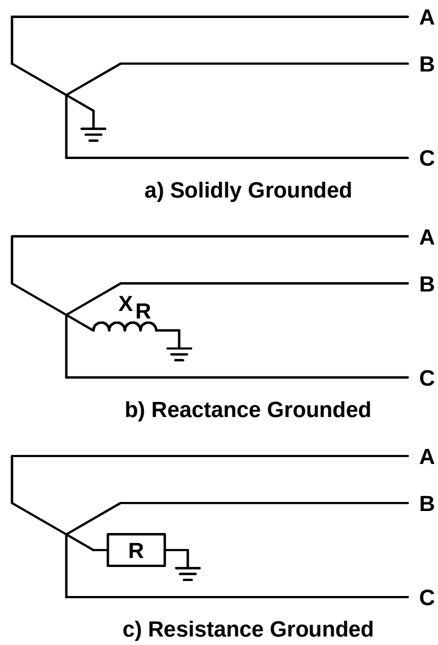

FIGURE 3
Three-wire, single-point grounded system w/o a neutral (Solid, Reactance and Resistance Grounded)

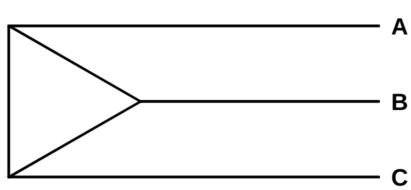

FIGURE 4
Three-wire, ungrounded delta connected transformer

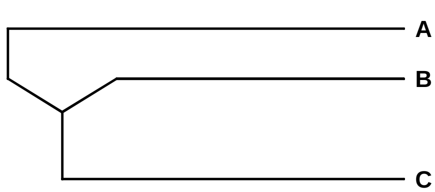

FIGURE 5
Three-wire, ungrounded-wye connected transformer

IV. SAFETY AND CODE CONSIDERATIONS

The multi-grounded system is referenced in both the NESC and the NEC. The NEC requires single point grounding on low voltage systems, 600 Volts and below. However, the NEC allows the use of a multi-grounded system for voltages above 600 Volts. On the other hand, the NESC is quite specific that a three-phase, four-wire system must have a multi-grounded 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 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 mile) 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) Multi-grounded 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 voltage 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 volts. This practice of multi-grounding cable shields includes the grounding of concentric neutrals on power cables thereby extending the need for multi-grounding of neutrals on the power system.

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

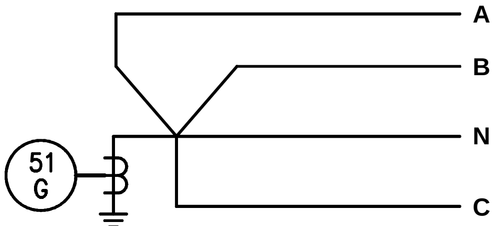

Figure 6(a) Current transformer in ground

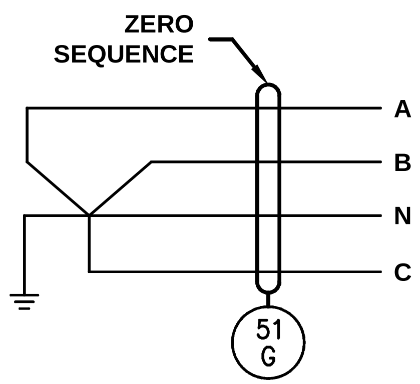

Figure 6(b) Zero sequence CT including neutral

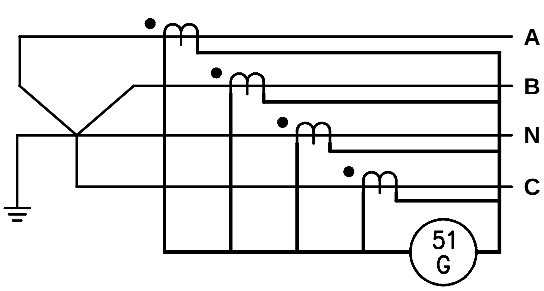

Figure 6(c) Residual current with neutral cancellation

FIGURE 6
Ground Current Sensing

Protecting against ground faults on a multi-grounded 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 which may flow in the circuit, and the ground fault setting must be above this neutral current. This is self-explanatory from Fig 7.

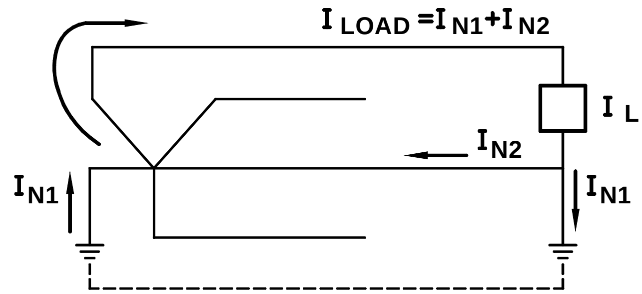

Figure 7(a) Neutral current flowing in neutral and ground

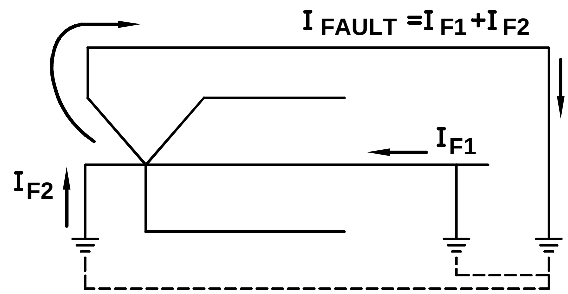

Figure 7(b) Ground fault current flowing in the neutral and ground

FIGURE 7
Current distribution in multi-grounded system

While the sensing of the ground fault current in the single point grounded system is less complex than the multi-grounded 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 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 multi-grounded neutral system improves the probability of sensing a ground fault under all conditions and, therefore, provides more a more reliable and thus safer means of isolating ground faults from the system.

VI. 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 Equation 1 shows this relationship.

$$R_e = 0.00296f \quad \Omega/km \qquad (1)$$

Where,

R_e = Earth Resistance in Ohms/km

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

$$X_e = 0.004338f \log_{10} [4.665600 \times 10^6 \ (\rho/f)] \quad \Omega/km \qquad (2)$$

Where,

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

Based on equations 1 and 2, table shows Re and Xe for 60 Hz with various soil resistivities.

TABLE 1
R_e and X_e @ f = 60 Hz

ρ Ohm-meters	R_e (Ohms/km)	X_e (Ohms/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

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
- Temperature.

TABLE 2
Typical Soil Resistivity and Gnd Rod (16 mm x 3m) Resistance

Soil Group *	Range of Resistivity (Ω-m)	Rod (16mm x 3m) Resistance (Ohms)
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)

Soil resistivity of the permafrost is typically in the range of 3500-4000 Ohm-meters.[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 Ohm-meters at 10 ^{o}C, 20 Ohm-meters near 0 ^{o}C and 1000 Ohm-meters at –15 ^{o}C. Another example is silt in the Fairbanks, Alaska area which has a relatively constant soil resistivity of 300 Ohm-meters down to freezing to as high as 8000 Ohm-meters at –15^{o}C. [10]

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

$$R = \frac{\rho}{2\Pi}(\ln \frac{4L}{a} - 1) \ \Omega \qquad (3)$$

Where,

L = Length of rod (meters)
a = radius of rod (meters)
ρ = resistivity of soil (Ω-m)

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

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

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 to 10,000 Ω-meters. 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 is: [11]

$$R_{t2} = R_{t1}[1 + \alpha_{t1}(t_2\text{-}t_1)] \qquad (4)$$

Where,

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

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 ^oC to –50 ^oC 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.

VII. 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 $\pm$ 5% of the nominal value for distribution systems and $\pm$ 10% of the nominal value for transmission systems. Under ground-fault conditions, the line-to-ground voltage can increase up to 1.73 per unit on the two, unfaulted phases for a ground fault that occurs on an ungrounded an impedance grounded system.

Application of surge arresters on a power system is dependent on the effectiveness of the system grounding. The over voltage 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, multi-grounded 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 mulit-grounded, it would be good engineering practice to place surge arresters at appropriate locations on that conductor

The zero sequence self-Impedance, Z_{oa}, of three-phase circuit without ground wires is shown in Equation 5.

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

Where,

R_c = Phase conductor resistance in Ohms/km
R_e = Earth Resistance in Ohms/km
X_e = Earth Reactance in Ohms/km
X_c = Phase Conductor self reactance in Ohms/km
$X_d = 1/3(X_{d(ab)}+X_{d(bc)}+X_{d(ca)})$ Ohms/km

The zero sequence self impedance of one multi-grounded, ground wire with earth return, Z_{og}, is shown in equation 6.

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

Where,

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

The zero sequence self impedance of n ground wires with earth return is shown in equation 7.

$$Z_{og} = 3R_a/n + R_e + j(X_e + 3X_a/n - [3(n-1)/n]X_d)\ \Omega/\text{km} \qquad (7)$$

Where,

$X_d = 1/(n(n-1))(\sum X_d$ for a possible distances between all ground wires) Ohms/km

The zero sequence mutual impedance between one circuit and n ground wires is shown in equation 8.

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

Where,

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

Zero sequence impedance of one circuit and n ground wires and earth return is shown in equation 9.

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

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 equations 10 and 11 must be met.

$$\frac{X_o}{X_1} \leq 3 \qquad (10)$$

$$\frac{R_o}{X_1} \leq 1 \qquad (11)$$

Table 3 shows an example of how the X_o/X_1 ratio for a typical distribution line consisting of 477 ACSR phase conductors with a multi-grounded 4/0 ACSR ground wire and without a multi-grounded 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 multi-grounded neutral does not meet the criteria of being effectively grounded.

TABLE 3
X_o/X_1 ratios with and w/o gnd 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

VIII. 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 multi-grounded 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 and needed to be treated as such including the recommendation that surge arresters be properly located including 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.

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 multi-grounded 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]

IX. EFFECT OF CAPACITORS AND RESISTIVE LOADS ON ZERO SEQUENCE CIRCUIT

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.

X. ZIPSE'S LAW

Donald Zipse in 2001 introduced to PCIC "Zipse's Law" which states: *In order to have and maintain a safe electrical installation: All continuous flowing current shall be contained within an insulated conductor or if a bare conductor, the conductor shall be installed on insulators, insulated from the earth, except at one place within the system and only one place can the neutral be connected to the earth.* [13] This author takes great exception to that statement and believes it to be false and misleading.

Zipse's Law is contrary to the National Electrical Safety Code [1] that not only allows, but also advocates the use of the multi-grounded neutral system. Next, the National Electrical Code [2] not only allows the use of the multi-grounded system, it specifies the maximum distance of 400 meters between grounds on the neutral.

The single-point, grounded system is seriously limited by any neutral current flow which 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 three-phase, four-wire system would have to be totally replaced. The price of such a system would be cost 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.

In conclusion, Zipse's law is not only invalid, but it also presents potentially unsafe conditions for the utility workers and general public.

XI. SINGLE CONDUCTOR LINE WITH EARTH RETURN

The ultimate reliance on earth grounding occurs on the single conductor line with earth return. Photo's 1 and 2 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 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 multi-grounded, neutral be considered on all single phase and three-phase, four-wire circuits.

Photograph No. 1 – Single Phase Service in South Australia with Earth Return

XII. 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 equations 12 and 13 which show the allowable step and touch voltages, respectively. It is evident from equation 12 that a person can withstand a greater step potential than touch potential.

$$V_{step} = (1000 + 6\rho_s)0.157(t_s)^{-1/2} \quad \text{Volts} \qquad (12)$$

$$V_{touch} = (1000 + 1.5\rho_s)0.157(t_s)^{-1/2} \quad \text{Volts} \qquad (13)$$

Where,

ρ_s = Surface resistivity in Ω-m,

t_s = Duration of shock current in seconds

(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 how the utility industry limits ground voltages due to ground potential rises within an electrical substation. In addition, another important aspect of the multi-grounded system is the fact that the substation grounding is improved with the use of a multi-grounded distribution system.

Photograph No. 2 – Single Conductor 19 kV Circuit with Earth Return

XIII. EXAMPLES OF STRAY VOLTAGES PROBLEMS AND SOLUTIONS

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

A. Mount Evans Elk Herd

One of the more unfortunate examples on the impact of stray voltages on animals occurred in the late 1990's on 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 it electrocuted the elk. Unfortunately, there is no solution to prevent a similar occurrence in the future.

B. 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.

C. 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.

D. 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.

E. 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.

XIV. CONCLUSIONS

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

- Safety is enhanced to utility personnel and the general public with the multi-grounded 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.
- Cost of Equipment for the multi-grounded system is lower.

Problems occur and will continue to occur on all power systems. Three-phase, three-wire; three-phase, four-wire multi-grounded; 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 the three-phase, four-wire, multi-grounded power systems.

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XVI. VITA

John P. Nelson received a BSEE from the University of Illinois, Champaign-Urbana, in 1970 and an MSEE from the University of Colorado in 1975. Mr. Nelson spent 10 years in the electric utility industry and the last 24 years as an electrical power consultant. Mr. Nelson has been active with PCIC for approximately 25 years, and has authored numerous papers typically involving electric power systems and protection of electrical equipment and personnel. Mr. Nelson is the founder and president of NEI Electric Power Engineering Inc located in Arvada, Colorado. He is a registered professional engineer in numerous states. Mr. Nelson has taught graduate and undergraduate classes at the University of Colorado at Denver along with a number of IEEE tutorials and seminars.

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