

STRAY VOLTAGE

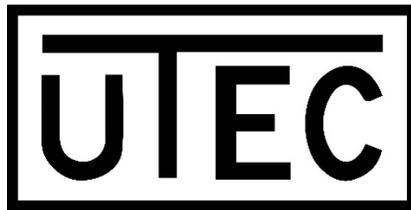
- WHAT IS IT
- HOW TO ANALYZE IT
- WHAT TO DO ABOUT IT



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Presented By:

J. Ted Orrell, PE, President



**UTILITY TECHNOLOGY
ENGINEERS-CONSULTANTS, PLLC**

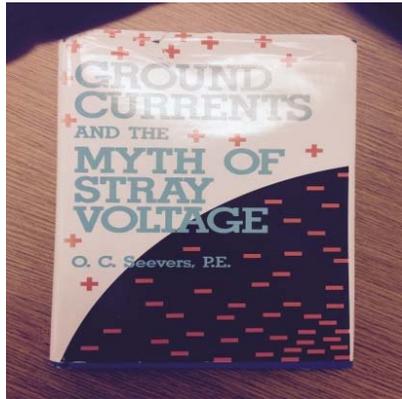
147B Dublin Square Road
PO Box 2629
Asheboro, NC 27203
336-625-0917

775 Spartan Boulevard
Suite 207
Spartanburg, SC 29301
864-579-1577

www.utilitytec.com

What is “Stray Voltage”?

A very good reference on the subject is the book “Ground Currents and the Myth of Stray Voltage” by O. C. Seevers, P.E.



Mr. Seevers' book focuses on stray voltages in dairy farms, but the principles addressed apply to any stray voltage situation.

Mr. Seevers makes several interesting and important comments and observations:

- Stray voltage is “voltage which appears where it has no business being”.
- “There is no such thing as stray voltage! Voltage does not “stray”. Voltage does not go anywhere. It exists at a location as electrical pressure between two points, A and B.”
- “Nowhere in any of the horror tales which I have studied dealing with “stray voltage” have I seen that anyone looked at the distribution system and analyzed how it works. How primary neutral current returns to its source.”

What Causes Stray Voltage?

Simply stated, stray voltage is caused by current flowing in the earth producing voltage drop.

There is more than one reason why current might flow in the earth and ground current can result from a combination of reasons:

1. Faulty cable or equipment (See Figure 1)

This situation is a high impedance fault to ground resulting in a low level ground fault current raising the voltage of faulted equipment frames and metal buildings with respect to earth. The situation depicted in Figure 1 was an unfortunate electrocution investigated by UTEC in 1990.

2. Transferred Potential, or “Neutral to Earth Voltage” (NEV) (See Figure 2)

Transferred potential, also referred to as Neutral to Earth Voltage (NEV), is a condition in which the voltage, or potential, of a point along the electrical system neutral is transferred to another point where the earth voltage is less. This difference in voltage between the utility neutral and ground can be measured.

For grounded wye systems, all primary system load current flows back to the substation source via a combination of the neutral, the connected ground electrodes, and the earth itself. This parallel network of the neutral conductor and ground rods exhibits impedance to current and therefore voltage drop as current flows through the parallel paths. As a result, the neutral voltage is higher than earth potential along the line route. The insulated customer service ground wire is connected to the utility system neutral at the customer service entrance and is routed to the customer loads. For safety reasons this insulated ground conductor is connected to metal buildings, equipment frames, etc. Therefore, the potential of the utility neutral is “transferred” to such equipment frames. This situation is a natural phenomenon of electric circuits. The voltage difference between the grounded equipment (utility neutral voltage) and the earth can be measured and if high enough, can be felt by animals and humans. Transfer of utility neutral voltage is the major reason for voltages measured between grounded equipment and earth at dairy farms, chicken farms, rock quarries, swimming pools, and other such locations.

For balanced 3-phase systems, the vector addition of the fundamental frequency (60 Hz) current for the three phases is zero at the neutral and ground connection and therefore the sum of these currents does not cause NEV. However, 1-phase loads served from a 3-phase line do experience NEV. For 1-phase circuits, the entire 60 Hz current returns through the neutral and earth creating NEV. Also, for 2-phase circuits, the vector sum of the two 60 Hz phase currents is not zero and this vector sum of these currents returns in the neutral and earth, creating NEV.

NEV is the result of operating grounded electric systems and therefore, NEV will always exist for 2-phase and 1-phase circuits.

Another cause of NEV is Transformer Magnetizing Current.

The magnetizing current for any transformer is distorted (non-sinusoidal) because of the non-linear magnetic characteristics of the transformer steel core. The distorted transformer magnetizing current is typically 50% fundamental frequency and 50% 3rd harmonic (180 Hz) if the primary transformer coils are connected phase-to-neutral/ground. For 3-ph transformers, or banks of three 1-phase transformers with the primaries connected grounded-wye, the fundamental portion of the charging currents for the three phases add to zero and do not flow into the neutral or ground system. However, the vector addition of the 3rd harmonic components of magnetizing current for each phase are in phase with each other and add numerically at the neutral/ground point and flow into the combination of the neutral conductor and the ground. The 3rd harmonic charging currents of all grounded single phase transformers flow into the combination of the neutral and the ground electrodes back to the source substation. The magnitude of charging current is low compared to load current. However, the 3rd harmonic portion of the charging current frequency is 180 hertz and the current returns deeper in the earth than 60 hertz current producing wider spread ground potential. The conductor inductive reactance to 180 hertz frequency is higher than the conductor impedance to 60 hertz which results in more of the magnetizing current returning in the ground rods and earth creating voltage drop along the earth surface.

3. Neutral conductor High Resistance or Open Point in Utility System's Primary Neutral (See Figure 3)

If a utility neutral conductor is broken or has a high resistance at a splice, most, if not all, of the neutral current beyond the high resistance point cannot flow in the broken or high resistance neutral and will flow into the earth to return to the substation. These higher than normal ground currents produce surface voltage profiles which can be high and dangerous.

4. Stray Ground Currents from Outside Sources (See Figure 4)

"Outside" sources can be DC, fundamental frequency, other harmonic frequency currents, or a combination of harmonic frequencies. These ground current sources could be caused by loads connected to other circuits served by the utility, loads served by another utility substation in the general area, transmission line shield and ground currents, or currents associated with any other electric or communication systems that are grounded. If ground current associated with an outside source flows through a site, the ground current will create voltage profiles along the surface in the area. These voltage profiles are typically depicted as equipotential lines drawn along the earth's surface.

If the primary line and neutral conductors for a tap serving a customer load were completely opened and isolated from the utility system, any then measured voltage between the service entrance ground electrode and a point on earth will be the

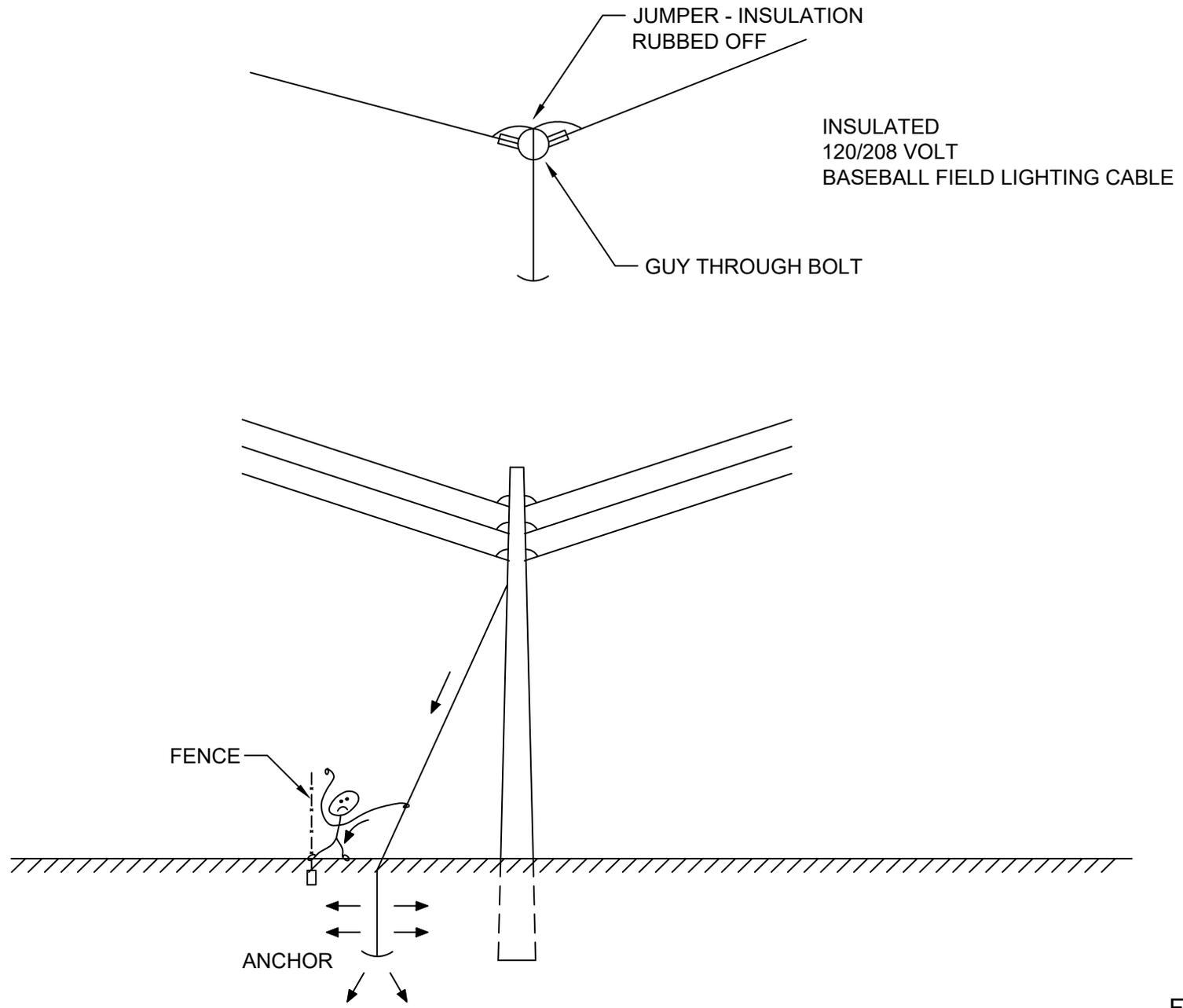


FIGURE 1

HIGH IMPEDANCE FAULT

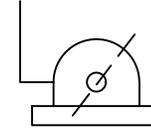
LEGEND:



EARTH



GROUND ROD RESISTANCE



EQUIPMENT GROUNDED

NEV

NEUTRAL TO EARTH VOLTAGE

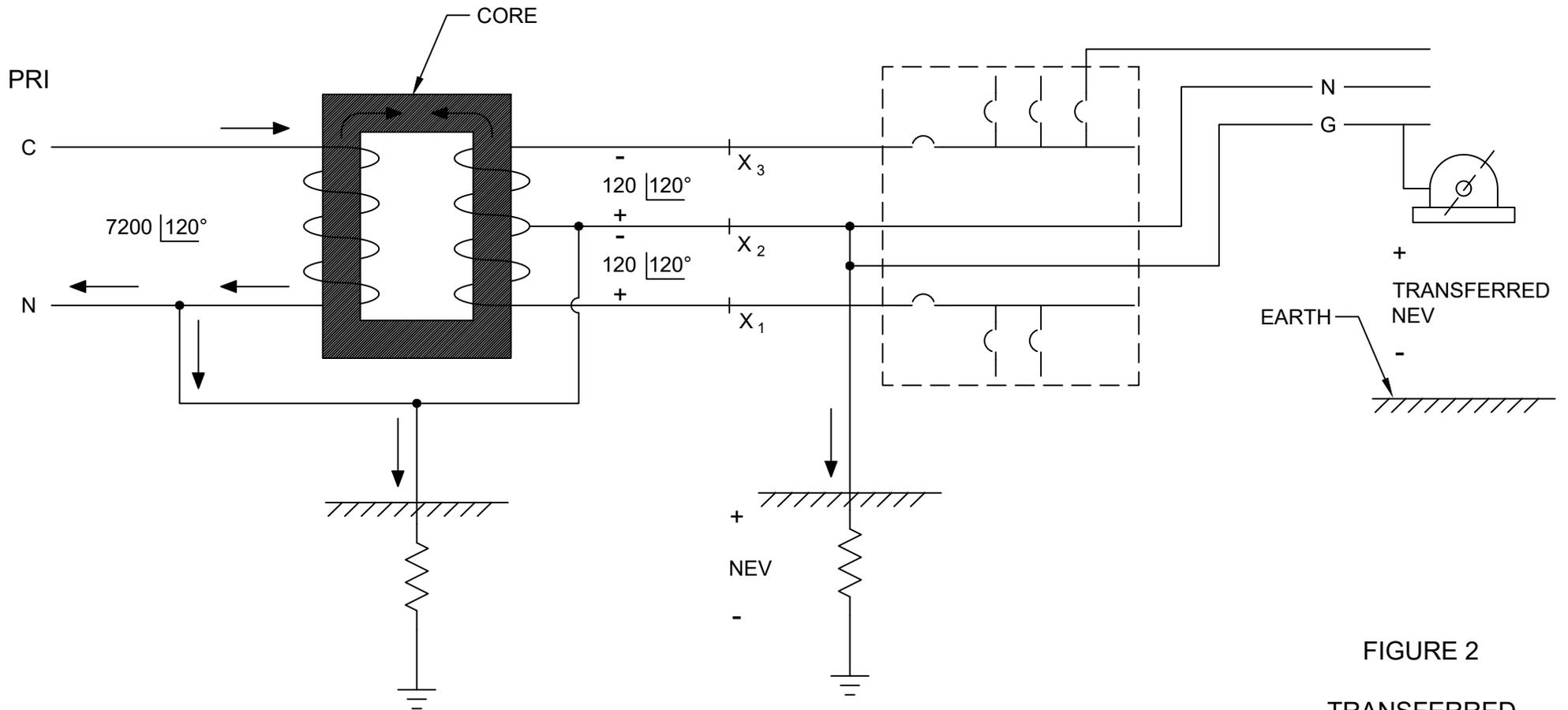


FIGURE 2
TRANSFERRED
NEV

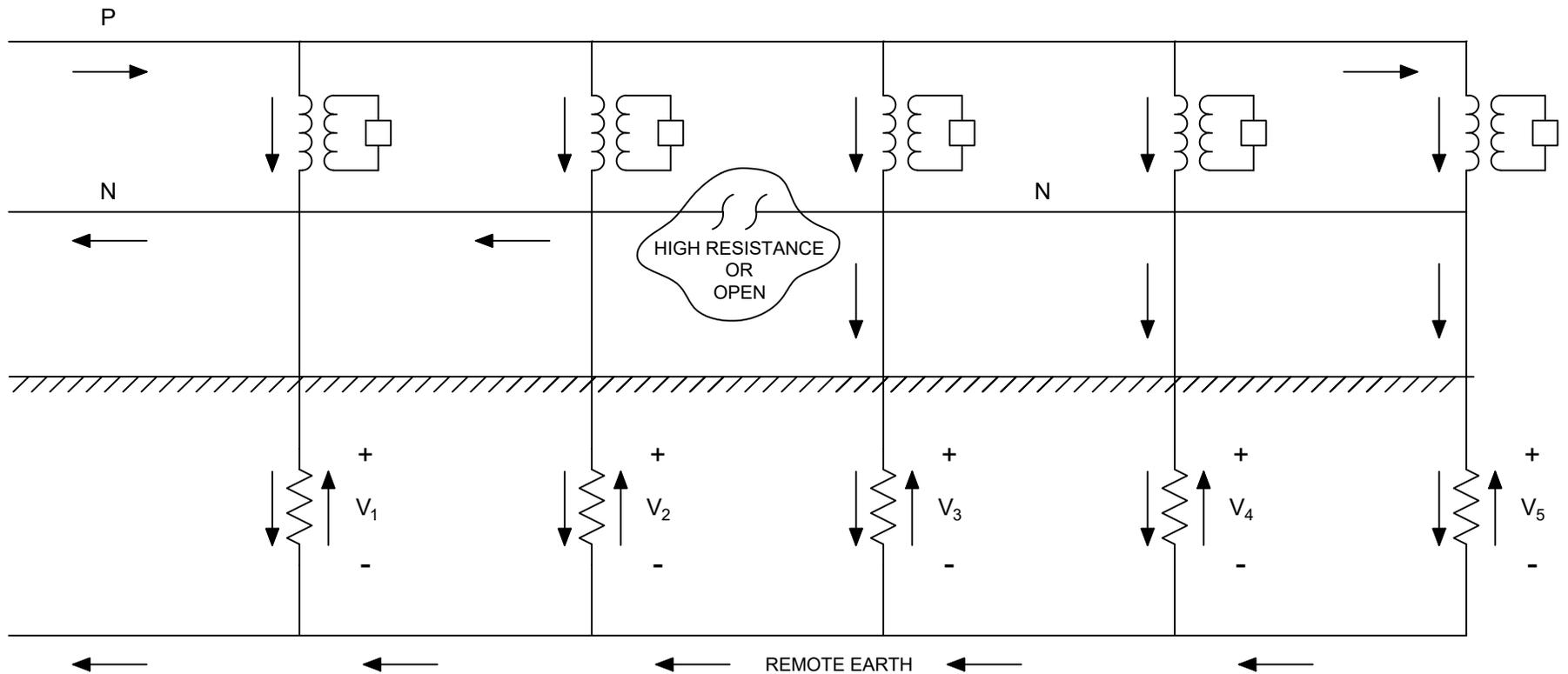
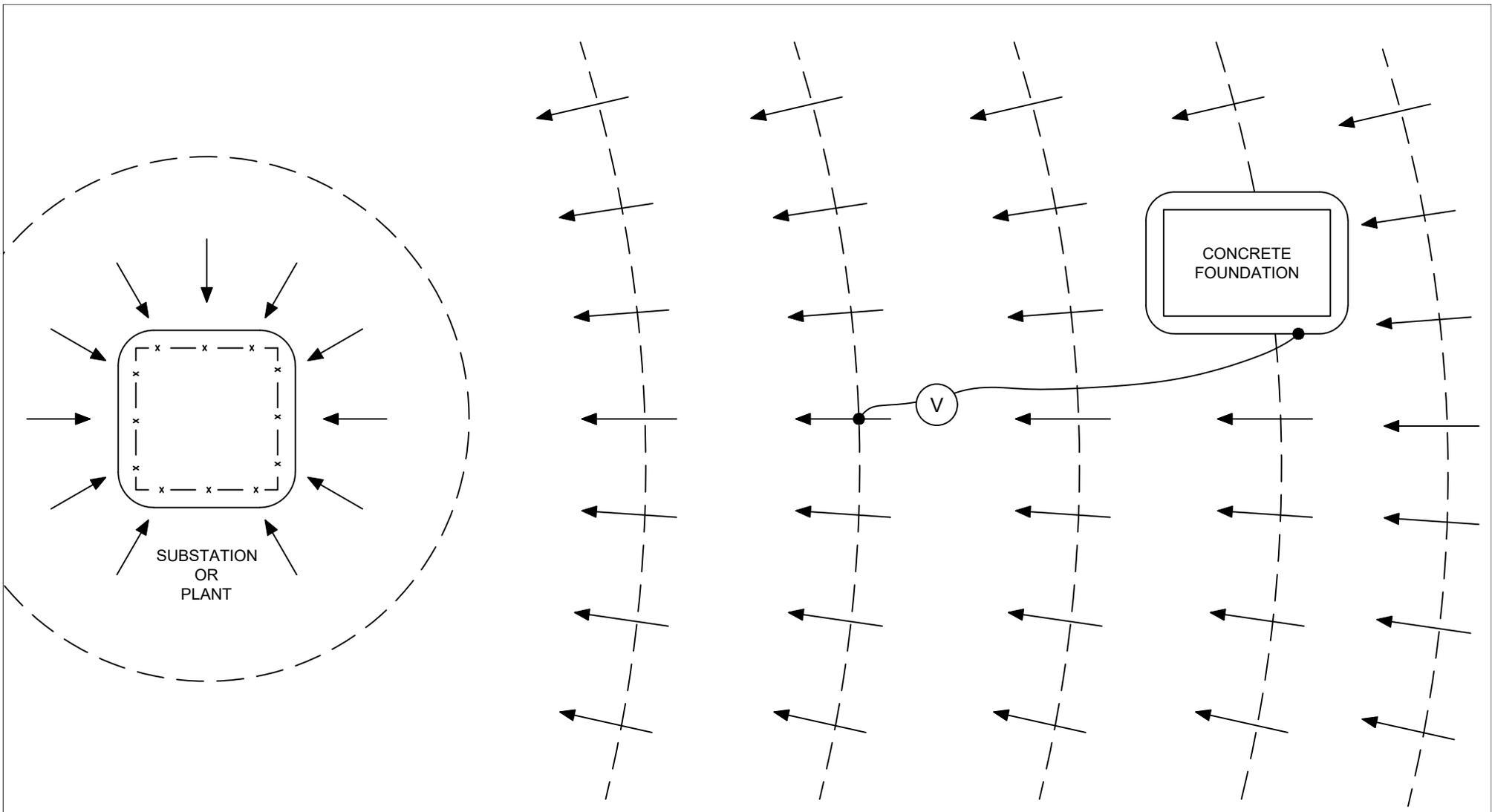


FIGURE 3
 NEUTRAL OPEN
 OR
 HIGH RESISTANCE



LEGEND:

← GROUND CURRENT FLOW

— — — EQUAL POTENTIAL LINES

● GROUND ELECTRODE

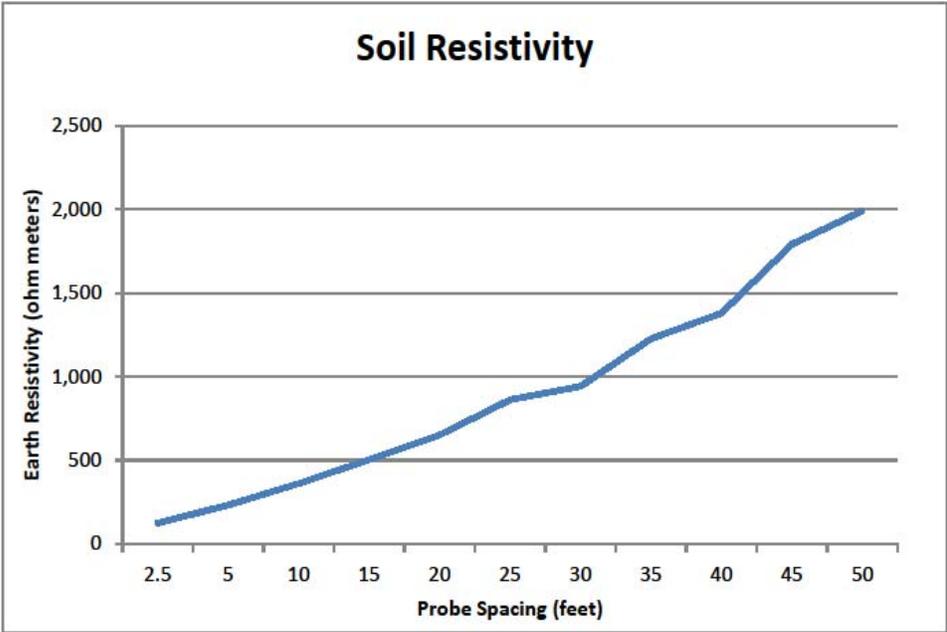
Ⓟ VOLTAGE MEASUREMENT

FIGURE 4
CURRENT FROM
OUTSIDE SOURCES

earth potential at that point caused by stray ground current flow from outside sources. If an insulated ground conductor is routed from the isolated service entrance ground to other points, the voltage of the service entrance is “transferred” to those points.

Multi-Grounded Neutral and Ground Rod Resistance Calculations

One of the circuit parameters that affects NEV is soil resistivity. Soil resistivity indicates the conductivity of the soil within a project vicinity. In order to calculate the impedance of neutral conductors with ground return and connected ground rods, one must determine the value of soil resistivity to use in calculations. Soil resistivity can be determined from soil resistivity tests on site, or can be estimated from recorded data for a site of interest. Following is a chart of the field measured Average Soil Resistivity in Ohm-Meters versus depth at a rock quarry in North Carolina.



UTEC uses SAFE Engineering software to determine the equivalent multi-layer soil model. The equivalent 2-layer soil model for this site is:

- 71.7 ohm-meters for a depth of 2.5 feet
- 10,870.5 ohm-meters infinitely deep below 2.5 feet

Soil resistivity data is used to calculate the neutral conductor impedance and the ground electrode, usually driven ground rods, and resistance.

Neutral Line Section Impedances

The impedance of an overhead conductor with ground return is calculated using the classic “Carson” equation. This equation is presented in the Westinghouse Transmission and Distribution Reference Book, Fourth Edition, Page 40, Section 3, Zero-Sequence Resistance and Inductive Reactance. Further development of this equation can be found in technical literature.

The equation for self-impedance of a conductor with earth return in ohms/mile is:

- $Z_{11} = (R_e + R_1) + j (X_e + X_1)$, where:
- $R_e = 0.00159 f$, where f is the frequency in hertz, (earth resistance)
- $R_1 =$ conductor resistance in ohms/mile
- $X_e = 0.002328 * f * (\log_{10} 4,665,600 \rho / f)$, where $\rho =$ soil resistivity in ohm-meters, (earth return path reactance)
- $X_1 =$ conductor inductive reactance in ohms/mile for one-foot spacing

The Carson equation determines the resistance of the conductor with earth return and the inductance of the conductor with earth return. Two variables in the equation are the system frequency and the soil resistivity. For high soil resistivity the return current is deeper than for low soil resistivity. For high frequency the return current is also deeper than for low or zero frequency.

Ground Rod Resistance

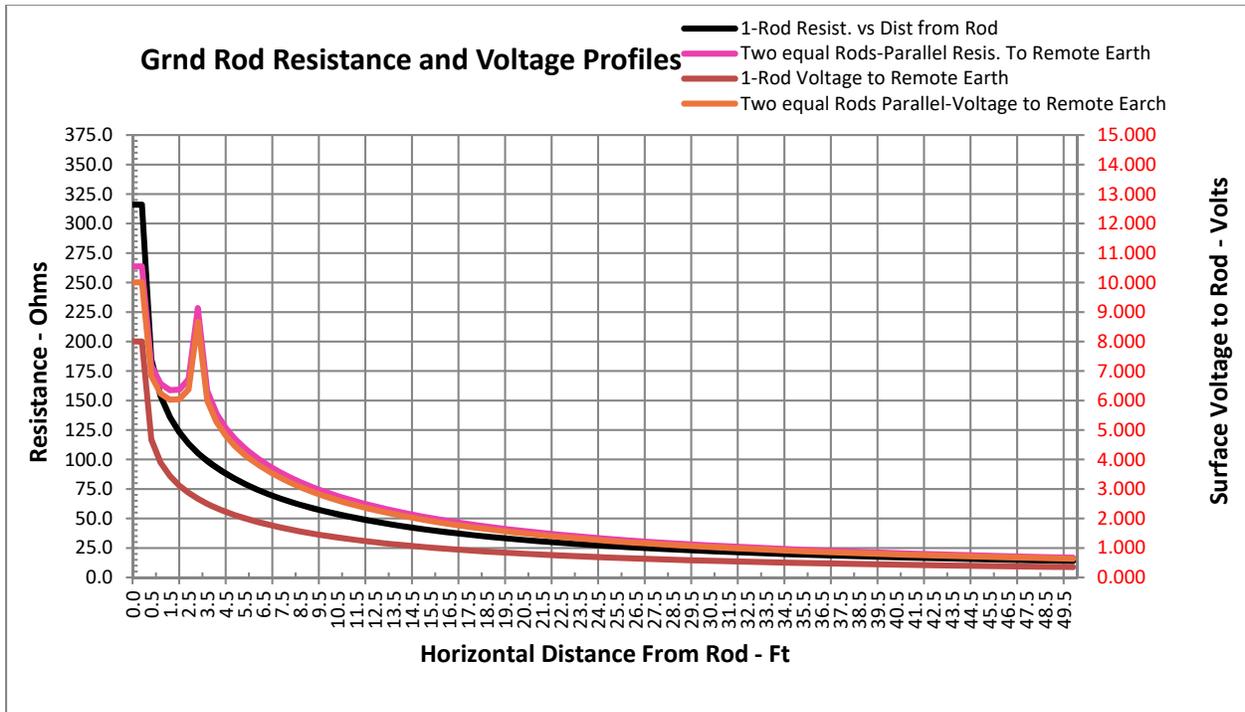
The equation for the resistance of a single ground rod versus radial distance from the rod, derived in the IEEE 80 Grounding Guide, is:

- $R = \rho / (2 * \pi * L) * [\ln(\text{COT}(\Theta/2))]$, where:
 - ρ is the homogeneous soil resistivity in units of ohm-meters
 - L is the ground rod length in meters (For example, 2-5/8" X 8' rods connected to make a 16' rod, 4.877 meters)
 - Θ is the angle formed between the axis of the ground rod and a point of interest on the earth surface
 - COT is cotangent of $\Theta/2$
 - \ln is the natural log of the value $\text{COT}(\Theta/2)$

Mathematically, the full resistance of a ground rod is calculated at a distance infinitely far away where $\Theta/2 = 45$ degrees.

Following is a chart showing ground rod resistance versus distance from the rod for one 3/4" X 16' copperweld ground rod and then two parallel 3/4" X 16' copperweld ground rods separated by 3', both installed in a homogenous soil with 1361 ohm-meters resistivity.

The calculated resistance of one rod is 316 ohms. The calculated resistance of the two rods separated by 3' is 211 ohms. If the separation of the two rods is increased to 30', the total resistance goes down to 169 ohms. While not ½ of the resistance of one rod, the resistance quickly approaches ½ with increased separation distance.



Knowing the current flow in each ground rod in a group, one can calculate the surface potential at points along the surface on a customer's premises.

Is Stray Voltage a Problem?

At a minimum, stray voltage can be annoying. At a maximum, stray voltage can be lethal.

Examples of Stray Voltages:

1. Shock when in a swimming pool and touching the metal ladder to get out of the pool
2. Shock when touching a pole down guy wire
3. Shock to cattle when attached to a milking machine or feeding
4. Shock when touching grounded equipment in a rock quarry

NEV Analysis

As stated previously, neutral to earth voltage, NEV, occurs naturally in grounded electric systems and is typically the culprit causing “stray” voltage complaints. NEV is a normal result of operating grounded wye electric systems. A circuit model of the neutral conductors, connected ground electrodes, and transformers’ injecting current into the neutral connection points can be developed to analyze NEV. The points of transformer current injection are modeled as “Current Sources”. Regardless of changes made to the neutral or ground rods, at a given point in time, the current delivered into the neutral and ground system does not change. What does change are the current flows in the neutral and ground rods and the resulting NEV.

Nodal matrix equations of the neutral/ground model can be prepared. The matrix admittances are complex values (real and imaginary components). Analysis using complex numbers increases the complexity of the math. The number of rows and columns in the Admittance matrix is two times the number of modeled nodes. The mathematical solution of the matrix equations produces the unknowns which are the neutral node voltages and element currents (neutral sections and ground rods), both real and imaginary components.

There are two reasons to go through this modeling effort:

1. To be able to mathematically match the problem that one is experiencing with actual field voltage measurements, confirming what is causing the problem
2. To be able to evaluate various solution options to determine how well they correct the problem before actually performing the system changes

Nodal matrix modeling can be used for a 3-phase line, a 2-phase line, or a 1-phase line. Figure 5 is a 1-phase line tapped from a 3-phase line routed several miles and serving several 1-phase customers along the line. Figure 6 is the circuit model for the 1-phase line. The primary current entering the neutral at each 1-phase transformer is the load being served by the transformer at the time of the analysis. Figure 1 (previously referenced) is a typical 7.2kV-120/240V single phase transformer. If this transformer is serving 15 kVA, the primary current is $15 \text{ kVA} / 7.2\text{kV} = 2.08$ amps at an angle determined by the power factor of the load. This primary current flows through the transformer primary coil and into the connection with the neutral. At the neutral connection, the current distributes itself based on the complex admittance matrix for the tap line neutral and grounds. The current at each transformer connection to the neutral divides and flows among each of the following paths:

1. Neutral section returning back to the source along the neutral conductor

2. Neutral section downline from each transformer
3. Transformer pole ground and all other pole grounds along the route connected to the neutral
4. Secondary neutral to the service entrance ground of each customer

In addition to the primary line neutral current flow, the secondary neutral currents also flow in the interconnection of neutrals. However, if the loads served by the transformer are relatively balanced between the two hot legs, very little current flows in the secondary neutral and ground. For simplification, one can usually assume the loads on the secondary are relatively balanced.

This same scenario of current flow occurs at each transformer in the system. The transformer currents along the line tap, and in particular the transformer currents close to the customer having stray voltage problems, cause the biggest part of the problem.

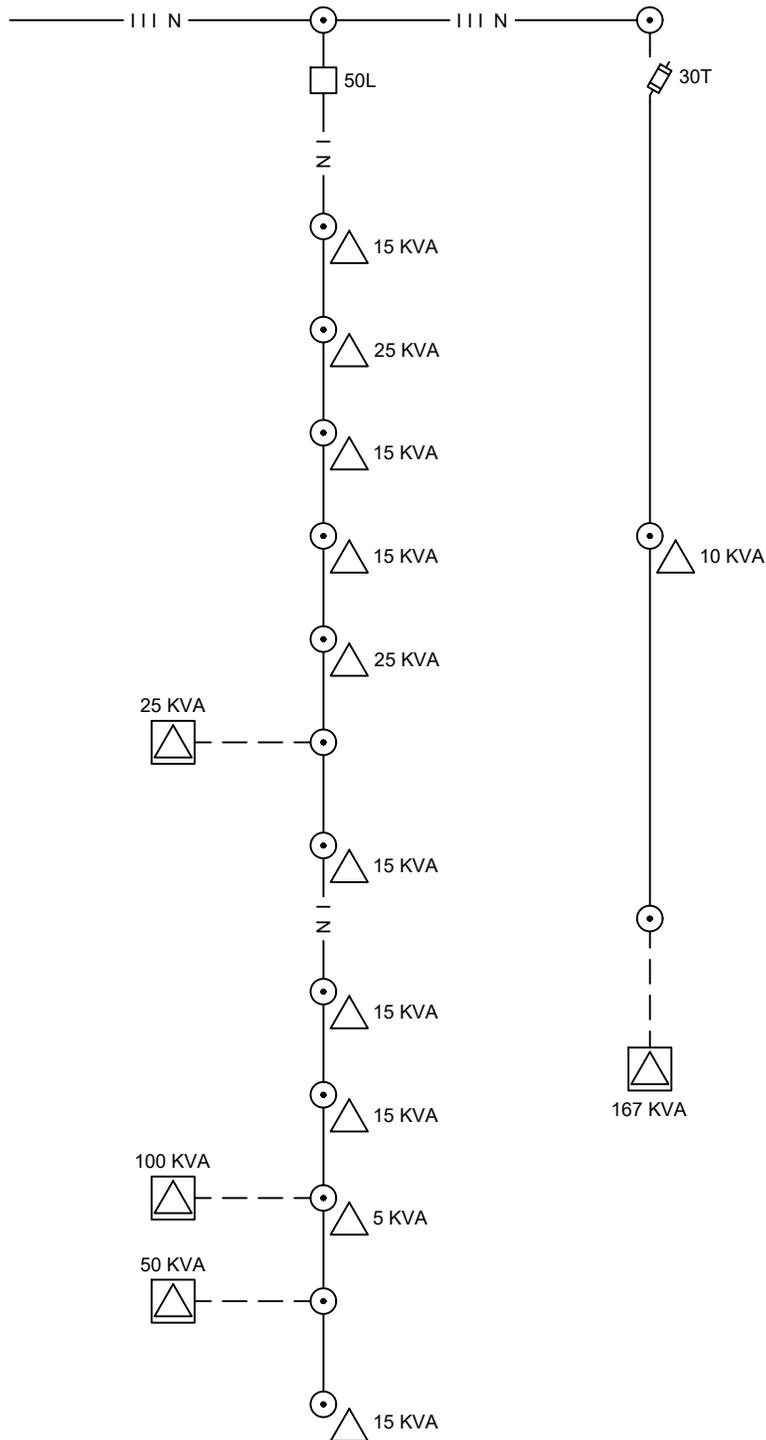
Model Results

Figure 5 is an example 1-phase circuit with several transformers serving customers along the line. Figure 6 is the neutral/ground nodal model of the circuit. Each transformer is injecting primary current into the neutral and is represented in the model as a current source. The admittance of the neutral conductor with ground return is calculated between each node point. The ground surface is represented by the cross hatching and the resistors shown below the grade line represent the resistance of each ground rod as current flows from the ground rod into the earth and ultimately back to the substation source.

UTEC developed a detailed spreadsheet to calculate all of the element admittance values and calculate the matrix values to perform a matrix solution. The results of this analysis are presented in the following table. The table shows the main 16 nodes and the results for each node voltage and element current. Node 13 is the location of customer NEV concern. The measured voltage in the field was 8-volts. Note that the calculated voltage to ground of node 13 is 7.95 volts. Also provided in the table are the current flows in each element, including the ground rods.

The chart shows the nodal voltages and the voltage angles throughout the system.

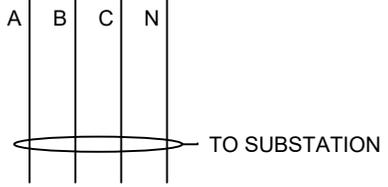
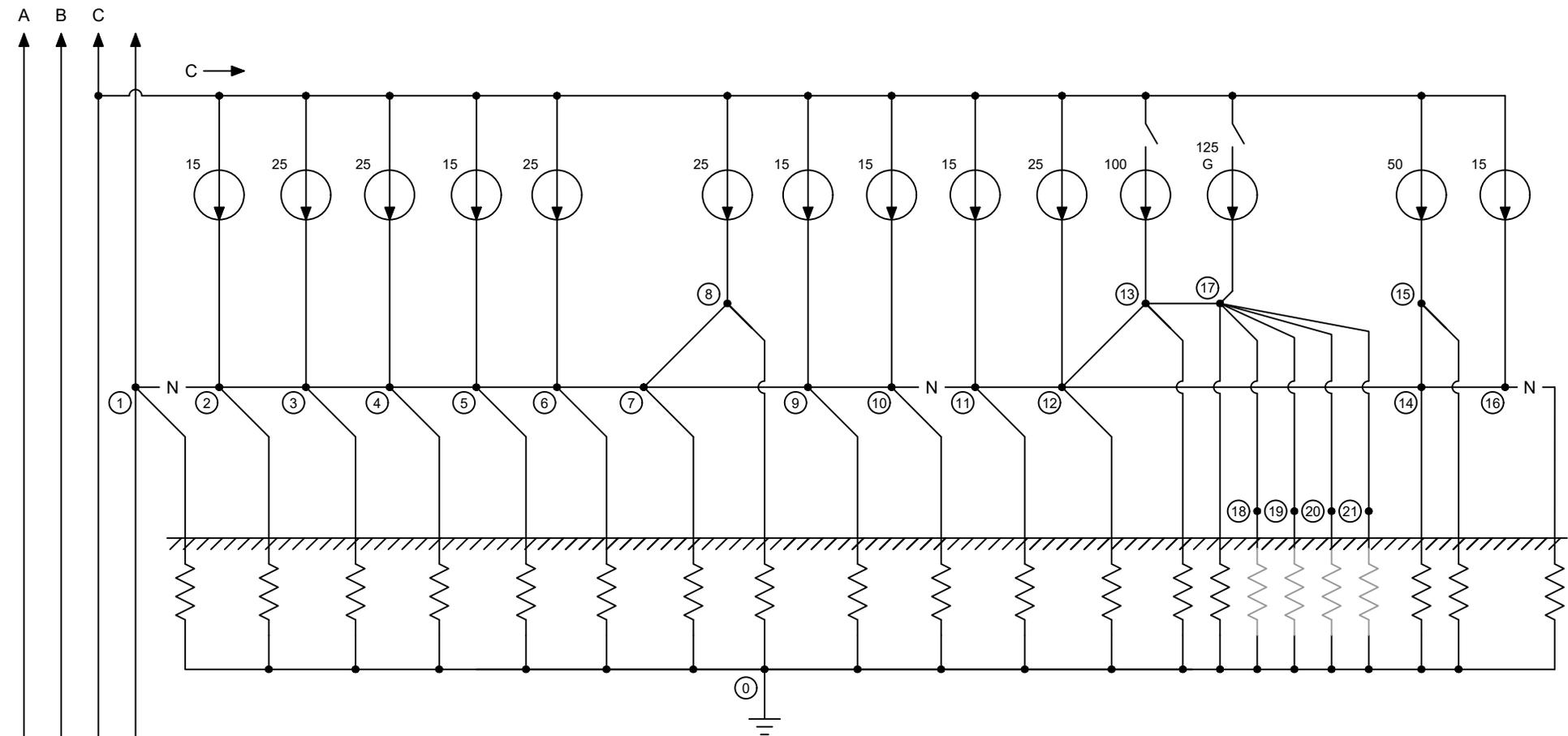
We are able to make various adjustments to the model and see how the results change. For example, we can add more ground rods in the vicinity of node 13 and determined that NEV actually increased. We examined adding ground rods at other locations along the line route and determined that neutral current was diverted into these nodes and the NEV at node 13 reduced. We also developed the spreadsheet so that customer loads can be adjusted, and/or the node voltage changes noted.



LEGEND:

- ⊙ NODES
- △ 15 KVA TYPICAL OH TRANSFORMER
- ▢△ 100 KVA TYPICAL PADMOUNT TRANSFORMER
- I N — OH SINGLE PHASE 2ND NEUTRAL

FIGURE 5
TYPICAL
1-PH 7.2 KV TAP



LEGEND:

100  TRANSFORMER MODELED AS CURRENT SOURCE TO NEUTRAL, KVA SIZE NOTED

125 G  240 VOLT STANDBY GENERATOR

 GROUND ELECTRODE RESISTANCE

 POSSIBLE GROUND ELECTRODE RESISTANCE

 CIRCUIT MODEL NODE NUMBER, TYPICAL

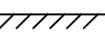
 EARTH SURFACE

FIGURE 6

**1-PH 7.2 KV TAP
NEV CONCERN
CUSTOMER AT NODE 13**

Nodal Matrix Solution

Nodes	Node Voltage - Volts	Node Voltage Ang - Deg	Line Sect Neut Current - Amps	Line Sect Neut Current Ang- Deg	Gnd Rod Curr - Amps	Gnd Rod Curr Ang - Deg
1	7.006	179.275			0.02217	179.275
2	7.026	179.169	0.21454	-84.068	0.02223	179.169
3	6.961	179.664	0.80715	86.846	0.02203	179.664
4	6.901	179.910	0.61057	103.900	0.02184	179.910
5	6.832	-178.500	1.84394	60.970	0.02162	-178.500
6	6.761	-177.240	1.50807	68.152	0.02140	-177.240
7	6.749	-174.142	3.32654	46.686	0.02136	-174.142
8	6.792	-175.085	2.41979	-135.328	0.02149	-175.085
9	6.636	-170.123	5.25958	45.769	0.02100	-170.123
10	7.723	176.860	17.78179	-102.615	0.02444	176.860
11	7.851	173.364	4.47996	-129.335	0.02484	173.364
12	7.989	169.766	4.69853	-132.431	0.02528	169.766
13	7.954	169.791	0.71525	91.985	0.02517	169.791
14	8.316	167.241	4.42182	-108.746	0.02632	167.241
15	8.307	167.359	0.39559	33.590	0.02629	167.359
16	8.329	165.731	2.00046	-149.572	0.02636	165.731
13	7.9539845	169.7914939	0.715250078	91.98481055	0.025170837	169.7914939

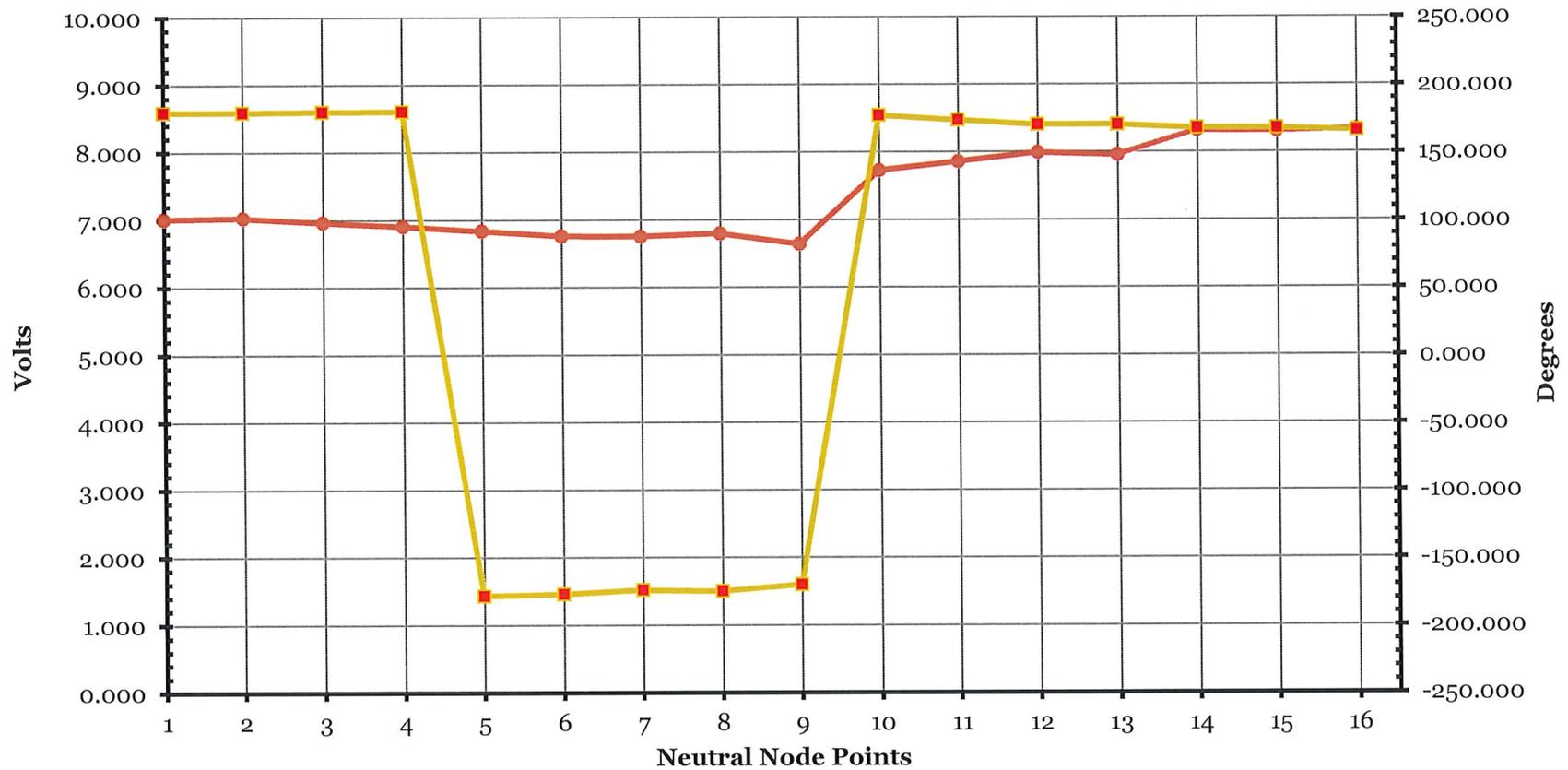
1-Phase Circuit (Figure 6)

Nodal Matrix Solution

1-Ph Neutral Circuit
Neutral Node Voltages



Node Voltage Mag. Node Voltage Ang



1-Phase Circuit (Figure 6)

What to Do About Stray Voltage

Let's discuss what may not be intuitive.

Oftentimes when experiencing shock voltages from touching objects thought to be un-energized, the reaction is to add more grounding at that location to minimize voltages to ground. Adding more grounding might actually be the wrong thing to do because more grounding reduces the ground resistance at that location which shunts more ground current flow into that location and may increase NEV at that location.

A better solution is likely to separate the utility neutral from the customer service entrance so the utility neutral voltage is not transferred to the customer service entrance. Isolation equipment is commercially available that accomplishes this separation. However, the utility ground must be sufficiently separated from the customer service ground. The reason is because the surface potential surrounding a ground rod diminishes with distance from the rod. If the customer service entrance ground rod is too close to the utility ground and intended to be separated, the voltage of the service entrance ground rod could be impacted by the utility ground rod voltage profile. The term used to describe this problem is "mutual resistance". The further separated the two grounds, the better. Most manufacturers of neutral isolation equipment recommend a minimum separation of 10'.