Grounding Equivalency of Steel Poles

A white paper prepared for:

AMERICAN IRON AND STEEL INSTITUTE

by

J. Patrick Donohoe, Ph.D, P.E.
Department of Electrical & Computer Engineering
Mississippi State University
Box 9571
Mississippi State, Mississippi 39762
http://www.ece.msstate.edu

phone: (601) 325-2180
fax: (601) 325-2298
e-mail: donohoe@ece.msstate.edu

April 1999

1. Introduction

An increasing number of utilities are installing metal transmission and distribution poles due to the many advantages of metal poles over wood poles. The purpose of this white paper is to present evidence that the embedded portion of a representative steel pole offers significant grounding capability. In fact, the grounding resistance of the embedded portion of a steel pole can be shown to be lower than standard ground rods under specific conditions.

In this white paper, the Numerical Electromagnetics Code (NEC-4) [1] is used to compute the grounding resistance of a variety of grounding electrodes. NEC-4 is a method of moments [2] code originally designed for the analysis of antennas and scatterers. NEC-4 can be used in the computation of ground resistances since it allows for conducting structures over a finitely conducting ground which may penetrate the ground. Of particular interest is the grounding resistance of a representative steel pole such as a typical 40 foot class 3 steel distribution pole. The specific characteristics of this steel pole are shown in Figure 1.

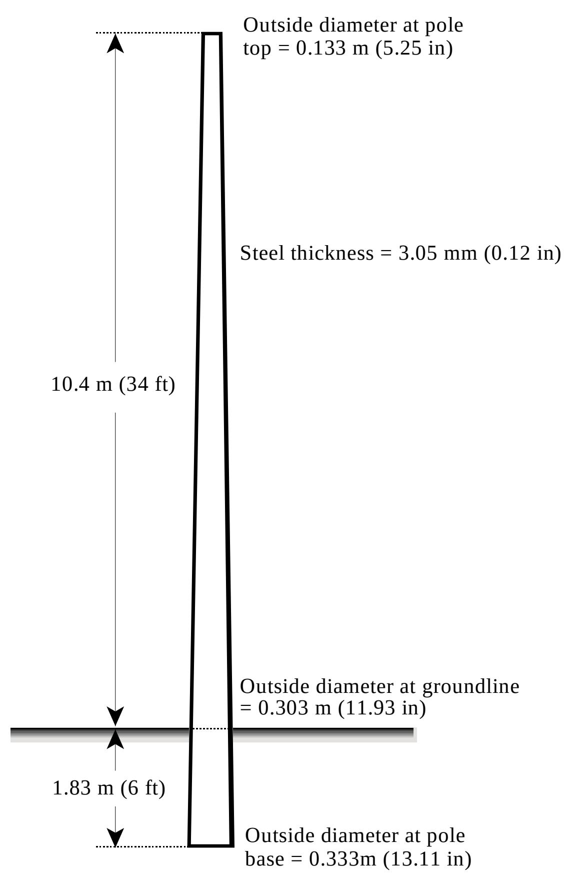

Figure 1. 40 ft class 3 steel pole.

The computational technique for determining ground resistance is first validated using standard ground rods. The computed results are compared with the analytical equation for cylindrical ground rods as given in the IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems (ANSI/IEEE Std 142-1982) [3]. As with any ground resistance calculation, the soil characteristics are of prime importance. Two soil types are considered for each ground resistance computation: a relatively low conductivity sandy soil and a relatively high conductivity clay soil. Average values for the conductivities of these general soil types are taken from [3].

Several different scenarios of grounding for the steel pole are considered. Given that the steel pole may be treated with below grade protection in the form of a spray-applied polyurethane or heat shrink tubing, the effect on the ground resistance must be determined. Thus, the grounding resistance characteristics for the steel pole are determined assuming below grade protection at 0.305 m (1 ft) intervals.

Also, since "existing electrodes" such as steel reinforcing bars in concrete foundations and footings are considered to be acceptable grounds, the grounding resistance of an example reinforced concrete pile is computed for comparison. The dimensions of the concrete pile are chosen to be similar to those of the steel pole.

2. Computational Modeling of the Fall-of-Potential Method

The ground resistance of the various electrodes considered here are computed using NEC-4 by applying the so-called *fall-of-potential* method [3]. This technique is commonly used in field measurements of ground resistance. As shown in Figure 2, the fall-of-potential method employs three terminals: the ground electrode under test, a current electrode and a voltage probe. The current is driven through the ground electrode under test and the potential is measured at different locations with the voltage probe. Using NEC-4, the conductor system consisting of the source, current electrode and ground electrode are included in the model. The voltage as a function of position $V(x)$ is determined by integrating the electric field within the soil.

The electrode ground resistance as a function of distance away from the ground electrode is given by

$$R(x) = \frac{V(x)}{I} \qquad (1)$$

The potential $V(x)$ varies rapidly in the vicinity of both the ground electrode and the current probe. By placing the current probe far enough away from the ground electrode, the electrode resistance approaches a near constant value over the midrange distances between ground electrode and the current probe. The total spacing between the ground electrode and the current probe in Figure 2 is designated as s. The so-called "62% Rule" may be applied where the fall-of-potential resistance given in (1) should match the theoretical ground resistance at a distance of 0.618s under ideal conditions.

3. Code Validation

The computational model for the fall-of-potential technique is validated by computing the grounding resistance of a standard ground rod in sandy soil and clay soil. The overall resistance

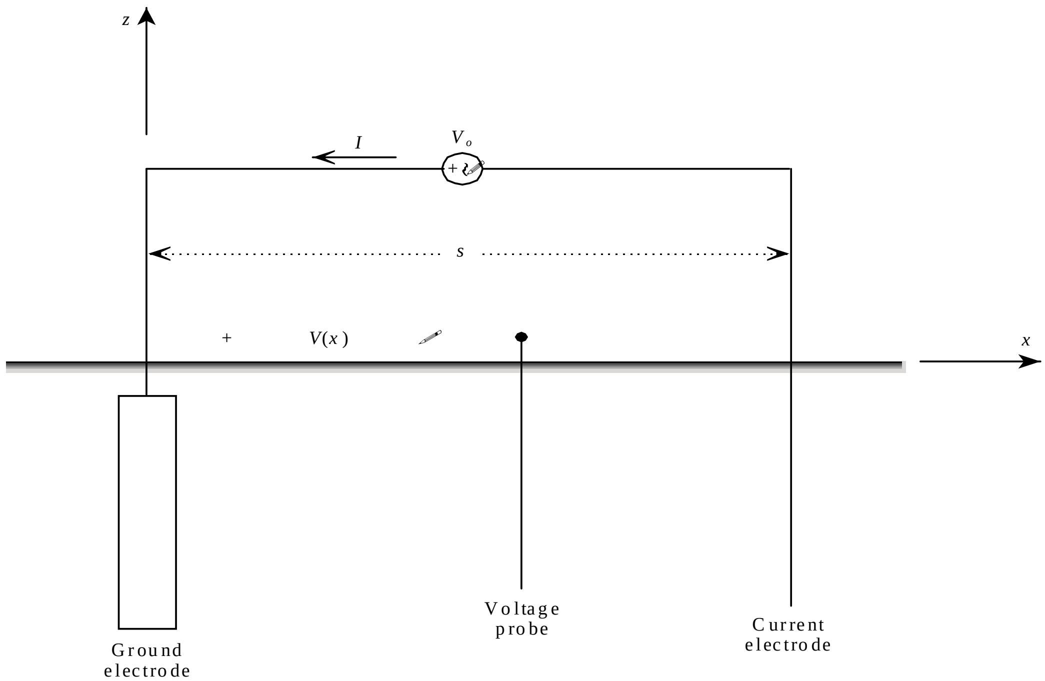

Figure 2. Fall-in-potential method.

of an installed ground electrode is actually the sum of three components: the resistance of the electrode conductor, the conductor/soil contact resistance, and the resistance of the soil surrounding the electrode. Typically, the total resistance of the electrode conductor and the conductor/soil contact resistance (being a small fraction of an ohm) is negligible in comparison to the resistance of the soil. Thus, the most analytical formulas for the electrode ground resistance usually account for the resistance of the soil only. The analytical expression for the ground resistance of an installed cylindrical ground rod of length *L* and radius *a* is [3]

$$R = \frac{1}{2\text{®}\pm L}\left(\ln\frac{4L}{a} - 1\right) \tag{2}$$

where Φ is the conductivity of the soil.

The electrode chosen for the NEC-4 code validation is a ground rod of length 3.05 m (10 ft) and radius 16 mm (5/8 in). The resistance of this ground rod is given in the ANSI/IEEE Std 142-1982 for different soil types at maximum, minimum and average soil conductivities. The average conductivities of sand (Φ = 1.064 m⊃/m) and clay (Φ = 24.63 m⊃/m) are used here in the code validation examples. The source voltage is assumed to be V_o = 1 volt and the overall separation distance between the ground rod and the current probe is assumed to be *s* = 30.5 m (100 ft). The current probe and the connecting wires are assumed to be perfectly conducting while the finite conductivity of the steel rod (Φ = $7.69\text{x}10^6$ ⊃/m) is included in the code. The resulting fall-of-potential plot is shown in Figure 3. Note that the potential varies rapidly in the vicinity of both the ground rod at *x* = 0 and the current probe at *x* = *s*.

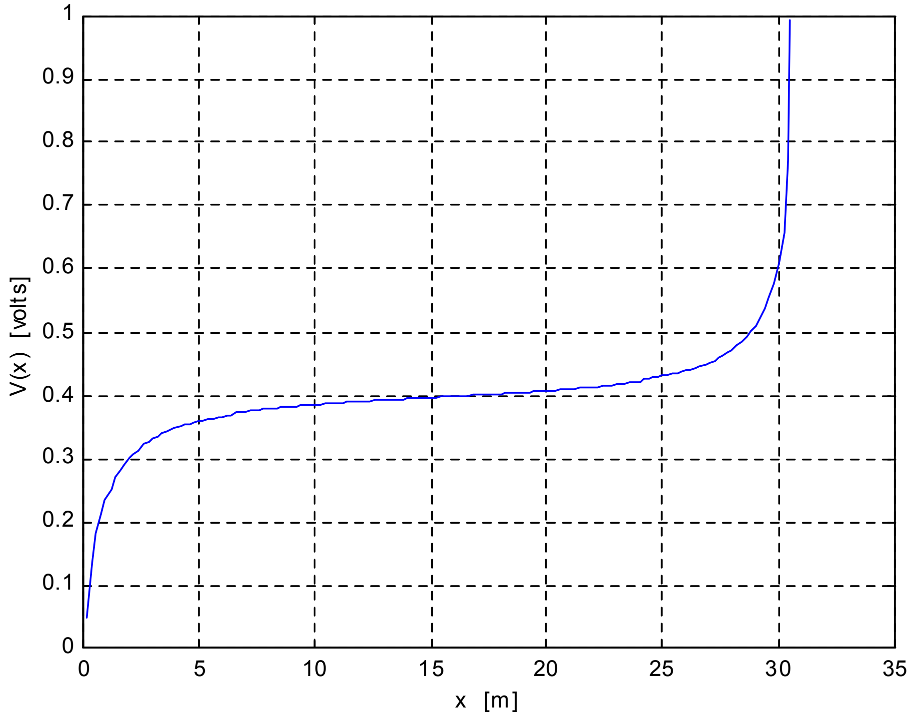

Figure 3. Computed variation in the potential between the ground rod and the current electrode [L = 3.05 m (10 ft), a = 16 mm (5/8 in)].

The computed ground rod resistances in sand and clay (using average conductivities for each soil) are compared to the analytical results in Table 1. Additionally, the ground resistances of 8 ft (2.44 m) ground rods of ½ in (13 mm) and 5/8 in (16 mm) diameters are computed in sand and in clay. The computed ground resistances are compared to analytically determined values in Table 2. From Tables 1 and 2, one finds that the computationally-obtained ground resistances are in close agreement with the analytically-obtained values.

Ground rod dimensions	Soil type	$V(0.618s)$	I	$R_{computed}$	$R_{analytical}$
L = 3.05 m (10 ft) a = 8 mm (5/8 in diameter)	sand	0.456 V	1.46 mA	313 Σ	310 Σ
L = 3.05 m (10 ft) a = 8 mm (5/8 in diameter)	clay	0.456 V	33.7 mA	13.5 Σ	13.4 Σ

Table 1. Comparison of computed and analytical ground resistances of 3.05 m (10 ft) ground rods with a = 8 mm (5/8 in diameter).

Ground rod dimensions	Soil type	$V(0.618s)$	I	$R_{computed}$	$R_{analytical}$
L = 2.44 m (8 ft) a = 8 mm (5/8 in diameter)	sand	0.497 V	1.33 mA	374 Σ	374 Σ
L = 2.44 m (8 ft) a = 8 mm (5/8 in diameter)	clay	0.497 V	30.9 mA	16.1 Σ	16.2 Σ
L = 2.44 m (8 ft) a = 6.5 mm (1/2 in diameter)	sand	0.509 V	1.31 mA	389 Σ	387 Σ
L = 2.44 m (8 ft) a = 6.5 mm (1/2 in diameter)	clay	0.509 V	30.4 mA	16.7 Σ	16.7 Σ

Table 2. Comparison of computed and analytical ground resistances of 2.44 m (8 ft) ground rods with a = 8 mm (5/8 in diameter) and a = 6.5 mm (1/2 in diameter).

4. Steel Pole Grounding Resistance

The same technique used to determine the resistance of the steel ground rods is applied to the class 3 steel pole of Figure 1. One limitation of NEC-4 is that the conductors which penetrate the ground plane cannot be tapered. Thus, the ground resistances for the steel pole are computed assuming a straight steel pole of radius equal to the mean value of the tapered pole below the soil. This mean radius for the forty foot class 3 steel pole is 0.159m (6.26 in).

In order to model the effect of below grade protection in the form of a spray-on coating or a heat shrink tubing, the code must be able to account for the insulating layer on the conductors. NEC-4 allows for conductors with insulating sleeves but does not allow for these coated conductors to penetrate the ground plane. Thus, the exact ground resistance of a steel pole with below grade protection cannot be computed using NEC-4. However, one may use NEC-4 to determine the ground resistance for a bare steel pole of equivalent conductor/soil surface contact area. The ground resistance of the coated steel pole (R_{coated}) should then be smaller than the ground resistance of the equivalent bare pole (R_{bare}) since the bare portion of the coated pole is located at or below the same span on the bare pole. Thus, the current in the coated pole has a larger cross-section of soil through which to flow. This concept is illustrated in Figure 4 where the depth of the bare portion of the coated pole is designated as d_b. The ground resistance of the equivalent bare pole which penetrates the soil to a depth of d_b will represent an upper bound on the grounding resistance of the coated pole such that R_{coated} #R_{bare}. Thus, the measured value of ground resistance for the coated steel pole will always be lower than the computed value (the upper bound). Even though the exact value of the ground resistance for the coated pole will be unknown, knowing the upper bound on this ground resistance allows for a definitive comparison of the grounding effectiveness of the coated steel pole and standard ground rods. The upper bound on the ground resistance of the class 3 steel pole is computed as the length of the bare portion is varied from 6 ft (1.83m) down to 1 ft (0.305m) in 1 ft intervals. The results of these ground resistance computations are shown in Table 3.

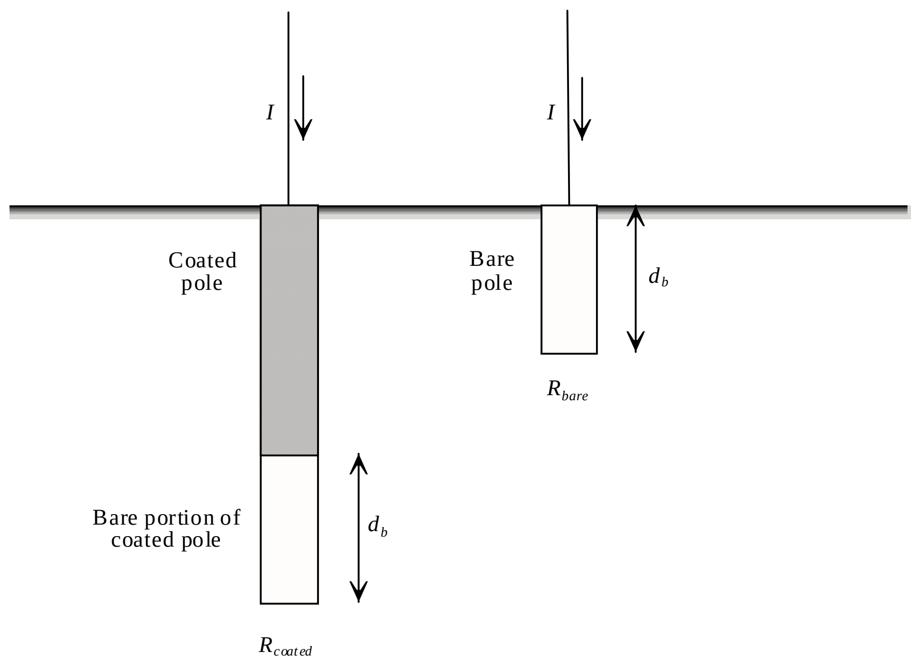

Figure 4. Illustration of R_{bare} as the upper limit on R_{coated}.

Length of bare portion (d_b)	Soil type	$V(0.618s)$	I	R
d_b = 1.83 m (6 ft)	sand	0.342 V	1.56 mA	219 Σ
d_b = 1.83 m (6 ft)	clay	0.342 V	36.1 mA	9.5 Σ
d_b = 1.52 m (5 ft)	sand	0.361 V	1.48 mA	244 Σ
d_b = 1.52 m (5 ft)	clay	0.361 V	34.3 mA	10.5 Σ

d_b = 1.22 m (4 ft)	sand	0.381 V	1.39 mA	274 Σ
d_b = 1.22 m (4 ft)	clay	0.381 V	32.1 mA	11.9 Σ
d_b = 0.914 m (3 ft)	sand	0.402 V	1.27 mA	317 Σ
d_b = 0.914 m (3 ft)	clay	0.402 V	29.4 mA	13.7 Σ
d_b = 0.610 m (2 ft)	sand	0.417 V	1.12 mA	372 Σ
d_b = 0.610 m (2 ft)	clay	0.417 V	25.9 mA	16.1 Σ
d_b = 0.305 m (1 ft)	sand	0.425 V	0.903 mA	471 Σ
d_b = 0.305 m (1 ft)	clay	0.425 V	20.9 mA	20.3 Σ

Table 3. Computed ground resistances (upper bounds) of a partially coated 40 foot class 3 steel pole [These computed values will always be larger than or equal to the actual ground resistance].

5. Concrete Pile Grounding Resistance

The geometry of the concrete pile represents an inhomogenous ground with the concrete surrounding the conductors and the soil surrounding the concrete. NEC-4 requires that the conductors be located in a homogenous ground to accurately compute the grounding resistance. However, the electrical characteristics of concrete are quite similar to dry sandy soil. Thus, the two soils considered here (average conductivity sand and clay) are better conductors than concrete. For this reason, the concrete pile conductor system of reinforcing steel located in a homogenous sand or clay ground of average conductivity yields a computed grounding resistance which is smaller than the actual grounding resistance of the concrete pile (conductors, concrete and soil). The computed ground resistances therefore represent lower bounds of the actual concrete pile ground resistances.

The geometry of the reinforcing steel of the concrete pile is shown in Figure 5. The dimensions of the concrete pile conductors are chosen to closely match those of the steel pole. The vertical conductors have an overall length of approximately 1.83 m (6 ft) while the radius of the horizontal circular conductors is 0.159m (6.26 in). The longer vertical conductor in Figure 5 represents the connection of the down conductor to the concrete pile. All of the conductors are assumed to be steel with a diameter of 13 mm (½ in). The grounding resistance results for the concrete pile are shown in Table 4.

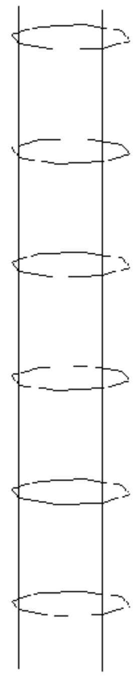

Figure 5. Geometry of the reinforcing steel of the concrete pile.

Soil type	*V*(0.618*s*)	*I*	*R*
sand	0.406 V	1.60 mA	254 Σ
clay	0.406 V	36.7 mA	11.1 Σ

Table 4. Computed ground resistances (lower bounds) of the concrete pile shown in Figure 5 [These computed values will always be smaller than or equal to the actual ground resistance].

6. Summary and Conclusion

Comparing the computed ground resistances of the 8 ft ground rods in Table 2 with those of the coated steel pole in Table 3, one finds that the coated steel pole performs as well as either the ½ in or 5/8 in diameter ground rods given at least two feet of bare length at the base of the buried portion of the coated steel pole. Since the computed grounding resistances of the coated steel pole represent upper bounds (the computed grounding resistances are always larger than or equal to the actual grounding resistances), the required bare length of steel pole to be equivalent to the 8 ft ground rod is actually less than 2 ft.

When the computed ground resistance of the coated steel pole is compared to that of the concrete pile in Table 4, one finds that the coated steel pole is an equal or better ground for bare lengths between 4 and 5 ft. Again, since the computed ground resistances of the coated steel pole are upper bounds (always larger than the actual grounding resistance) while the concrete pile ground resistances are lower bounds (always smaller than the actual grounding resistance), the amount of bare length required on the coated steel pole to make it equivalent to the concrete pile should actually be significantly smaller than the given range of between 4 and 5 ft.

7. References

[1] Burke, G. J., Numerical Electromagnetics Code - NEC-4, Part I: User's Manual. Lawrence Livermore National Lab, January 1992.

[2] Harrington, R. F., *Field Computation by Moment Methods*. Malabar, Florida: Robert E. Krieger Publishing Company, 1982.

[3] ANSI/IEEE Std 142-1982, *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems*. New York: IEEE, 1982.