# DISTRIBUTION LINE GROUNDING IMPROVEMENTS AND THEIR EFFECTS ON EXTREMELY LOW FREQUENCY INTERFERENCE

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## ABSTRACT

*A lattice network is used to study the interaction between improving the grounding effectiveness along a multigrounded conductor, such as a power line neutral, and the manner in which steady state interference voltages are distributed along this conductor. The model provides analytical means of tackling the problem and is used to study practical cases of distributed sources of interference. A dynamic model is outlined that shows how the voltages are reduced, redistributed, and spread out by specific grounding improvement actions. This provides informative and practical directions for the practicing engineer facing such problems.*

## INTRODUCTION

Multigrounding along a utility distribution system results from the basic need to ground at least one conductor for improved electrical safety, lightning protection, and electrical noise control. An ideally grounded conductor would have zero resistance to earth, but, as with all real and practical systems, grounding has some finite resistance that depends on the earth resistivity. Another factor that affects grounding is population density, because as the density of housing increases per square mile so do the number of services, miles of line, and consequently the incidental grounding. Urban systems tend to have more grounding than rural distribution systems [Ref. 1].

The grounding effectiveness along a multigrounded utility conductor affects the manner in which electrical sources of extremely low frequencies couple into this distributed network, producing objectionable voltages and currents. One concern is the appearance of voltages on multigrounded distribution conductors which are expected to be at earth potential and electrically safe. Improving the grounding effectiveness, either uniformly along the distribution line or at selected locations, allows the engineer to reduce and manipulate the levels and distribution of these voltages. The capability and effectiveness of this approach depend on circumstances, and therefore cover a wide range. Much of the uncertainty is caused by the soil conductivity and its variation over a region. The theory of it, however, is very simple and is based on lattice networks. This paper outlines how and where on a line the grounding improvement causes a reduction of these voltages, and how localized voltage rises can be spread out or pushed to other parts of the line.

## CASE OUTLINE

The purpose of this analysis is to study the DC and steady state AC response, at power frequencies, of multigrounded distribution conductors in the presence of distributed sources of interference. The power neutral of wye circuits is the most common and representative of this family, and is referred to as the multigrounded neutral (MGN) conductor. The sheath of a coaxial CATV system and the sheath of a telephone network are similar multigrounded conductors. When CATV and telephone cables are mounted overhead on the same power poles, they share the same grounding of the power plant. Other multigrounded conductors include the lightning shield wire of power transmission lines, other types of shield wires, and the messenger strand used for suspending CATV and telephone cables on poles. Railroads constitute specialized cases of long multigrounded conductors, as well as fences, pipelines, and urban water distribution systems, depending on construction material and techniques. One important difference among them is that some are simple, one-line systems (transmission lines, pipelines, railroads) while the others have a tree-like topology, with branches that continually divide (power, telephone, cable, city water).

Extremely low frequency signals that couple into multigrounded conductors create interference by causing longitudinal currents and voltages that can saturate magnetic devices, affect trip levels of safety devices, stress insulation, and increase transverse circuit noise on utility systems. However, the interference at these frequencies is rarely high enough to cause serious operational difficulties. Some utilities, such as telephone, routinely take these problems into consideration and design appropriate remedies. These voltages are apart from and in addition to those created by system operating currents, such as power imbalance and harmonic currents flowing on the MGN. Systems such as pipelines, fences, and water systems have their own unique concerns, mostly related to corrosion. A concern in all of these cases is electrical safety, because these voltages are unavoidably carried inside the premises on the utility services, and also because these voltages are on outdoor transportation and utility facilities alongside roads and accessible to passersby.

Examples of distributed sources of interference include power transmission lines inducing voltages on fence wires, pipelines, and railroads [Ref. 2-5], telluric currents, and special earth return circuits [Ref. 6 and 7]. The electromagnetic pulse [Ref. 8] also presents area-wide exposure, but this is a special concern of a transitory nature, with interest at the higher frequencies as well. Similarly, lightning does not meet the criterion of distributed and steady interference, although grounding improvement will increase the safe dispersion of lightning energy in the earth. Neutral-to-earth stray voltages, of interest to dairy farms, will also be affected by grounding improvements [Ref. 9]. Such voltages are often caused by the flow of power imbalance and harmonic currents on the MGN. These currents are randomly distributed both in time and along the power line, and represent an extreme case of the problem at hand, which is not addressed directly in this paper.

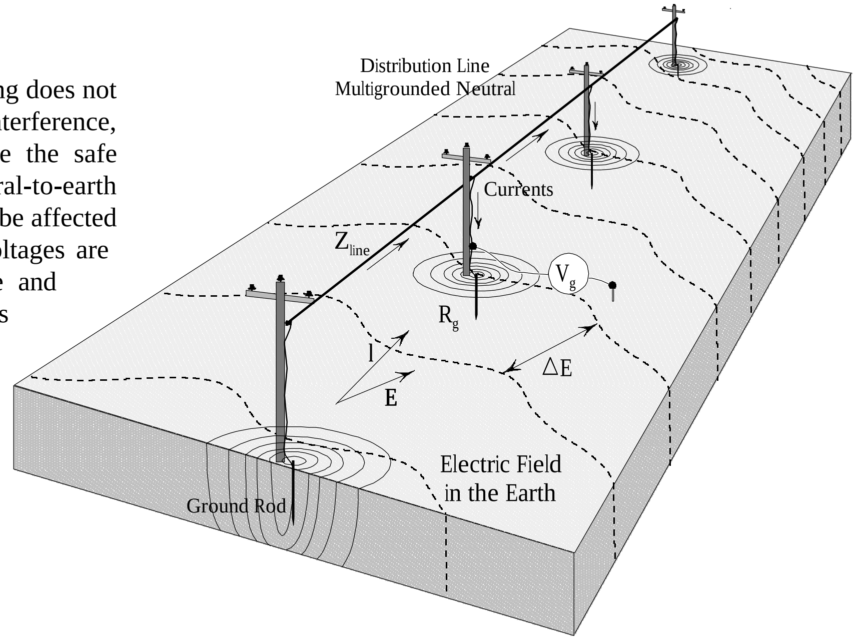

Figure 1. MGN section exposed to a distributed source of interference.

### ANALYTICAL MODEL

A section of the MGN is shown in Figure 1 grounded at every pole. In actuality, MGNs are grounded less frequently; the National Electrical Safety Code requires only a minimum of four grounds per mile. The electrical interference source can be one that couples magnetically with the MGN, or it may be present in the earth; it is shown as a gradient electric field in the earth in Figure 1. Because of the distributed nature of the source, the amount of interference that the MGN is exposed to depends on the length of the line. Often the exposure is nonuniform along the path of the MGN, because of variations in the source, and because the exposure depends greatly on the angle between the MGN line and the source field gradient. Indeed, the exposure in Figure 1 is described in general terms by the vectorial integral:

$$V = \int_l \bar{\boldsymbol{E}} \cdot d\bar{\boldsymbol{l}}$$

The result is that electric forces cause current to flow on the loops formed by the pole grounds (Figure 1). On a larger scale, these loops form lattice networks such as the one shown in Figure 2. The interference is shown as a simple voltage source, at the bottom of the loop in this case, to match the source described in Figure 1. $Z_l$ represents the line impedance of the MGN, and $R_g$ represents the grounding resistance at a pole. The MGN in Figure 1 resembles a transmission line, where $Z_l$ and $R_g$ are respectively the serial impedance and the shunt resistance. For modeling purposes, these quantities can represent physical line segments, such as a single overhead power line span, or measurements per unit length of line. This indeed would be the case for a buried power cable with bare concentric neutral, where the parameter $R_g$ would be of a distributed nature. $R_s$, at the beginning of the lattice, represents a power line substation or a telephone central office, which typically have very low grounding resistance compared to $R_g$. More generally, using transmission line theory, $R_s$ can be replaced by $Z_o$, the line characteristic impedance, to substitute in the lattice model the part of the line that is of no interest, because there is no exposure beyond that point on the line. For tree-like utility systems, the lattice is “two-dimensional,” with ð meshes nested laterally (Figure 3).

The simple ideal model of Figure 2 is useful, because it provides a clear understanding of how voltages are affected by the lattice parameters, and how the resulting voltages can be lowered and redistributed by improving the grounding, without the complications caused by too many details. The latter includes shielding effect of other wires and cables nearby, impedance of grounding wires, shunt capacitance to earth, the magnetic material of pipes in the case of pipelines, and the many branches, spurs, and even loops on utility distribution systems. To simplify the analysis even further, a completely resistive lattice is used for this analysis (Figure 4),

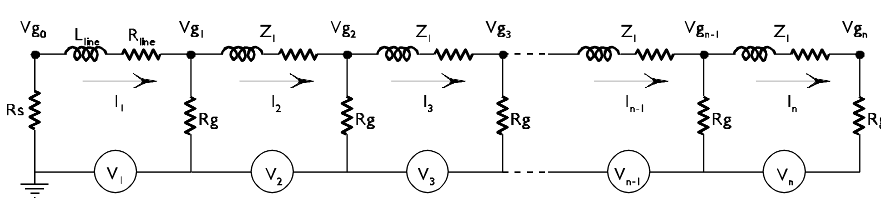

Figure 2. Lattice for modeling MGN in the presence of interference in earth.

where $Z_l$ is replaced by an equivalent resistance. The source impedance and the earth resistance are both assumed to be negligible. The approximation is very good for the MGN, with very little difference between the real part of the complex answer (using the lattice of Figure 2) and the resistive answer (using the resistive lattice of Figure 4). The results of this analysis represent, therefore, the DC response and a very good approximation of the AC response at extremely low frequencies.

The model used for this analysis assumes an overhead power line with spans 265 ft long (about 20 spans per mile), with four ground rods per mile (standard 8 ft long, 5/8 in. diameter). The grounds installed at utilization transformers and the grounds of residences tied to the power network constitute scattered additions to the MGN line grounding; for simplicity they are not included here. It has also been shown that customer grounding can be viewed as a form of improved grounding of the power distribution line [Ref. 10]. This example is more the case for a rural system.

The soil resistivity is assumed in this analysis to be one of two extreme cases, either 63 or 2500 Ù·m. Using Sunde's formula [Ref. 11], the rod resistance to ground is calculated to be either 25 or 1000 Ù for the two cases, respectively. Five spans are lumped together and represented by a ð mesh in the lattice, with $R_g$ being either 25 or 1000 Ù. The inductance of the neutral wire is estimated to be 785 µH for 5 spans, while the resistance of the wire is taken from standard tables to be 0.161 Ù/1000 ft (1/0 Al), or 0.215 Ù for 5 spans. The impedance of the line ($Z_l$) is calculated to be 0.365 Ù at the power frequency (60 Hz). This is 1.5% of the smallest values considered here for $R_g$. Even at the highest frequency of the ELF spectrum (300 Hz), this impedance is less than 6% of the $R_g$ values considered here. In the resistive lattice, the line resistance is set to be equivalent to the line impedance, 0.365 Ù for 5 spans.

The interference source is represented as an electric force in the earth (Figure 1). The resulting exposure can vary along the path of the MGN ($V_1$, $V_2$, ... $V_n$ in Figures 2 and 4). The distribution of the resulting exposure is assumed to follow one of three patterns (see Figure 5): uniform distribution, exponential rise, and a swell. The uniform distribution is a pattern typical for exposure of a utility line, such as the influence of power on telephone cables or the influence of transmission lines on power distribution lines, pipelines, and fences in the same right-of-way. The exponential pattern is typical for geographically fixed sources as utility lines radially approach them from far away. The swell (a pulse-like surge) is, instead, the case where the source is localized along a narrow band, and the exposure occurs as the MGN crosses this band; this may be the case of telluric currents concentrated along geological features, or a local aberration in what can otherwise be categorized as either uniform or exponential exposure. For analytical purposes, all long and complex exposures can be divided into a sequence of shorter exposure segments within each of which the exposure is one of these basic forms. Superposition can then be used to combine the effects. The three exposure patterns used for this analysis are each set to add up to 80 volts (Figure 5). This minimizes the effect of the overall interference voltage in this comparative analysis, where the interest lies in the distribution of the resulting MGN voltages.

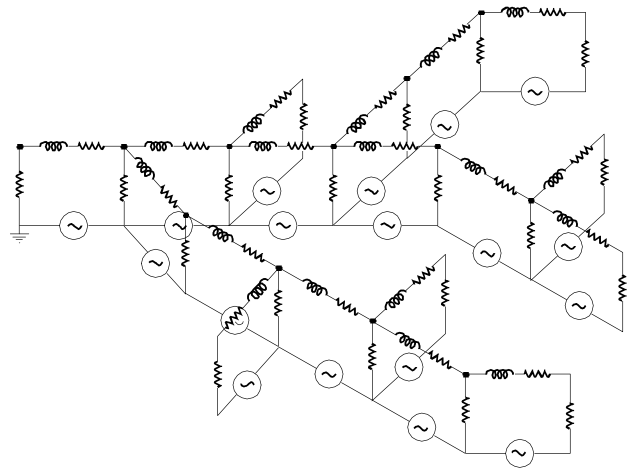

Figure 3. MGN lattice for a tree-like topology.

## RESULTS

Figure 6 shows the voltages along a ten-mile-long MGN with a uniform exposure to a distributed interference source. Curves **a** and **c** show the voltage along the MGN with $R_g$ set at 25 and 1000 Ù, respectively. Curve **a** shows the catenary curve pattern that is typical for such lattice networks. The voltage rises to the highest value at the line ends. For a uniform lattice, the curve would be a mirror image left to right. $R_s$, at the beginning of the lattice, causes the curve to

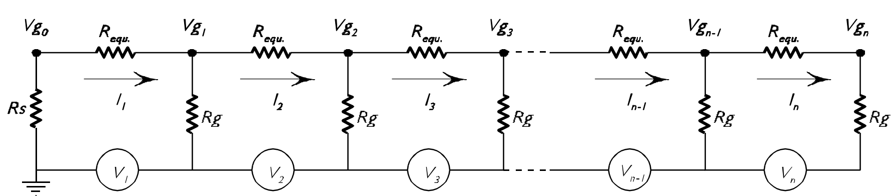


Figure 4. Resistive lattice for modeling MGN exposed to interference in earth.

be skewed to the left. The point with minimal voltage, in the middle of the curve, is referred to as the fulcrum, and, as we shall see later, has significance in the redistribution of MGN voltages. The fulcrum is also the point at which voltages change polarity along the line. Curve **c** shows what happens when the MGN is located in an area of poor ground conductivity. For the same type of grounding pattern (four grounds per mile) and exposure to interference, a poorly conductive soil causes the voltage on the MGN to rise, four-fold at the end of the line in this case. This will be true in general; the resulting MGN voltages will be much higher when the earth has lower conductivity.

One of the grounding improvements possible in these cases is to add a ground rod at every pole that does not have any. This indeed has been the requirement by the Public Service Commission of Wisconsin in rural systems since 1994. Curves **b** (25 Ù case) and **d** (1000 Ù case) in Figure 6 show that the result is a significant drop in the MGN voltage at the end of the line (35 to 60%). This has been documented in other studies as well [Ref. 12]. Curves **b** and **d** also show that the fulcrum has shifted to the right and that, just as in a scale, the voltage has fallen on one side of the fulcrum and risen on the other. While the drop does not equal the rise mathematically, the paired effect is characteristic of a lattice network. Changing the grounding resistance causes the fulcrum to shift, with voltages on one side rising and voltages on the other side dropping.

With the new patterns, curves **b** and **d**, we have achieved overall lower voltages on the MGN, although the voltage has risen slightly on the left of the fulcrum. This is considered a beneficial result, because the drop of voltage on the right of the fulcrum far exceeds the rise on the left. Furthermore, if there is a safe voltage threshold, the MGN voltage on the left may still be below this threshold even with the rise. Indeed, the grounding effectiveness of the line can be increased to reduce the voltage on the right of the fulcrum until the voltage on the line to the left of the fulcrum reaches either an equal level or the threshold level. The risk that these voltages pose to utility customers and the public is reduced substantially and disproportionately, because not only body current decreases as the voltage is reduced, according to Ohm's law, but the total body impedance is nonlinear with voltage and increases at the lower voltages [Ref. 13]. Improving the grounding uniformly along the line, therefore, has had two effects: (1) shifting some of the voltage along the MGN line, and (2) lowering voltages overall on the MGN line.

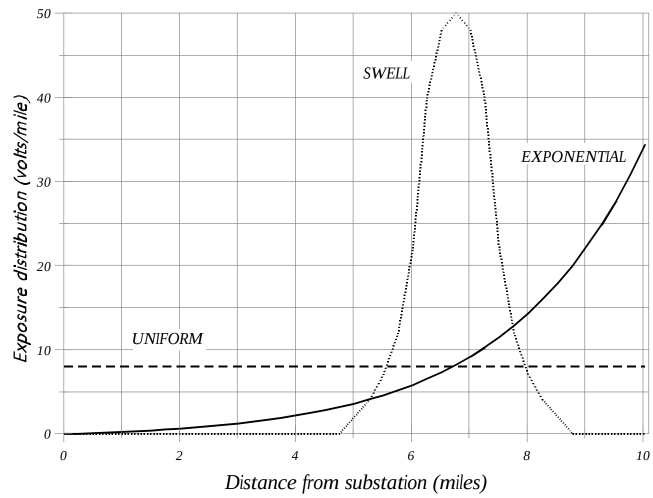


Figure 5. Three patterns of interference exposure.

Curve **b** in Figure 6 is nearly symmetrical, with the fulcrum near the center of the line. Making additional grounding improvements uniformly along the line, such as doubling the number of ground rods at every pole, will serve only to flatten this curve further. If the voltage levels at both ends are then satisfactory (i.e., below a safe threshold), this could be the end of any action. In the case of curve **d**,

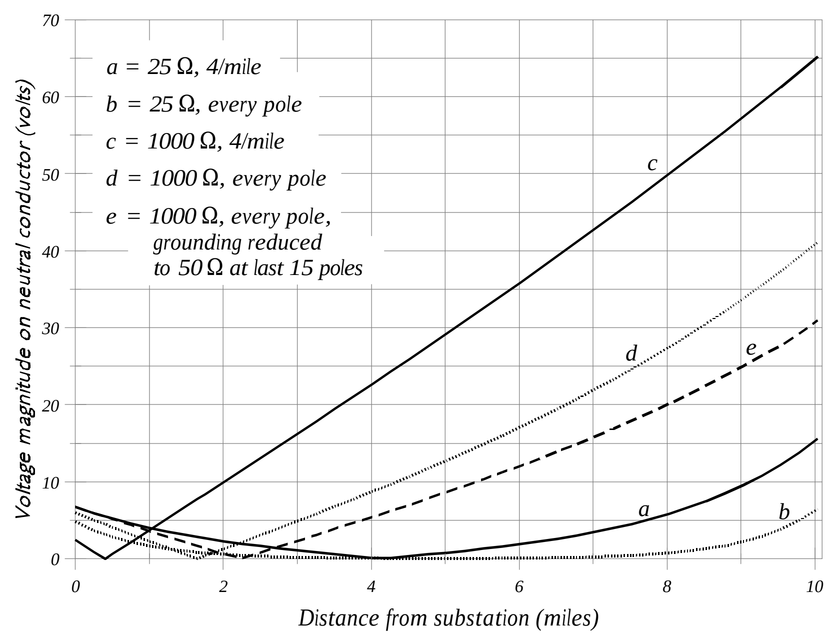


Figure 6. MGN voltages with a uniform interference exposure.

however, although the situation is better than it was before the intervention, the MGN voltage at the end of the line is still very high. Adding ground rods uniformly along the line is very expensive, and not very effective when the voltage problem is localized. Another approach is to use a limited number of deep grounds at the end of the line.

Deep grounding refers to the installation of long ground rods that reach deep below the surface. This is achieved by coupling standard ground rods one after another as they are installed, typically until a point is reached at which the rod will not penetrate further. Deployed like this, the effort and material are much more effective, because the decrease in grounding resistance is nonlinear with depth. Indeed, when the deep ground rod is sunk, its resistance to earth drops significantly and abruptly as the rod reaches and enters the water table. This technique will, of course, be limited in cases where rock formations prevent reaching the water table.

Curve **e** in Figure 6 is the result when the pole ground rod, initially at 1000 Ù, is turned into a deep ground rod with a final 50 Ù resistance at each of the last 15 poles on the line. The result is a shift of the fulcrum toward the end of the line, the side of the line where the grounding improvements have taken place. The MGN voltage on this side has dropped even more, to less than half what it was before any grounding improvements were made. The voltage on the other side of the fulcrum, toward the substation, has risen, but minimally, kept in check by the good substation grounding. So we conclude that localized improved grounding similarly causes the voltage to drop in the grounding improvement area of the MGN, and to rise slightly on the other side of the fulcrum.

Figure 7 shows the currents flowing on the MGN in correspondence to cases **a**, **b**, **c**, **d**, and **e** above. The current curves have a pattern that is inverted compared to that of the voltage curves. The current is highest toward the center of the line and lowest at both ends of the line. The asymmetry of the curves again is caused by $R_s$. The current is higher when the earth resistivity is lower, and the current becomes higher as the grounding is improved. So, a lowering of the MGN voltage at the end of the line is accompanied by an increase of the current on the MGN. The current increase may not be a desirable effect. There is a tradeoff here, depending on the concern being addressed. The goal in this analysis is the reduction and redistribution of MGN voltages, because they are unsafe.

Repeating the analysis for the case where the source and the MGN path are such to yield an exponential exposure, produces the voltage curves shown in Figure 8. Because the exposure is greater toward the end of the line (Figure 5), the MGN voltage curves are skewed further to the right. The voltage rises steeply toward the end of the line in a pattern referred to as "tail-end rise." The movement of the fulcrum, the overall drop in MGN voltage, and the shifting of the voltage from one side of the fulcrum to the other follow the same pattern examined earlier as we consider the standard cases of 25 and 1000 Ù grounding electrodes (curves **a** and **c**), adding electrodes at every pole (curves **b** and **d**), and reducing

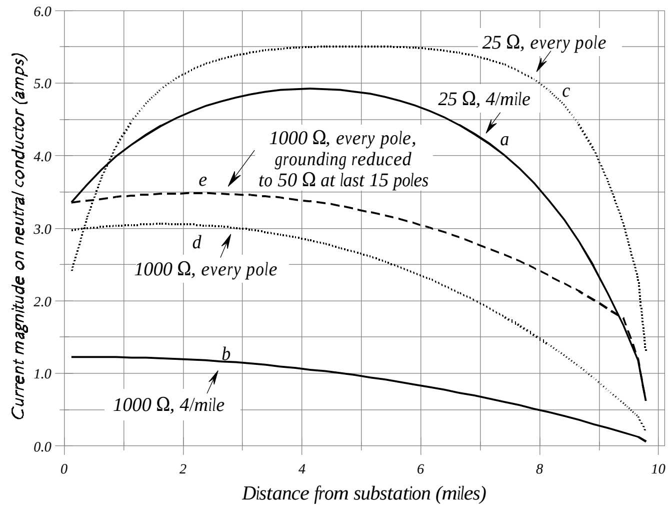


Figure 7. MGN currents with a uniform interference exposure.

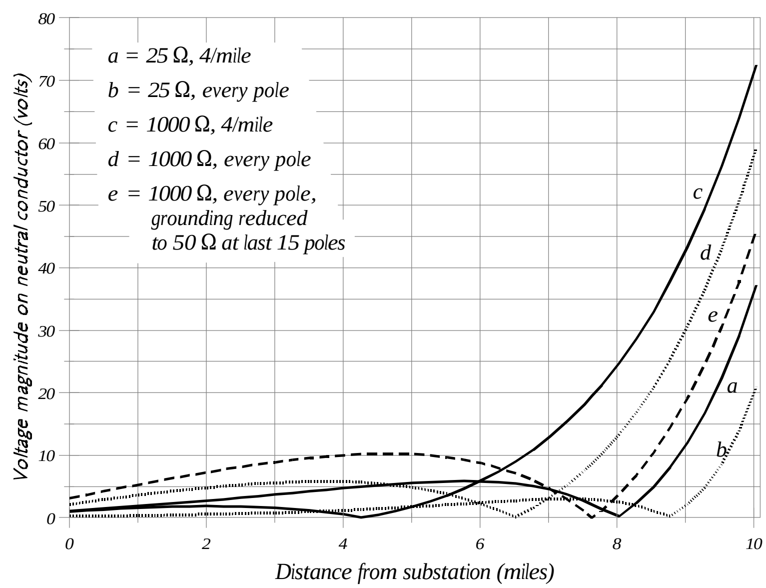


Figure 8. MGN voltages with an exponential interference exposure.

the grounding at the last 15 poles from 1000 to 50 Ù (curve **e**). The difference here is that with the interference so highly concentrated toward the end of the line, the grounding improvement seems less effective. Also, the shifting of voltage, as in the case of curve **e**, causes the MGN voltage to rise faster on the other side of the fulcrum, to a point where it can be objectionable.

Figure 9 shows the results where the exposure is in the form of a swell occurring within a few miles, approximately 6.5 miles away from the substation. However, the analysis in this case is focused on improving the grounding at the end of the line. The line has an initial grounding of 200 Ù/mile (curve **d** in Figure 9). The grounding improvement is localized at the last 15 poles of the line, first with 100 Ù, then 50 Ù, and finally 25 Ù (curves **f**, **g**, and **h** respectively). Curve **i** is for a single ground of 5 Ù at the end of the line. The fulcrums are located near the center of this exposure, where MGN voltages are the lowest. The effect of the increasing and concentrating grounding improvements at the end of the line is striking, especially as it shifts voltage from the right to the left side of the fulcrum. Curve **i** shows clearly that a point exists in this improvement effort at which the voltage on the left of the fulcrum is equal to the voltage on the right (balancing point). A strategy then becomes obvious: It is best to reduce high MGN voltage in this way, with localized intervention and up to the balancing point, because the risk of electric shock is reduced in the most efficient and cost-effective manner by diminishing the higher voltages. Beyond this, grounding has to be improved uniformly along the line to achieve still lower voltages overall.

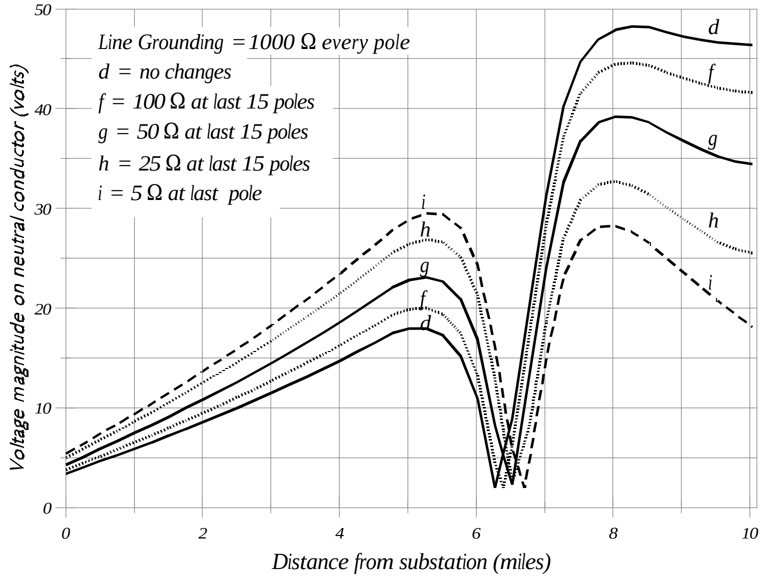


Figure 9. MGN voltages with an interference surge exposure.

It seems from the above examples that grounding improvement in dealing with tail-end rises is at first most effective when done toward the end of the line. An interesting question arises: Is there an optimal number for grounding improvement in such cases? Figure 10 shows the results of analyzing how much the MGN voltage drops at the end of the line, as a function of the number of poles treated for improved grounding, starting at the end of the line. The analysis is repeated for different levels of grounding improvements, with the pole grounding resistance being reduced to half, a quarter, and finally an eighth of the original value. The analyses are also repeated for the cases of uniform and exponential exposure. The voltage drops are larger for the case of uniform exposure, as discussed earlier. In all cases, though, the voltage drop at the end of the line becomes only marginally smaller as more poles are treated from the line end. Eventually, there is hardly any effect, as the curves asymptotically approach a flat no-response. Not too surprisingly, the curves in Figure 10 say that the reduction of tail-end voltage depends both on the type of interference exposure and level of grounding improvement. What is most interesting, however, is that most of the

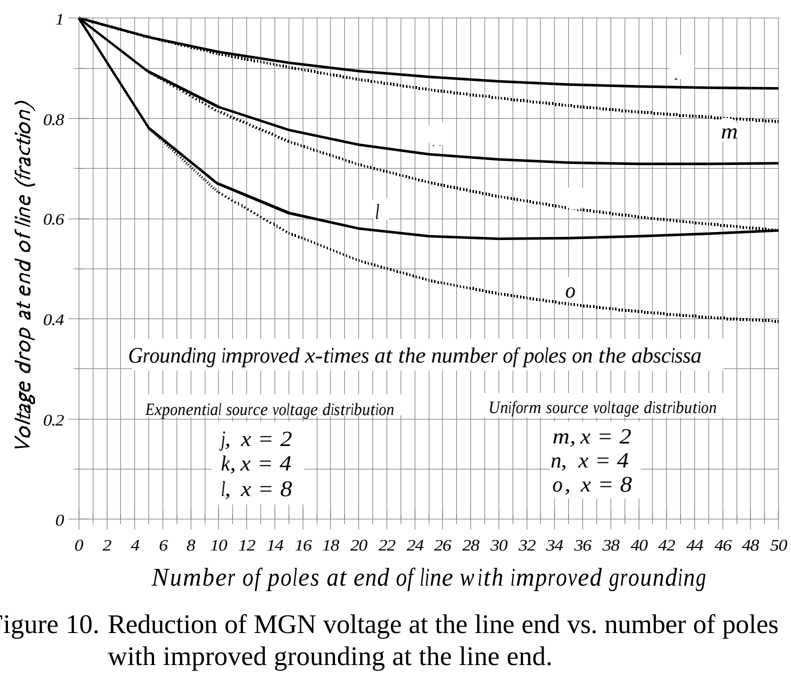


Figure 10. Reduction of MGN voltage at the line end vs. number of poles with improved grounding at the line end.

reduction in tail-end voltage rise using localized intervention can be achieved by treating only the last 10 to 15 poles.

## CONCLUSIONS

Electrical grounding at multiple locations of utility distribution systems is important, is a requirement sanctioned by decades of practice, and is a standard regulated by code. It is also a natural occurrence for other systems, such as pipelines. Most grounding problems arise from the fact that the earth has a finite resistivity, and all grounding electrodes, as a result, have a finite resistance. These limitations, however, provide opportunities for addressing and resolving unique problems.

The problem addressed here is that of distributed electrical interference at extremely low frequencies. The resulting voltages on the MGN and similar multigrounded conductors in other utilities are affected by the effectiveness and pattern of grounding along the line. It is often possible to go beyond the minimal requirements set by code and industry practice to improve grounding, and thus affect the resulting MGN voltages. The main tool used here to study these effects is the lattice network of Figures 2 and 4.

We have seen that improving the grounding is most effective as a technique when the earth has a very high resistivity. We have seen as well that the interference source has an effect on the voltage distribution and the way voltages respond to grounding improvements. Interference swells and tail-end voltage rises are most sensitive to grounding improvements. We have also seen that improving grounding only at the ends of a distribution line can be very cost-effective as a first step, followed by uniform grounding improvements along the line if more voltage reduction is needed. We have also learned a bit about the dynamics of the problem, and the usefulness of thinking about these voltages as being balanced on a fulcrum; lowering voltages on one side of the fulcrum often means seeing them rise on the other side. The lattice networks and the mechanical model of the fulcrum provide the engineer with the tools and a practical theory to intervene and mitigate for interference voltages on the MGN line, and similar multigrounded circuits.

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