SEASONAL VARIATIONS OF GROUNDING IMPEDANCE AND NEUTRAL VOLTAGE IN COLD CLIMATES

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ABSTRACT

The cyclical changes in grounding impedance and neutral voltage are investigated as they relate to seasonal climatic changes at northern latitudes, where seasonal frost is common. Attempts to deal with these effects are often frustrated by their unpredictability, which is related to weather uncertainty. The power industry standard 8-ft ground rod is the focus of this study. A statistically sufficient sample of data was obtained over a period of two years that has led to a measurement of these seasonal variations and an experimental formulation of these effects. The study finds that the overall effect of seasonal climatic changes on the grounding impedances of an 8-ft ground rod and on the neutral voltages at these rods along a power distribution line is best described by simple sinusoids that attain maxima during winter and minima during summer. Notable relationships are also clarified among the ambient air temperature, the soil conductivity at various depths, the grounding impedance of the standard 8-ft grounding electrode, the grounding impedance of residential grounding, and the neutral voltage. This investigation has provided a better understanding of this seasonal occurrence, but also has raised interesting new questions along the way.

INTRODUCTION

The grounding of power distribution systems, whether they are of the 4-wire/3-phase system, as used predominantly in the United States, or of the 3-wire/3-phase system, as used predominantly in Europe, is a requisite that has acquired deep roots as the use and applications of electricity have spread and standardized [1]. Safety of operation and electromagnetic coupling have been the dominant concerns shaping the requirements for good and effective grounding practices, but newer concerns include the dairy farm stray voltage problem [2,3] and the possibility of health effects due to power-frequency electric and magnetic fields associated with ground currents [14].

The main grounding component of a power distribution line is the multitude of 8-ft ground rods (2.44 m) installed uniformly along the distribution line. Customer residential grounds also contribute to the good grounding of power distribution lines, especially in rural systems. The effectiveness of the power line 8-ft grounding electrode depends on earth resistivity, although the effect as seen by the line neutral is mitigated by the mass of single electrodes connected in parallel on the line. The resistivity of the earth at the surface changes considerably (and sometimes erratically) from region to region, and is affected by seasonally varying ground conditions that are correlated to seasonal climatological changes. The seasonal changes tend to be minor compared to geographically related changes in soil type and composition, and are often ignored in the overall characterization of the problem. Isolated measurements that outline the seasonal variation in grounding resistance of man-made electrode abound in the literature. More recently, new studies [4,5] have investigated the seasonal variation in grounding impedance and neutral voltage at a number of selected rural sites in Minnesota.

This paper reports the results of a newer research study attempting to isolate and quantify statistically this seasonal effect for a whole region and apart from confounding factors that are site-dependent. This study looks at the statistical behavior of the grounding impedance for a substantial sample of 8-ft ground rods over a period of two years. It draws a connection between a representative measure for the changing meteorological conditions, the ambient temperature, and the annual variations in grounding impedance of the 8-ft rod. The study defines both variables as a function of time of year. It also looks at related variables such as the neutral voltage and the residential grounding impedance as they vary seasonally.

BACKGROUND

The opportunity for this study was provided by the U.S. Navy ELF antenna located in Michigan, the presence of which required that some modifications be made to the nearby power utility distribution circuits to minimize coupling effects [6-10]. The antenna is essentially an earth-return circuit, many miles long, and carrying a current of 150 amperes at 76 Hz. An ELF voltage (76 Hz) appears on long conductors nearby, including the multigrounded neutral wire of power distribution circuits. All service transformer installations nearby were modified [6-10] to mitigate for the safety problems that the presence of such voltages would cause when conducted inside a residence by the standard neutral connection. The modification, illustrated in Figure 1, separates the residence neutral from the distribution line neutral. In conformity with rule 97.D.2 of the National Electrical Safety Code a neutral isolator (in this case, a spark gap with a rated breakdown voltage of 530 V ac) is installed between the two isolated neutrals, which are grounded separately -- the cooperation of other utilities is necessary to achieve an effective grounding isolation. The isolated grounds are typically located 4.9-7.3 m (16-24 ft) from each other and display little mutual coupling.

One permanent reference ground rod was installed nearby, to provide a remote earth connection during testing. An industry-standard ground rod--2.44 m (8-ft) copperweld rod 15.8 mm (5/8 in) in diameter--was installed with the top end buried 0.3 m (1 ft) below the surface and at least 15 m (50 ft) from the service transformer grounds and any other known ground or metallic object. As we shall see later, the reference ground rod provides the basis for the additional tests that have led to this study. Figure 2 outlines more clearly the neutral circuits of interest to this study and the grounding elements. Z_g is used to denote the grounding impedance of the standard 8-ft ground rod, and V_n is used to denote the neutral voltage at any point on the line (in this study, it was measured only at service transformer locations).

The ELF antenna provides a steady operation throughout the year, with extensive and deep antenna grounds that are not much affected by superficial ground resistivity and related seasonal variations. The operation of the ELF antenna depends mostly on the deep earth conductivity. The coupling with the power line, voltage V_e in Figure 2, depends, among other things, on the earth resistivity near the surface, so it is expected to be affected by seasonal meteorological variations. The ELF neutral voltage, V_n in Figure 2, depends on V_e

and the neutral line grounding. The latter is composed of a multitude of 8-ft ground rods, Z_g in Figure 2, which are affected by seasonal changes in superficial ground conductivity.

TESTING DETAILS

Neutral isolation has been installed at 1250 utilization transformer locations in a 2330 km^2 (900 mi^2) area. One hundred and sixty customers were selected as a statistically sufficient sample of locations where measurements would be made repeatedly over a period of two years to measure this seasonality effect. The distribution of the test locations was a balance between regional representation and customer density distribution. Testing was conducted at each selected location four times a year, once for each season. Data quality was prescribed by the measured data available for each season over a two-year period.

Ambient temperature data were obtained during visits to each location during 1990 and 1991. The time of day of each visit was the same to the extent that conditions permitted, but was not precise. Temperature was measured with ordinary inexpensive mercury thermometers, and ambient temperature should therefore be considered as nominal.

The primary neutral line voltage at the mitigated service transformer was measured once each season at each test box with a Fluke Model 87 voltmeter. The voltmeter was preceded by a narrow-band-pass filter and a 60-Hz notch filter to discriminate the 76-Hz signal from neutral line voltages associated with line loading. The voltage measured was the ELF open circuit voltage between the primary neutral conductor and the reference ground rod. In essence, the measured ELF-V_n produces a fortuitous neutral voltage, as a result of the ELF induced voltage V_e, that is much higher than the small and noisy 60-Hz voltage normally present on a power line neutral; this ELF-V_n voltage is amenable to examination and more helpful in understanding the seasonal behavior.

The reference ground rod impedance to ground was measured with a Biddle Earth Tester Model 250241 in the point-to-point mode as a loop impedance between the primary neutral and the reference ground rod. The loop impedance actually includes the primary neutral impedance to ground in series with the earth impedance and the reference ground rod impedance to ground. The primary neutral impedance to ground is small (in the order of 5 Ω) because it is the aggregate of many pole grounds in parallel. The reference ground rod impedance to ground is large because it represents a single ground rod buried in soil of relatively high resistivity. For all practical purposes, and discounting the small mutual coupling effects and the small earth impedance, the measured loop impedance gives the grounding impedance of the reference ground rod itself, that is, Z_g. Any other 8-ft ground rod nearby is expected to exhibit an equal grounding impedance.

The secondary neutral impedance to ground, Z_s in Figure 2, was similarly deduced from a loop impedance measurement between the primary line neutral and the isolated secondary neutral that included the residential grounding, again using the Biddle Earth Tester.

RESULTS

Eight clusters of data were obtained for each of the following: the temperature (T), the ELF neutral voltage (ELF-V_n), the 8-ft reference ground rod impedance to ground (Z_g), and the residential impedance to ground (the whole service transformer secondary system impedance to ground denoted as Z_s). Each cluster represented a season of the year.

A final quality check of data reduced the total number of samples for some parameters. Ambient air temperature was available for all seasons and all sample locations. Complete measurements, which included 8 seasonal clusters of data, were available at 114 locations for Z_g, at 151 locations for V_n, and at 130 locations for Z_s. Missing or bad data were the common cause for dropping sites. A recurring problem with Z_g data was values over 10,000 Ω, the upper limit of the measuring instrument.

A computer spreadsheet was used to analyze the data statistically. Least-sum-of-squares curve fitting was used to derive equations describing the behavior of parameters of interest.

Ambient Temperature

A scatter diagram of ambient air temperature measurements and the best-fit curve is shown in Figure 3. The equation describing temperature T as a function of the sequential day of the year (Day) as counted from January 1st is:

$$T = 5.28 + 15.8 \, \mathrm{Sin} \left\{ \frac{2\pi}{365} (Day - 108) \right\} \qquad (^\circ C) \tag{1}$$

$$T = 41.5 + 28.5 \, \mathrm{Sin} \left\{ \frac{2\pi}{365} (Day - 108) \right\} \qquad (°F)$$

The regression coefficient, r, is 0.98. Thus, almost all of the variation in temperature, 96% (r^2 x 100), is explained by the change in the date (Day of the year). The 95% confidence interval is ±10 °C (18 °F), and also is shown in Figure 3.

Reference Ground Rod Impedance to Ground

Reference ground rod impedance to ground was transformed to eliminate variability associated with customer location. This was done by first obtaining the average value of Z_g for each site, which is denoted Z_{ga}. Then each Z_g datum was divided by the site Z_{ga}. The result is a value (Z_g/Z_{ga}) normalized to 1, that emphasizes seasonal deviation of Z_g from the site two-year average. The behavior of the normalized Z_g is shown with its best-fit curve in Figure 4. The normalized impedance to ground function is described by the equation:

$$\frac{Z_g}{Z_{ga}} = 1 + 0.24 \, \mathrm{Sin} \left\{ \frac{2\pi}{365} (Day + 71) \right\} \tag{2}$$

The regression coefficient, r, is only 0.47, indicating that only about 22% (r^2 x 100) of the observed variation is related to seasonal changes. The 95% confidence interval, also shown in Figure 4, is ± 0.64.

The two-year mean value of Z_g was 1313 Ω. Recall that test locations where ground rod impedance to ground exceeded 10,000 Ω were omitted from this study, because they exceeded the range of the measuring instrument. The calculated mean value therefore is likely to be higher if all measurements above 10,000 Ω in the sample were known and included in the calculation of the mean. The population mean is estimated to be close to 2000 Ω.

Secondary Neutral Impedance to Ground

Data for secondary neutral impedance to ground were transformed in the same way that Z_g data were treated. The resulting normalized data, best-fit curves, and 95%

confidence interval are shown in Figure 5. The curve best fitting the data follows the equation:

$$\frac{Z_s}{Z_{sa}} = 1 + 0.28 \text{ Sin } \left\{ \frac{2\pi}{365} (Day + 44) \right\} \qquad (3)$$

The regression coefficient, r, is 0.36, which means that about 13% of the variation is explained by seasonality. The 95% confidence interval of the normalized Z_s variability is ± 1.18.

The mean value of Z_s is about 90 Ω. The 95% confidence interval for Z_s ranges from about 5 Ω to 1570 Ω.

Line Neutral Voltage

The induced 76-Hz neutral voltage V_n is location dependent like Z_g and Z_s, and therefore required a similar transformation. The resulting normalized quantity, V_n/V_{na}, thereby indicates the seasonal deviations of V_n from the two-year average value at that site. The normalized results are shown in Figure 6 with the best-fit curve. The equation describing the behavior of induced line neutral voltage as a function of time is:

$$\frac{V_n}{V_{na}} = 1 + 0.15 \text{ Sin } \left\{ \frac{2\pi}{365} (Day + 44) \right\} \qquad (4)$$

The regression coefficient, r, is 0.52 for the normalized V_n and indicates that 27% (r^2 x 100) of the observed variation in induced neutral voltage appears to be related directly to time. The 95% confidence interval, also shown in Figure 6, is $\pm$ 0.4 relative to the regression sinusoid.

The measured ELF primary neutral voltages had a mean value of 7.5 V, with some measurements as high as 64 V.

DISCUSSION

A yearly periodicity in ambient air temperature is to be expected, especially at more northerly latitudes where the seasons of the year are most pronounced. In this case, a regression sinusoid has been shown to describe ambient air temperature quite well for a region in the Upper Peninsula of Michigan. Statistically, the coldest day of the year is January 17th, and the warmest is July 17th.

Equation (1) is not likely to perfectly fit the ambient temperature profiles that may occur elsewhere in the northern United States. However, one would expect that somewhat similar expressions could be derived for any geographic region. As discussed below, obtaining such an expression is useful for understanding the behavior of grounding impedances and neutral voltages.

Reference Ground Rod Impedance to Ground

Figure 7 shows that the reference ground rod impedance to ground, Z_g, has a log-normal distribution, with a slight slant to the right, for larger $\mathrm{Log}(Z_g)$. The shift probably is due to omitting ground rod impedances exceeding 10,000 Ω from the study — note the absence of data near $\mathrm{Log}(Z_g) = 4$, which corresponds to 10,000 Ω.

Figure 4 shows that the normalized Z_g reaches its statistical maximum and minimum values on January 20th and July 20th, respectively. These dates lag the statistically coldest and warmest dates by three days. The lag appears to be attributable to soil conditions. Rod impedance to ground is affected by soil resistivity, which, in turn, is influenced by soil temperature and moisture.

A measurement of Z_g is an indirect measure of soil resistivity, as is evident from the expression [13,15]:

$$Z_g = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{a} - 1\right) \quad ohms \tag{5}$$

for $L >> a$,

where ρ = soil resistivity in Ω-meters

L = ground rod length in meters

a = ground rod diameter in meters

For the ground rods used in this study, Equation (5) reduces to:

$$Z_g = 0.4\,\rho \tag{6}$$

and substituting for Z_g in Equation (2) yields the same expression for soil resistivity as for reference ground rod impedance:

$$\frac{\rho}{\rho_{ave}} = 1 + 0.24 \text{ Sin } \left\{ \frac{2\pi}{365} (Day + 71) \right\} \tag{7}$$

That is, soil resistivity also reaches its statistical maximum and minimum values three days after the statistically coldest and warmest days of the year. It is important to recognize that Equation (7) applies to the top 7.6 m (25 ft) of soil [13,16], since it relates to the 8-ft reference ground rod. Gustafson et al. [4,5] have reported similar seasonal ground rod impedance changes in Minnesota.

All this is based on the assumption of a uniform earth resistivity. This, however, is rarely the case, especially in the top 3 m (10 ft) of the earth, where climatic seasonal changes are very pronounced and include seasonal frost. This top layer of the earth is best thought of as a multilayered medium. The measured Z_g integrates the effects of earth resistivity stratification. Equation (7) can then be interpreted as applicable to the equivalent earth resistivity that would yield the same Z_g using Equation (6).

It is obvious that the phenomenon is much more complex, as temperature and moisture content vary both as a function of depth into the soil and as a function of time. These changes are very dynamic and depend on topography, vegetation, rainfall, snow cover in winter, and the severity of climatic variables. Frost in winter is probably the most durable effect that can be addressed with a simple model. From the point of view of the 8-ft ground rod, the earth can be modeled as two layers: an upper layer that is frozen and poorly conductive, and a lower layer that is unfrozen, warmer, and much more conductive. It is this lower layer that stabilizes Z_g through the year, mitigating for the drastic changes in climatic variations in the upper layer. This explains why there is only $\pm$24% in the variation of Z_g. A deeper ground rod would tend to minimize this variation, as has been shown by Gustafson et al. [5].

In summary, Equation (7) states that about 24% of the variation that occurs in near-surface soil resistivity as measured by the reference ground rod over a one-year period appears to be due to seasonal changes of the climate in the Upper Peninsula of Michigan. The rest of the variability is also mostly related to ambient weather conditions, but is not describable by a sinusoid. Rainfall, for example, controls moisture level in the top soil during the warm seasons and can be thought of more as an on/off function than a sinusoid; frost, during winter, provides another on/off type function.

Secondary Neutral Impedance to Ground

Z_s data are nearly normally distributed, as shown in Figure 8. Data are lacking below about 10 Ω, $\text{Log}(Z_s) = 1$, due to difficulties in measuring low Z_s that included lack of precision. Furthermore, Z_s includes the primary neutral impedance to ground (around 5 Ω), which for values of Z_s below 20 Ω is a large component to consider.

Figure 5 showed that Z_s maxima and minima lagged temperature variations by about 30 days. The lag reflects the fact that Z_s is influenced by soil resistivity quite deep below the surface.

Induced Neutral Voltage

The log transform of V_n is normally distributed (Figure 9). Like Z_g, the actual distribution of V_n is slightly shifted to the right. In this instance, the shift may reflect a small bias. When there was a choice of customers at the selected location, the choice leaned toward the customer with the highest neutral voltage, on the assumption that higher V_n would yield a better measurement of the seasonal variation. While this possible bias may affect the mean, it does not modify the seasonal effect measurement.

Figure 6 and Equation (4) show that V_n , like Z_s, reaches a maximum value on Day 47 (February 16th) and a minimum value six months later, on August 15th. These dates lag minimum and maximum ambient air temperatures, respectively, by about 30 days. Recall that the time lags for Z_g were only three days.

There are significant differences between the nature of the ELF-V_n studied here for seasonality effects and the 60-Hz-V_n; these make it impossible to simply extrapolate the results. The ELF-V_n is a result of the coupled ELF voltage V_e from a nearby antenna circuit, while the 60-Hz-V_n is mainly the result of imbalance load current flowing in and out of the earth through Z_g.

Computer models indicated that for a uniform change in Z_g and constant V_e, the ELF-V_n should not change much. Because we have seen that the ELF-V_n does change and, furthermore, because the ELF-V_n lags the ambient temperature by 30 days, which we have interpreted to imply a deep earth effect, we have deduced that the observed changes in ELF-V_n must be caused by a change in the coupling factor with the antenna. This 30-day lag is an important fact for the ELF interference itself.

The 60-Hz-V_n is typically very small (around 1 V for the study area) and very dynamic for an simple characterization. It has to change somewhat seasonally as Z_g varies over the year. Gustafson et al. [3] and Surbrook et al. [2] have indicated ways to model this problem. The introduction of a seasonal effect in Z_g should provide for a study of expected variability in 60-Hz-V_n. However, in reality there may be other confounding factors that may wash out this effect. Power loading, for example, has its own seasonal patterns, which implies a possible seasonal change in 60-Hz-V_n due to a seasonal change in the loading current.

Time Lags

The time lag of three days associated with reference ground rod impedance to ground, Z_g, may be within the error range of this analysis, and therefore may be nothing more than a modeling imprecision. Alternatively, the brief lag may be associated with the onset of colder soil temperature and the development of frost close to the surface. In either event, the lag is so short that one can reasonably assume that Z_g will be at its maximum during the coldest days of winter. Likewise, warmer soil temperature near the surface is likely to minimize the value of Z_g during the summer.

The 30-day lags in Z_s and V_n maxima and minima are not likely to be the result of modeling imprecision or statistical chance. The inductively coupled V_e, which causes V_n, is greatly influenced by deeper earth resistivity. The effects of climatological changes at the surface diffuse into the earth with a decreased intensity as function of depth, but also with a time lag. Thus it is reasonable to conclude that the 30-day lags are due to the natural lag that exists in nature for the seasonal climatological changes at the earth surface to propagate deeper into the earth, at depths that also affect the coupling between antenna and neutral circuits.

As Figures 1 and 2 show, secondary neutral impedance involves a variety of elements, including ground rods at service poles, grounds at power meters, and customer grounds (typically plumbing). The parameter Z_s is likely to be influenced by changes in soil resistivity relatively deep below the surface.

CONCLUSIONS

This study was designed to collect field data from a ready-made situation and investigate possible relationships that may help in predicting changes to the 8-ft ground rod impedance and to the neutral voltage caused by seasonal climatic changes.
Simple sinusoids are best in capturing the overall seasonal effect. At this northern latitude, the seasonal change in the grounding impedance of an 8-ft ground rod is $\pm$24% from its annual average value, as described by Equation (2). The seasonal change in the 8-ft ground rod impedance also tracks closely the ambient temperature changes, with a minor delay of only few days. This kind of variability can be expected in other regions that exhibit the same yearly temperature profile derived here for the Upper Peninsula of Michigan.

Only 22% of the observed variability in the 8-ft ground rod impedance to ground can be attributed to a systematic change in climatic variations. This confirms the generally-held feeling that seasonal changes represent minor variations compared to other factors. This result is reasonable, since there is a loose causal relationship between ambient temperature and grounding impedance. The latter depends more closely on soil moisture and temperature. Tracking rainfall, soil moisture at various depths, and soil temperatures may provide better control variables, which should yield high correlation factors, and resolve much of the uncertainty. However, these are hard-to-come-by data, while the ambient temperature is more commonly known even in its natural swings between winter and summer.

Because R_g for a standard 8-ft ground rod depends on the earth ground resistivity, Equation (6), changes in R_g are a reflection of similar changes in the earth resistivity at the surface. However, it has been pointed out that the earth surface is more properly characterized as a multilayered medium. The statistical significance of R_g is in providing a bulk estimate of the earth surface conductivity from the estimated mean value of Z_g, using Equation (6), and its seasonal variability, using Equation (7).

Realizing that the neutral voltage is dependent on R_g, the study also examined for possible seasonal changes in neutral voltage. The stand-in ELF neutral voltage does vary $\pm 15\%$ with the seasons, as described by Equation (4). We have also concluded that the ELF-V_n lags the ambient temperature changes by 30 days, most likely because of the delays for the climatic changes to be felt deeper in the earth. It has also been pointed out that the 60-Hz-V_n would vary in step with Z_g and Z_s, depending on which one is more dominant at any particular point of the distribution circuit.

The time lags have provided surprising and interesting observations. One question that comes out of this is what the time lag would be between the 60-Hz line neutral voltage and ambient temperature when the residential grounds are tied to the distribution line grounds, as is normally the case? The answer may depend on how important the residential grounding is to the line neutral grounding. In a rural system, the residential grounding may determine the time lag, while, in a urban setting, the individual residential grounding is less important, just as the 8-ft ground rod. In urban systems, the most important part of the grounding is provided by other utilities, principally urban water distribution systems.

A better understanding of these variables and relationships remains an important objective as the interest in grounding practices and their implications for ground currents become more intense. For example, it appears that the direct statistical correlation between grounding impedance and soil characteristics such as moisture, frost, and temperature at various depths may provide better relationships. Thermo-conductivity models of the earth surface may also be able to pin down the effective depth in the earth to which seasonal climatic changes are experienced, which give rise to the 30-day lag in the inductive coupling. This could then be tied to multilayer models of earth conductivity for a better characterization of the grounding impedance question.

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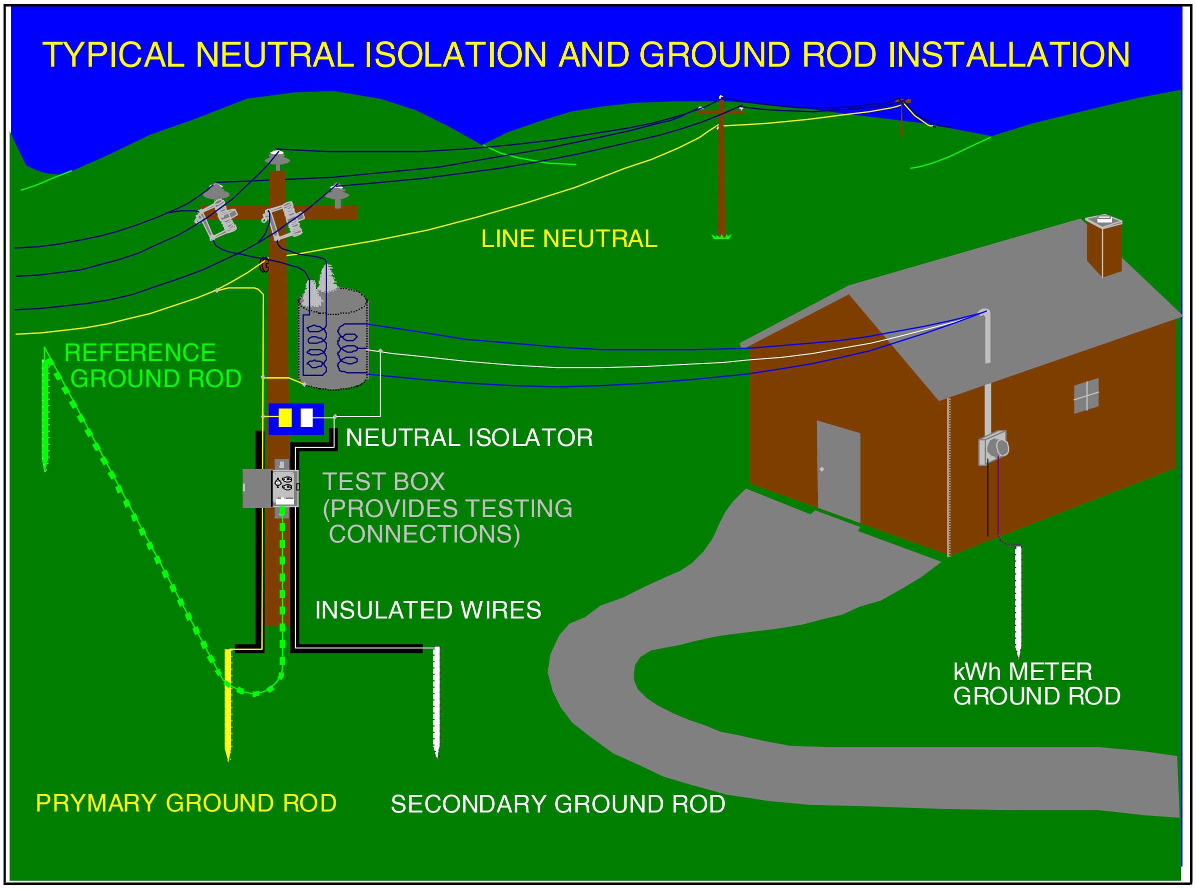

Figure 1. Typical neutral isolation and reference ground rod installation.

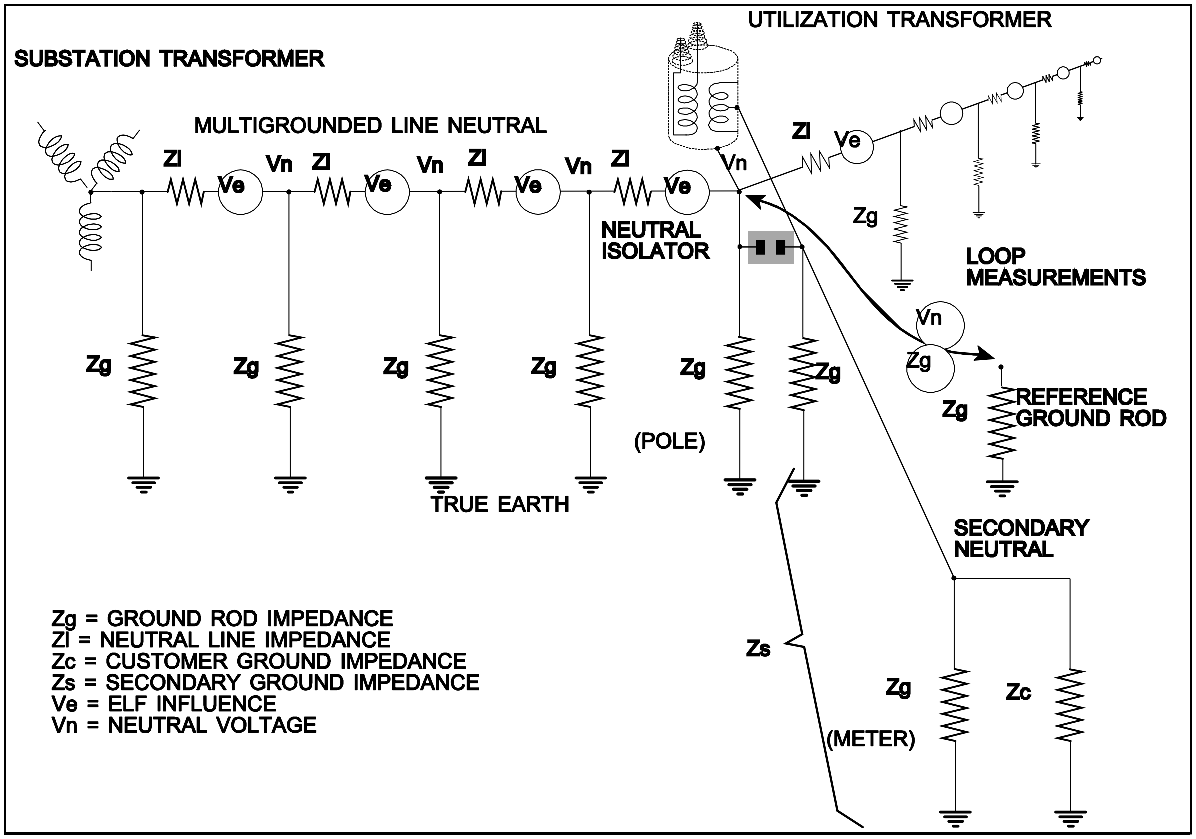

Figure 2. Grounding circuit formed by the neutral wire.

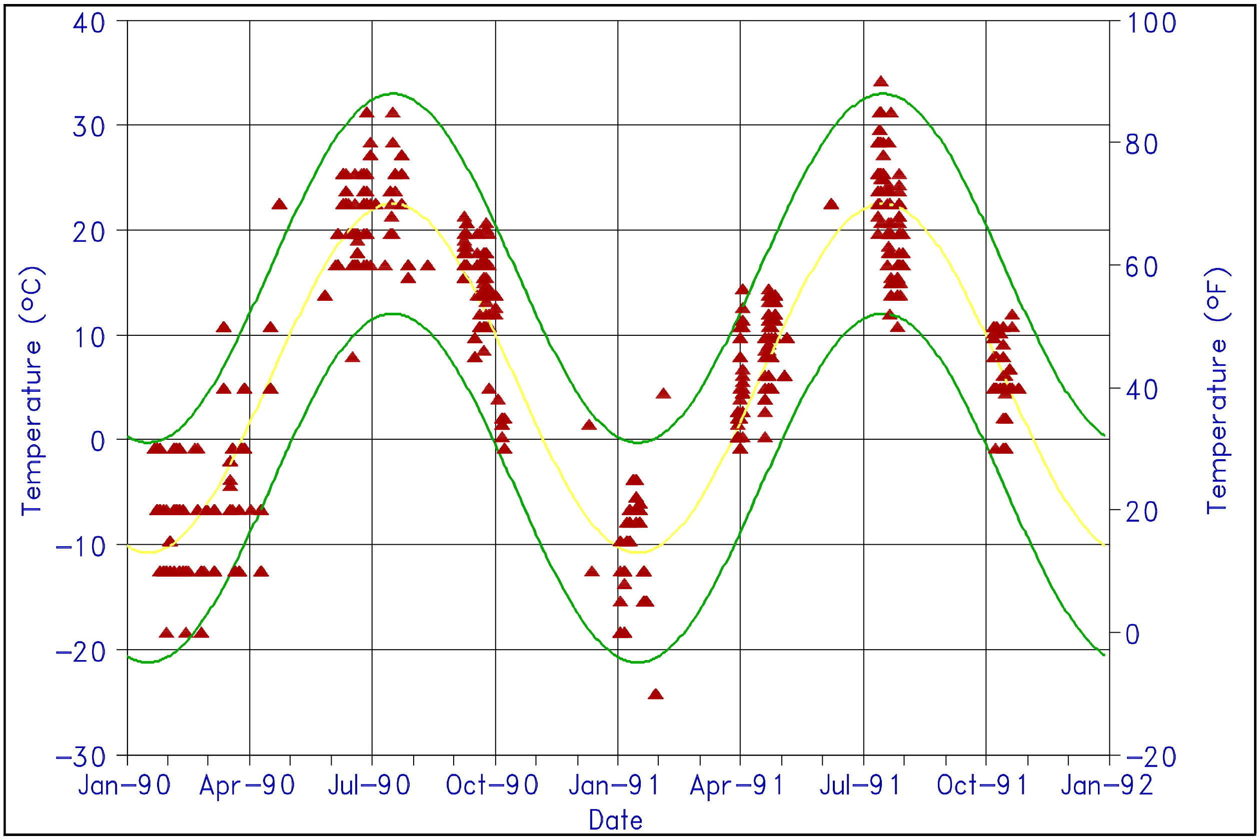

Figure 3. Seasonal variation, best-fit sinusoid, and 95% confidence interval for ambient air temperature.

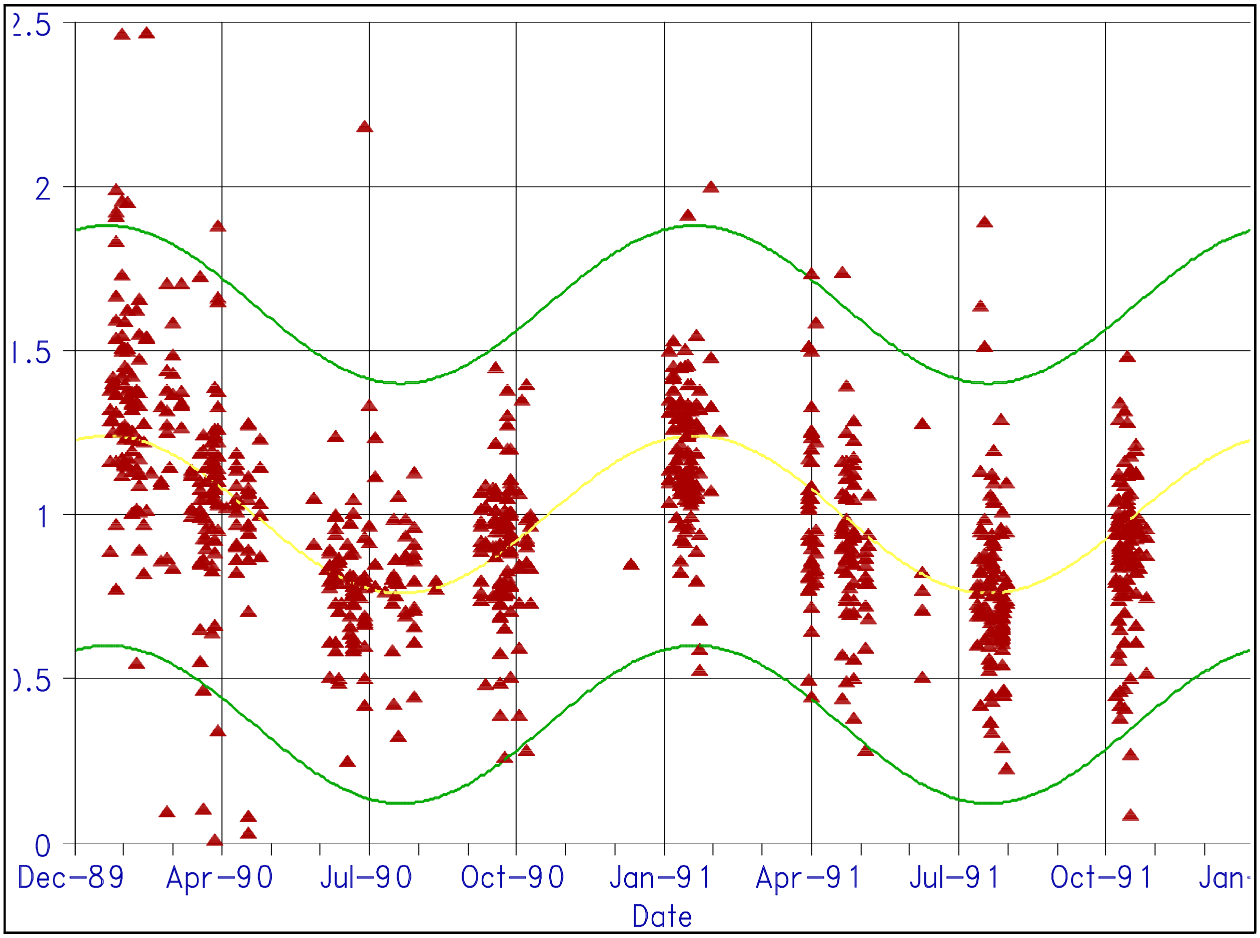

Figure 4. Seasonal variation, best-fit sinusoid, and 95% confidence interval for normalized reference ground rod impedance.

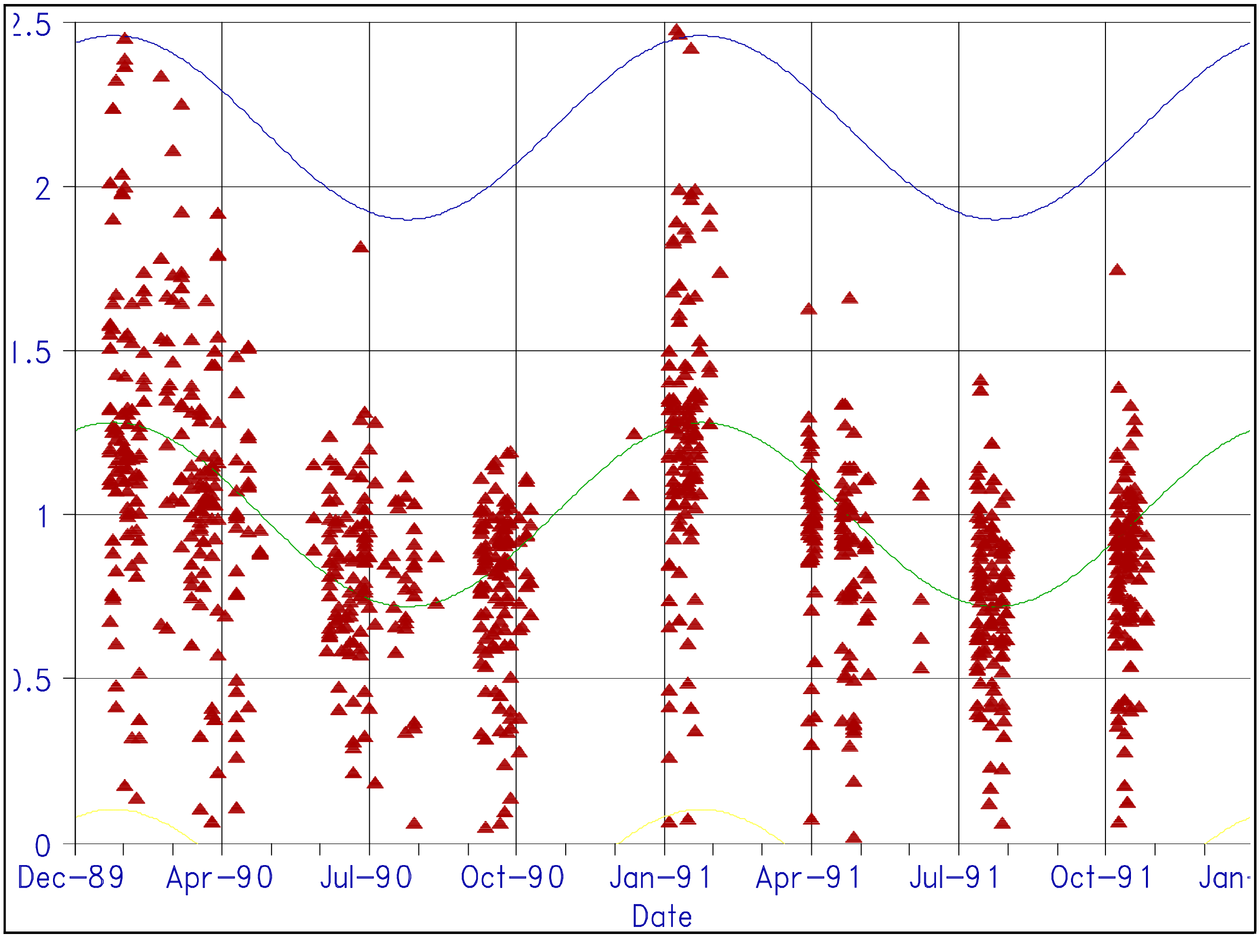

Figure 5.Seasonal variation, best-fit sinusoid, and 95% confidence interval for normalized secondary neutral impedance to ground.

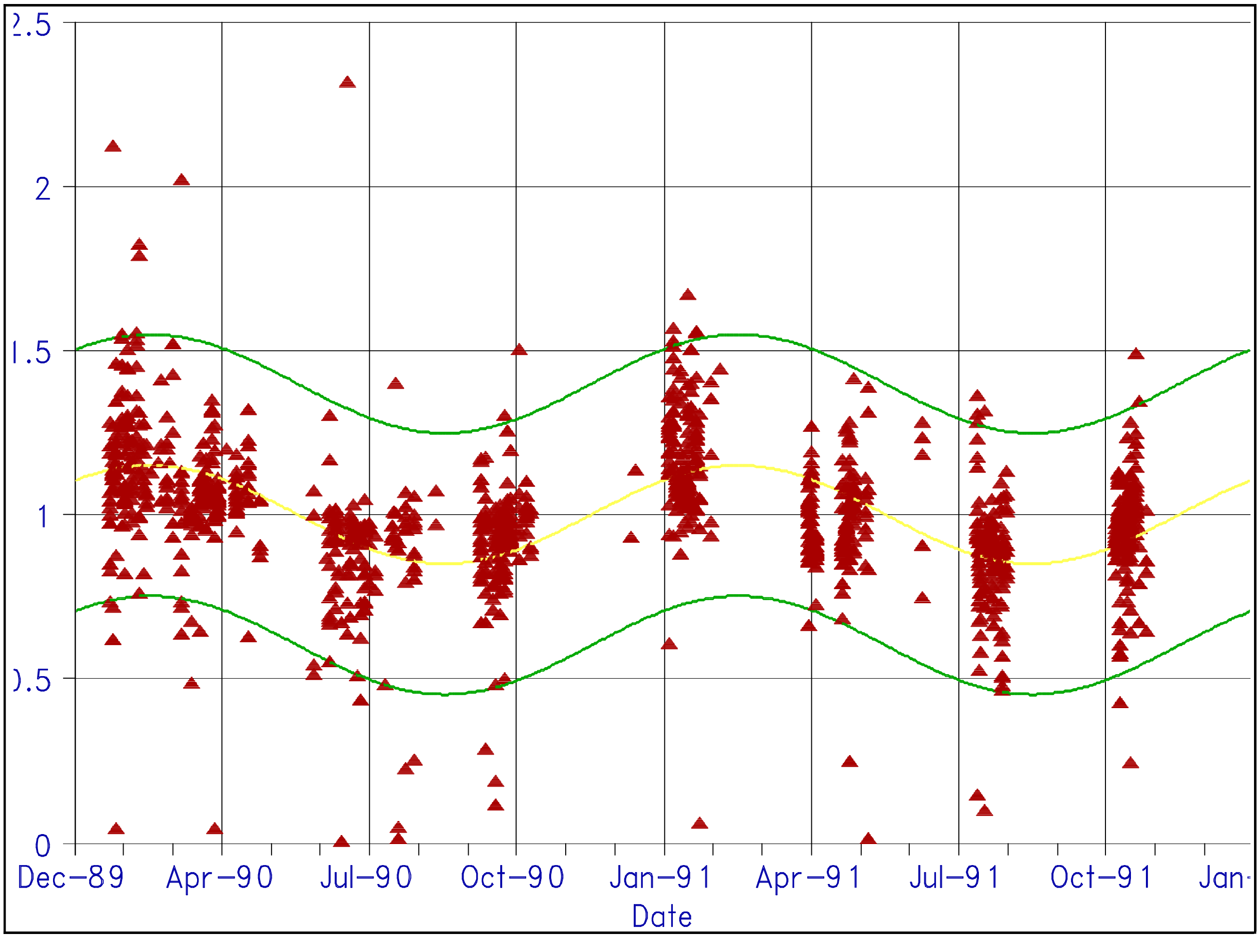

Figure 6.Seasonal variation, the best-fit sinusoid, and 95% confidence interval for normalized primary neutral voltage.

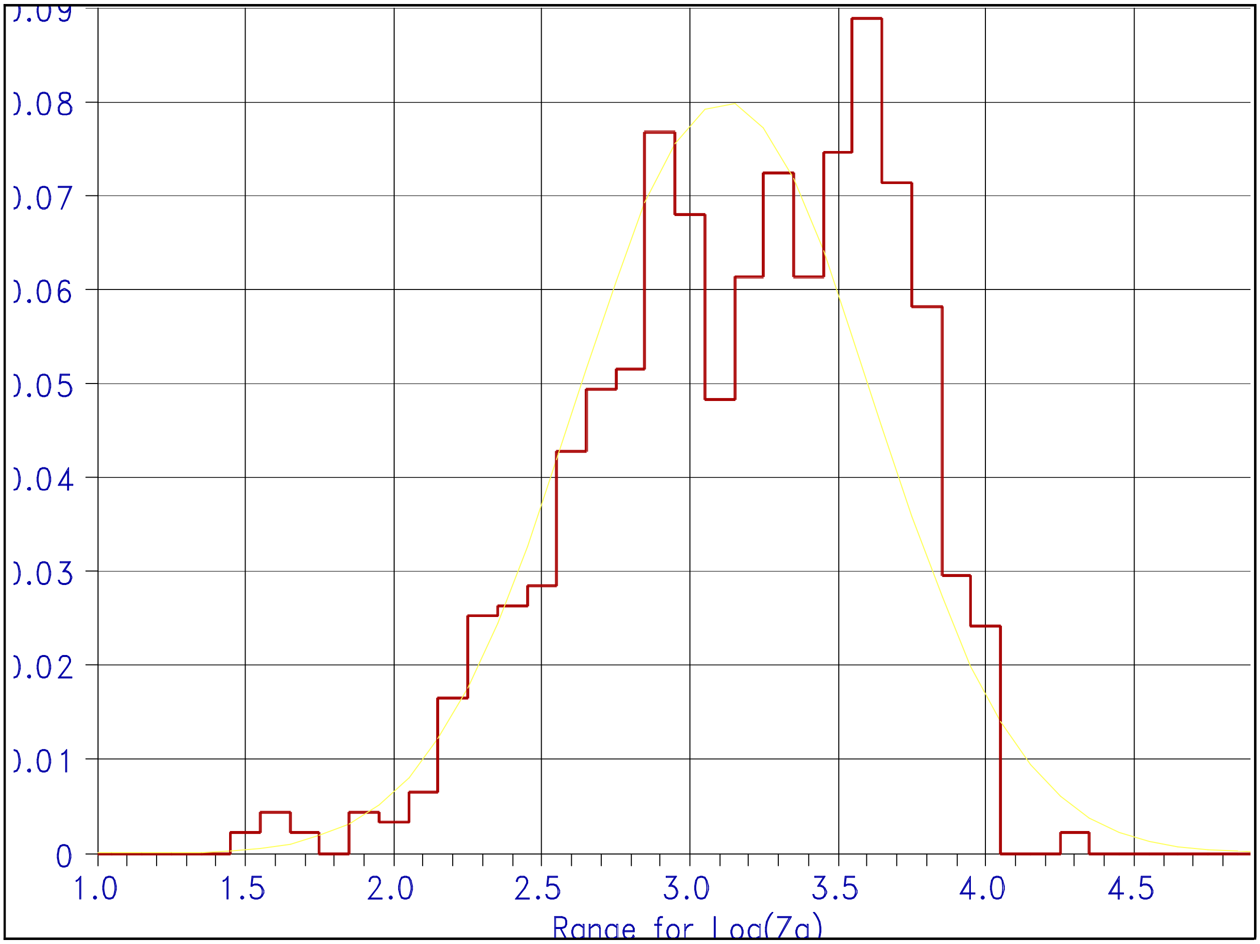

Figure 7.Frequency distribution and normalized distribution for the reference ground rod impedance to ground, Z_g.

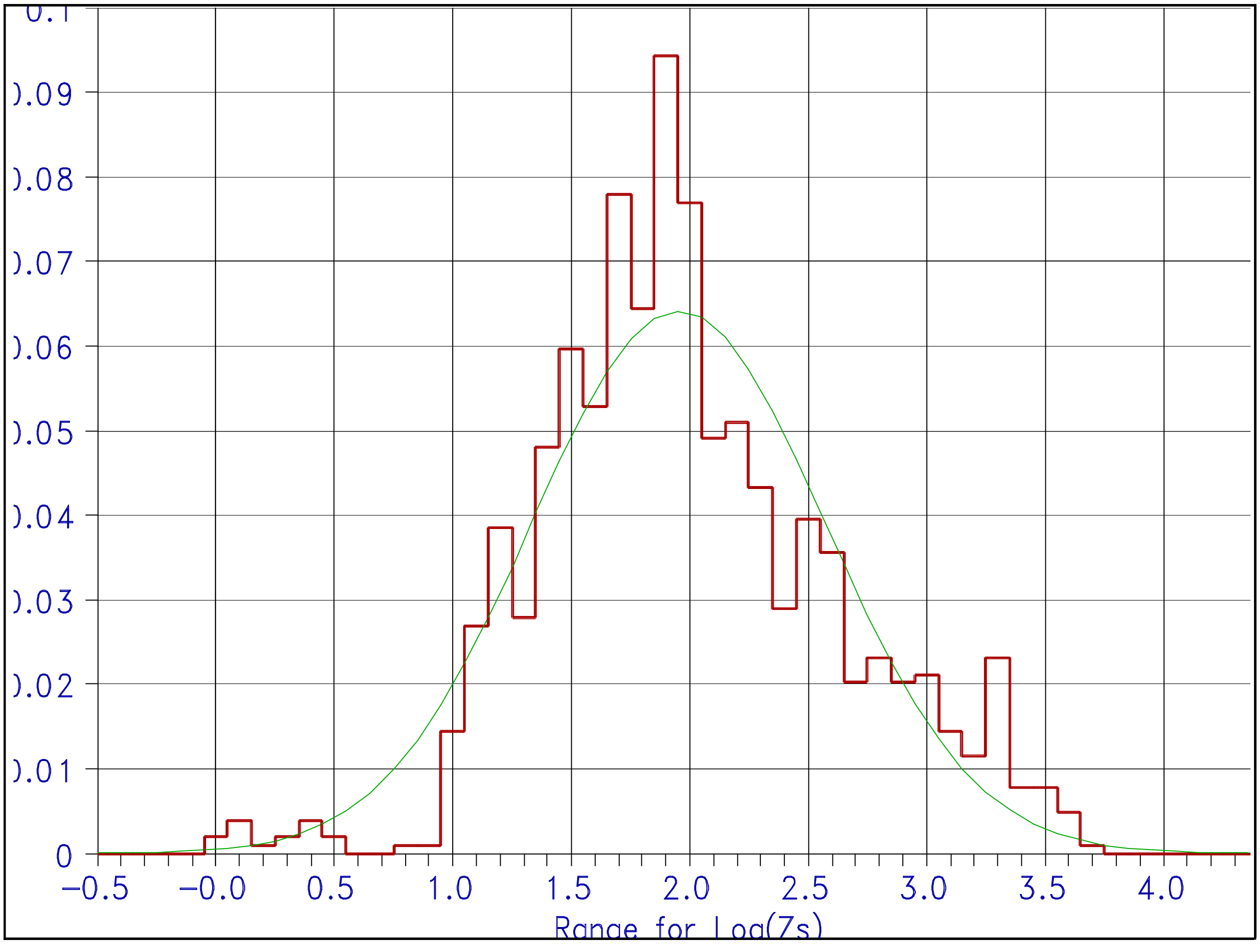

Figure 8.Frequency distribution and normalized distribution for the secondary neutral impedance to ground, Z_s.

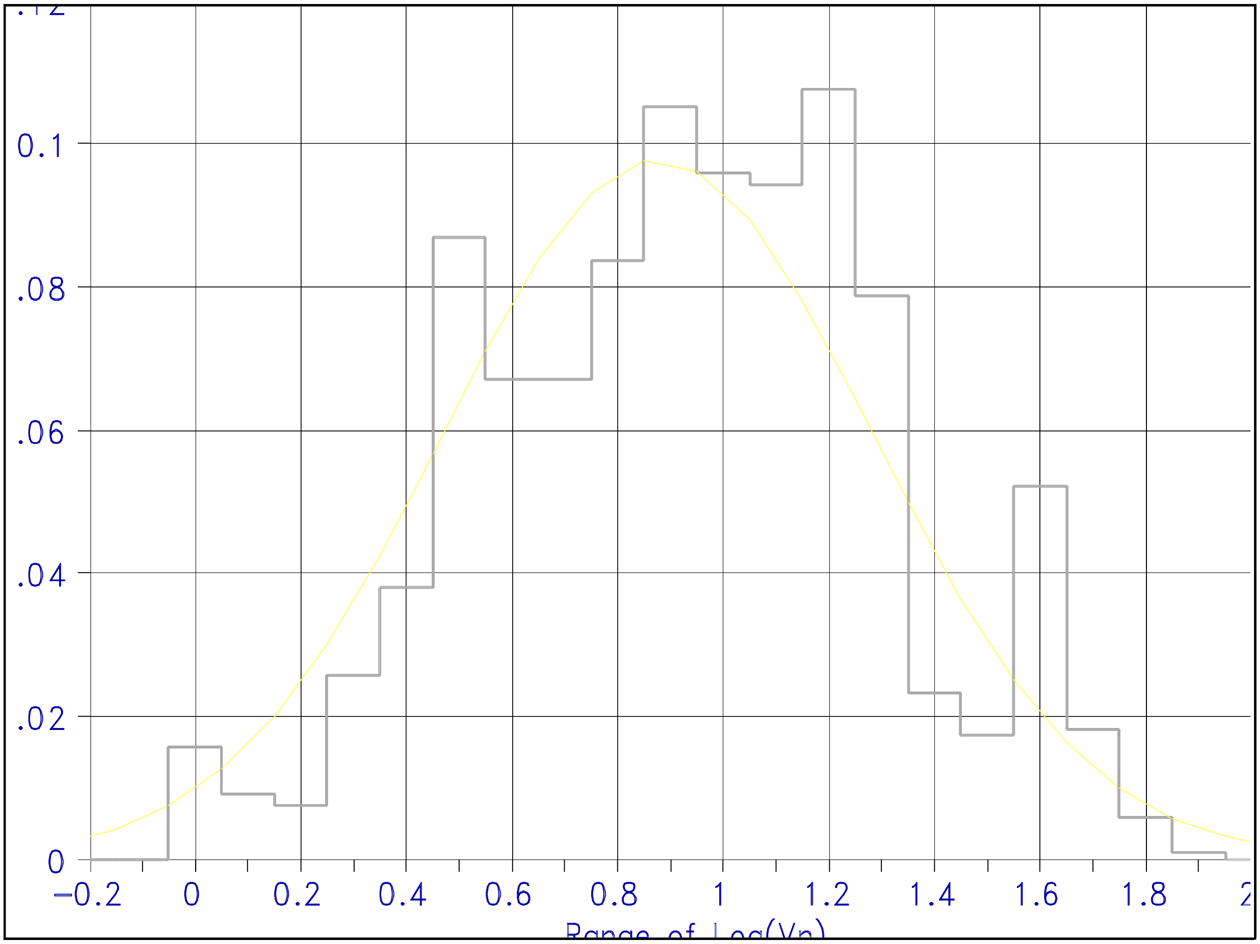

Figure 9.Frequency distribution and normalized distribution for the 76 Hz neutral voltage V_n.