Risk Management on Project ELF

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Background

The U.S. Navy developed a special radio communications system in the 1970s that was designed to reach deeply submerged submarines. Developed for strategic purposes, the system has proven to be very valuable for tactical operations as well. The Navy has many means of communicating with both submarines and conventional ships, from land-based stations that cover the electromagnetic spectrum and from satellites. However, none of the traditional radio communications systems could keep pace with increases in the operational depth of modern submarines. Because submarines operate on stealth and use sea depth to hide, the deeper they can descend, the more secure and untraceable they become. None of the traditional radio systems can reach submarines at their current operating depths.

Radio waves penetrate seawater to varying depths, depending on their frequency. The lower the frequency, the deeper the radio waves can penetrate seawater. Design considerations led to the formulation of the existing extremely low frequency (ELF) radio communications system. This system uses a land-based radio transmitter operating at 76 Hz that can be picked up by submarines at their operating depth, by means of sophisticated receivers. At this frequency the wavelength is 2453 miles, so a practical antenna is not feasible. What is used instead, are conductors many miles long strung on poles and grounded at their ends. If the transmitter site has very low ground conductivity, any current forced on this wire would have to penetrate deep inside the earth to complete the circuit, thus forming a loop many miles in diameter near the earth's surface. This loop acts as an antenna, although a very inefficient one. The released signal, however, being of very low frequency, travels around the earth with very little attenuation, trapped between the conductive layers formed by the ionosphere and the earth's surface. Over seawater, part of this signal penetrates the ocean and reaches the submarine.

Because of the inefficiency of this antenna, thousands of kilowatts of electrical power are used to generate a signal in the air that is only a few watts strong at the source. This is nevertheless sufficient to provide a low-capacity communication channel with deeply submerged submarines around the globe. Of course the reverse is not feasible, so the communication is in only one direction, from a land base to the submarine. This system affords the basic needs for the military to exercise command operations in real time. As difficult as it is to put a signal of such low frequency in the air, it is just as difficult to disrupt it. Thus, lightning continuously present around the globe is not a problem.

Because the wires used as transmitters are grounded at both ends and because the system relies on the current to complete a loop through the earth, interference problems arise for other systems located near the transmitter that also use the earth as a return path. All utility systems, for example, use the earth for both electrical safety and for current return. One safety feature of power distribution lines relies on a ground fault current to activate fuses or reclosers in order to detect fallen power lines and deactivate the line. The same power line grounding that makes such a safety feature possible also picks up the ELF signals that are present at detectable levels in the earth near the antenna.

A major consideration for such a communications system is its ability to generate in the air a signal sufficient to do the job. With receiver technology pushed to its limits, this capability depends on the efficiency of the antenna, which in turn is determined by the length of the wires, the current on the wires, and the conductivity of the earth. Years of research and wrangling led to the present design configuration. The transmitter complex comprises two separate facilities operated in synchronism, one in northern Wisconsin at Clam Lake and the other in the Upper Peninsula of Michigan at Republic, for a total wire length of about 80 miles carrying an average current of about 200 amperes. In the end, it was impossible to find totally unpopulated areas with acceptable low ground conductivity in the continental United States. The sites selected for the transmitters are remote wooded areas, with a very low population density. It was inevitable that some utilities would be present in the immediate vicinity of the antenna wires.

A major outcome of this collocation is interference that the operation of the transmitter can cause for the utilities nearby. Since the inception of the project, the U.S. Navy recognized this problem and has met its responsibilities by funding research to study the problems and find solutions. It has also provided to the utilities and other parties affected the know-how and means to change their systems to eliminate or minimize the interference. The Navy continues to provide technical support and mitigation compensation to anyone affected as a result of operation of the radio communications system.

Interference Voltages

The problem is strictly and solely one of electrical voltages being induced on long conductors near the antenna. There is a concern over electromagnetic fields (EMF) also, but that concern is a minor one in comparison. Direct electrical interference results from the electromagnetic coupling between the antenna wires and adjacent conductors, much like that which causes noise (extraneous voltages) to be induced on telephone circuits from power circuits when the two use parallel cables strung on the same pole for many miles alongside a road. Similarly, for ELF voltages to be induced on any wire the wire must be long, located nearby, and somewhat parallel to the antenna wire itself.

This electromagnetic coupling takes place at the separation layer of two media, the earth below and the air above, so there are different effects to consider in each medium. In the air, the ELF electromagnetic characteristics are not much different than those associated with many power lines. The coupling with the ELF wires in the air decreases rapidly and becomes insignificant within a few hundred feet, just as is the case with power lines. However, unlike power lines, which often share poles and right-of-way with telephone and cable TV systems, the ELF wires are secluded in wooded areas, far from any other system. For this reason, direct electromagnetic coupling in the air with the antenna wires is not a problem.

Within the earth, though, there are two different effects. First, unlike the case with power lines, where most of the operating currents are confined to the power line wires, the ELF antenna current is forced to flow in the ground. This current is necessarily concentrated at the antenna wire ends, both of which are grounded. The current spreads out from these points and flows deep and far, where it is basically untraceable. The second effect is the electric field in the earth that results from the ELF magnetic field in a conductive medium such as the earth. This electric field is the primary cause of interference to utility lines and other long conductors. While the current in the ground at the ELF antenna wire terminals represents a localized phenomenon, the magnetically coupled electric field in the earth is, on the other hand, a large and widespread phenomenon. Figure 1 is a computer representation of the absolute magnitude of the electric field at the surface of the earth for the ELF radio transmitter in Michigan. This specific transmitter uses three wires, two laid out east to west and one north to south, with a total of six antenna wire end-grounds. The electric field is seen to be highest in correspondence of the wires themselves, to peak at the wire terminations in correspondence of the antenna wire end-grounds, and to quickly decrease to insignificant levels as one moves far away from the antenna wires. This earth electric field decreases to practically insignificant levels at ten miles from the antenna wires.

There is a direction associated with the electric field at any location, which is not shown in Figure 1. Furthermore, a potential field is generated following a path parallel to the antenna wires. The outside closed loop shown in Figure 1 gives the outline of a path along which the electric field would add and be detectable. The electric field vector at any point on this line would be tangent to the line at that same point. Other inner loops can be traced inside the one shown, that enclose all of the antenna wires (Figure 2). These other loops would correspond to higher potential field levels as one moves closer to the antenna wires. The potential field along a closed loop around the antenna wires would, however, add to zero. Furthermore, paths that run perpendicular to these loops, like the spokes of a wheel, experience little or no earth electric field. But any wire or metallic facility on the ground or regularly connected to ground will sense this potential field which will cause a current to flow on the facility. The current and associated voltages will depend on the length of the wire and its path, and can be estimated from Figure 2, for example, using the potential field law ($V = \mathbf{E} \cdot d\mathbf{l}$).

The interference problem arises from the fact that all electrical utilities use metallic conductors that are connected to or referenced to ground. Some other utilities, such as railroads or pipelines, are either placed just on top of the earth or buried just below the surface. Fences represent another case where long conductors can be intentionally or accidentally connected to earth at multiple points, causing currents to flow because of the earth electric field. The effects are most intense within a few miles of the antenna wires, and some low-level effects can be detected at distances of up to 10 miles from the antenna wires. To put this matter in perspective, detectable effects extend to within only a fraction of the antenna wire length, making it a very localized phenomenon; nevertheless, this can be a considerable area. In the case of the ELF antenna, this area totals about 500 square miles in both Michigan and Wisconsin, and affects about 2500 residences.

The basic problem is the ELF voltages and currents that appear on these facilities. For the most part, these voltages and currents are not so strong as to cause disabling problems in operating these facilities. They can, however, cause operational degradation in some cases. Most importantly, they can cause electrical safety problems for individuals who work on or use such facilities, or for unsuspecting passersby who may touch any of these facilities along a roadside. For the purpose of this presentation the problems are divided among: (1) common mode voltages, (2) grounded conductor voltages, (3) single mode voltages, (4) touch and step voltages, and (5) antenna ground surface voltages. The following subsections present detailed descriptions of each of these problems.

Common Mode Voltages

Many wire configurations, such as the phase wires on power transmission and distribution lines or the pairs on telephone cables, are operated as groups of conductors with identical electrical characteristics, as part of a circuit. These systems are also referenced to ground, typically at the source and the utilization point, so they will experience the ELF potential field in the earth. Any ELF voltage induced on one wire, however, will also be induced on the others, with the same magnitude, phase, and direction. It follows that any device connected between the wires will experience no net potential voltage, because the two signals will be connected so as to cancel each other. This would be the case, for example, for substation transformers on transmission lines, or delta-connected transformers on distribution lines. Besides, for these systems that operate at thousands of volts, the few tens of volts induced because of ELF are within the power line voltage design tolerance and are totally inconsequential.

On telephone systems, the voltage induced on the tip wire would also be identical to the voltage induced on the ring. The two signals will similarly cancel each other at the receiving end of a telephone handset, or at the interface in a central office. However, interference voltages of tens of volts can be in the range of telephone operating voltages (50 to150 V approximately). On toll lines where operating voltage can be higher still (up to 250 V), similar architectures exist (send and receive pairs) that assure common mode cancellation of the ELF induced signals. The problem in this situation is that the ELF voltages, although basically not different from those induced on power lines, are relatively high when compared to the telephone operating voltages (7.2 to 130 kV on transmission lines and 250 V at most on telephone lines).

These voltages are, by and large, inconsequential as long as the wire system remains balanced. No current will flow because of these voltages, although the voltages themselves can actually be measured with respect to earth. These voltage, however, can turn into problems if the line becomes unbalanced. On power distribution lines, for example, the balancing of taps and transformers among the phase wires tends to be a problem, and may result in some common mode net voltage. Similarly, an aged or substandard telephone line may not have good balance and may be affected by these voltages.

Another substantial factor that differentiates the susceptibility of power circuits to ELF interference from the susceptibility of telephone circuits is the operating signal frequency range. Power transmission uses essentially a monotonic sinusoidal wave at 60 Hz. Harmonics, multiple frequencies of the 60 Hz, may be present in relatively-small amount, as undesirable by-products of the distribution process. The ELF signal, by comparison, is essentially a spectrum of frequencies about 80 Hz wide and centered around 76 Hz. For all practical purposes, the ELF signal is at the frequency of the power signal. Telephone distribution lines carry voice frequency signals, instead, basically in the 300 to 3000 Hz bandwidth, with some other specialized signals such as the ring signal (20 Hz), the pulse dialing signals, etc. Other telephone systems, such as analog and digital carriers that concentrate communication channels, operate at much higher frequencies. The ELF frequency spectrum is nearly outside the operating frequency spectrum of telephone systems, suggesting that ELF signals will cause small direct effects on the operation of the telephone system. Indirect effects, such as high ELF voltages and currents on equipment and facilities, can cause other problems including electrical safety problems and saturation of transformer cores.

Grounded Conductor Voltages

Any electrical system will have a conductor that is grounded.[1] This conductor is referred to as the neutral wire on power distribution lines, as the shield wire on power transmission lines, as the sheath on telephone cables, and also as the sheath on cable TV systems. Other facilities such as railroads and pipelines by their nature constitute a long metallic conductor that is in continuous contact with the earth or is intentionally grounded at various points. The earth ELF potential fields causes current to flow on these facilities and voltages can be measured at various points on these facilities, with respect to a reference point on earth.

Long and multigrounded conductors tend to have simple and predictable behaviors, and are amenable to modeling and mathematical analysis. Figure 3 shows the dominant voltage and current pattern that a long grounded conductor will experience in the presence of a uniform source such as ELF.

[1] There are still in use in the United States some delta power distribution lines that do not use a grounded conductor; however, these systems gradually are being replaced with wye systems that do include a grounded conductor.

The many deviations from this ideal situation that are found in the field, and the many other variations from ideal conditions, such as ground conductivity variations in the soil, create often complex and seemingly erratic voltage patterns. Signs of this basic behavior, such as the "tail effect," can be found in all of these patterns. The tail effect is a rapid rise in voltage at the end of a grounded line, as shown in Figure 3.

The resulting voltages on these grounded conductors depend on the level of potential field; the closer these conductors are to the ELF antenna wires, the higher the voltages will be. These voltages also depend on ground conductivity and on how effectively the conductor is grounded. These two parameters are somewhat interrelated, because ground conductivity will affect the grounding effectiveness of the conductor. The higher the ground conductivity and the more effective the grounding, the lower the resulting ELF voltages on the grounded conductor.

Stray voltages and currents are not uncommon on such conductors. ELF, however, can put sizable voltages on these conductors. Fortunately this is limited to very few runs, very close to the antenna wire. Furthermore, there are built-in features that limit the danger of these voltages. Voltages rise on grounded conductors because of lower ground conductivity, other things being equal. However, this same lower ground conductivity provides higher circuit impedance when considering touch and step potentials (discussed next), which limits the current that can be drawn from such a circuit. We will see later that this is a beneficial circumstance in addressing personal safety.

Single Mode Voltages

Because of the circulating currents, voltages on grounded conductors tend to be lower than those on ungrounded conductors. As we have seen above, ungrounded conductors tend to exist in pairs, in triplets, or their multiples as part of circuits, and the common voltage among them is almost inconsequential. However, a single mode voltage will exist between the grounded conductor and the ungrounded conductor. This can be seen as the third voltage vector, Figure 4, when the voltages on both the grounded and ungrounded conductors are measured with respect to a remote earth reference.

As a differential vector, the single mode voltage will vary inversely from the grounded conductor voltage: if the latter is made to drop, because of improved grounding, for example, the voltage between the grounded conductor and the ungrounded conductor will rise.

These single mode voltages are small compared to other ELF voltages, but will appear across any utilization device connected between the ungrounded and grounded conductors. This will be the case, for example, with utilization transformers on power distribution lines, which are connected phase to neutral, and on cable TV systems where the signal is between the coaxial cable center conductor and the sheath (which is the grounded conductor).

Touch and Step Voltages

Many structures and facilities in the residence and along the roadside are electrically connected to the grounded conductors of the utility systems. These connections are part of the electrical safety construction standards, which are fairly uniform across the country and sanctioned in the National Electrical Safety Code (NESC) and the National Electric Code (NEC). The ELF voltage on the utility grounded conductor is then conducted to any facility or system that is connected to it, and there are many such facilities. So it is that the ELF voltage on the power line distribution neutral wire will be passed on to the guy wires, because they are often electrically bonded to the line neutral wire, and to the residential neutral and grounding systems, because they are connected to the line neutral at the service transformer. From the residential grounding system, the voltage will then be passed on to other systems such as plumbing, because the residential electrical grounding is typically connected to the residential plumbing, to telephone systems, etc.

The most important consequence of this situation is that elevated voltages will be present on facilities and structures normally at earth potential. An individual touching them may experience some electrical current, hence the name "touch voltage" for this concern. Touch voltage is then a by-product of the voltage on grounded conductors. Touch voltage is the most pervasive of the ELF interference problems and the one of most concern. Touch voltage is a problem present on all utility systems--power, telephone, and cable TV systems--and it is then distributed to the customer just as if it were part of the service, and probably with the same effectiveness. Railroads, pipelines, and power transmission systems, because they do not interface with the ultimate user at the residential level, end up being a lesser problem, no more than a nuisance.

A second, related problem is point to point voltage that an individual might experience while bridging with his or her body (with the hands, for example) something that is connected to a utility grounded conductor and something that is not electrically connected to that system. One example of this would be to touch a faucet with one hand and a toaster with the other. This problem is a lesser concern, especially if all utilities and all facilities are electrically interconnected, as the codes specify. The intent in the codes is indeed to put all of the residential facilities and services at the same electrical ground potential, to avoid the development of voltage differences among systems. Most codes require all utilities to be jointly connected through their grounded conductors at the point outside the residence where they terminate their drops, before entering the residence. Residences will typically have power, telephone, and cable TV drops grounded together outside the residence and then grounded to the plumbing inside.

Step voltage is another related problem. This is another typical voltage that an individual would experience through his or her feet, when they are separated in a stride, on top of or near a grounding electrode that may be at an elevated ELF potential, because of being connected to the utility grounded conductors (Figure 5). Other situations are also of concern; these include knee to hand voltages, and chest to extremity voltages (Figure 5). These could be thought of as variations of the step voltage, but with other parts of the body involved in the proposed scenario. We should note, however, some important differences. The case of knee to hand voltage is a much more dangerous scenario, although not one to occur as frequent as step voltage. In the case of knee to hand voltage, one is not likely to have the electrical insulation protection of the shoes that he would have in a step voltage situation. A chest to extremity scenario may be more dangerous than a step voltage situation for the reason just described above--not having the electrical insulation protection that shoes often provide--and also by being so close to the heart as to cause the current to flow close to the heart in the body. However, the latter two cases may be rarer situations that the step voltage.

Antenna Ground Surface Voltages

These are point to point voltages on the surface of the earth, similar to the ones described above (step voltage, knee to hand voltage, etc.), except that they apply in different circumstances. The current on the ELF antenna is forced into the earth at the antenna wire terminals. An elaborate grounding system is used to keep the grounding resistance at a minimum. Nevertheless, as the current spreads into the earth at the contact points, voltage gradients are formed at the surface of the earth by this current. Indeed, a person walking in this area might experience these voltages. These voltages are a special electrical safety concern, one that is highly localized and dependent both on the antenna ground design and the type of soil involved. The use of horizontally buried wires is the source of many of these problems, and burying them deep tends to reduce the voltages at the surface of the earth. Deep, vertical wells put the current injection point far away from the surface of the earth and have almost none of these problems. The latter is nowadays the preferred design choice.

Interference Problems and Mitigation Techniques

The previous discussion has addressed the nature of ELF voltages induced on utility system from a perspective that helps to provide a way of classifying them and frame them within a common perspective. It is important, however, to understand the detailed nature of the interference that these voltages can create on specific utility systems, and how they can be dealt with, in order to lay a foundation to the understanding of risk and how to manage it. The following provides a detailed, case-by-case review of these problems. The discussion is divided along utility types.

Power Transmission Lines

Power transmission line voltages start at about 30 kV. Everything below it is usually considered distribution line voltage. The difference between the two of them, of course, is that transmission lines are used to transport electrical power in bulk among various generation, distribution, and consumer points. Distribution lines take over where transmission lines end, and distribute power to consumers. Transmission lines are invariably operated as single or multiple three phase delta circuits as shown in Figure ?. Shield wires are usually included for lightning protection.

The ELF voltage on the phase conductors is a common mode voltage, which means that is present on all three phase wires. As such, it is not a problem for transmission line equipment. Furthermore, the ELF voltage is typically tens of volts, perhaps hundreds of volts for lines very close to the antenna. These voltages are nevertheless insignificant with respect to the thousand of volts normally present on such lines.

The shield wires, because of their function of providing lightning protection, are grounded typically at every structure, or are bonded to the structure itself if the structure is metallic. When wooden poles are used, the most frequent case in the ELF antenna interference areas (see Figure ?), then ground wires are run down the poles. Guy wires are often used in conjunction with pole structures at corner locations to mechanically balance the line. Guy wires that reach to the height of shield wires (often referred to as shield guy wires) are often bonded to the shield wires with the express purpose of providing additional grounding through the anchor.

The shield wires pick up an ELF voltage (grounded conductor voltage) which will be passed on to all facilities normally tied to the shield wires. These include: metallic support towers or poles; grounding conductors and guy wires, when wooden poles are used; and substation grounds, which include fences. Because of design choice, there is no transmission lines located within or close to the ELF antenna right-of-way. The only transmission lines that get close to the ELF antenna are those that supply power to the sites. All other transmission lines are located further away and experience minor voltages. Figure ? shows a distribution of these voltages for the case of Michigan.

The obvious problem is for passersby who may touch the structures, guy wire, or fences at substations. Except for structures located near roadways, the rest of the structures are in remote wooded area, hardly accessible to the general population; but, nevertheless accessible to woodsmen, hunters, lumberjacks, etc. There are many simple and practical remedies to protect people. Where wooden poles are involved, ground wires are used that have insulation and are further protected with moldings, as shown in Figure ? Guy wires can be similarly protected with plastic covers (see Figure ?), which can help make them more visible, an added benefits for sites which have snow-mobile trails running near these lines. It is, however, difficult and not as reliable to cover the portion of the guy that attaches to the anchor, near to the ground. Various uses of rubber and tar-based tapes have been tried with some success (see Figure ?). Another approach is to use electrical insulators in the guy wires, as can be found in many other instances, such as with phase guy wires (the ones that balance the line at the height of phase wires). A guy insulator prevents the secondary role that the anchor performs, that of contributing to increasing the line grounding effectiveness. Furthermore, installing guy wire insulators in an operating line can be a very expensive undertaking because of the line shutdowns that have to be scheduled to do the job safely. On the other hand, the installation of such insulators is trivial and inexpensive if done at the time the line is built.

Uncommon measures may have to be taken when metallic support structures are involved. Shield wire segmentation is one very effective measure. Shield wire segmentation is not new to the power transmission industry. It has been tried to hold down 60-Hz induction losses without compromising the effectiveness of lightning protection. This technique was used in Michigan initially on the transmission line feeding the ELF transmitter itself. It was removed at a later time when a distribution line was underbuilt on the same poles. Figure ? provides an illustration of the principle. Adequate surge arresters can be installed between segmented sections of the shield wire to provide line continuity during lightning surge discharge.

The problem at substations is much harder to deal with, although it is not as serious because none of the substations is close to the ELF antenna wires. This is the result of care excersiced in the design and locating of the antenna wires. One exception is the small conversion substation that feed the antenna transmitter site. The obvious remedy, where the voltage is deemed to be excessive, is to either reduce the voltage by shield segmentation a number of spans away from the substation, or to upgrade the substation grounding to eliminate step and touch potentials. The perimeter outside the fence has to be particularly addressed so that passersby can touch the fence without being exposed to a possible electrical safety problem. This can be done by using ground rings properly designed to provide a sloping voltage gradient for people walking up to the fence.

Power Distribution Lines

There is more diversity in power distribution lines. The main distinction is between delta and wye systems. They both refer to three phase power systems, one were the supply and utilization transformers are connected to form a delta, the other where they are connected to form a wye (see figure?). They have different characteristic and performance. Three wires delta distribution systems were widely used in the U.S.A. in the past and are the dominant distribution lines around the world. They have come in disuse in the United States in recent decades in favor of the wye system, because the latter is believed to be safer and more reliable for power distributions. Some delta lines, operated at 13.8 kV do exist in the area of the ELF antennas in Michigan. Their main distinguishing characteristic is that they do not have a grounding conductor associated with them. Instead, they have surge arresters to protect them from lightning. The wye lines most common in the states, particularly in the area of the ELF antennas, are multigrounded four wire lines. They operate at either 2.4, 7.2, or 14.5 kV to ground. The respective voltages phase to phase are 4.2, 12.5, and 24.5 kV. The distinguishing feature of this line is the fourth conductor, the neutral wire, which is grounded at the substation, the utilization transformers, and other points periodically along the line, hence the reference “multigrounded.”

Delta distribution systems are nearly immune to ELF interference effects. The ELF signals picked up by the phase wires are common mode voltages. Balancing of the lines can affect the cancellation of these common mode voltages. The stepping down of the operating voltage at a utilization transformer from the primary (i.e., 13.8 kV) to the standard secondary voltage (120/240 V) provides for further attenuation of any net signal that may result from line unbalance. Assuming in a real bad situation that the common mode voltage were 100 V and the net voltage on the primary were 10 V as a result of the unbalance, the voltage on the secondary 120 V line would be 0.087 V because of the step down ratio of 115 across the transformer.

The absence of a grounded conductor on a delta line eliminates all of the problems associated with it: grounded conductor voltages, single mode voltages, touch voltages, etc. The service drop or main does include a grounded conductor, referred to as the secondary neutral. In the case of delta lines, it starts at the service transformer and ends at the residence. The secondary neutral is typically few hundred feet long, and with the exception of some rare situations (where the drop is very close to the antenna wires) it is not long enough to pick up significant ELF voltages. Delta systems are the most immune systems in power distribution to ELF interference. Unfortunately, they are the ones being used least nowadays. However, they represent a good alternative when considering relief from or mitigation from ELF interference effects.

Wye power distribution systems, on the other hand, are affected extensively by the ELF interference and require considerable and extensive mitigation. The common mode voltage on phase wires, as in the case of delta systems, does not seem to be a problem. This is deceptive because not all phase wires are carried to the many ends of a distribution line network. Furthermore, most devices and utilization transformers on wye systems are connected phase to neutral, rather than phase to phase. The fourth wire, the multigrounded neutral, picks up ELF voltages (grounded conductor voltages) which are extended to all facilities and systems interconnected to this wire, which are many. As discussed before, a host of problem voltages develop that start with the high voltage on the wire itself and extend to interrelated systems in the form of touch voltage, point to point voltage, step voltage, knee to hand voltage, etc. These are commonly referred to as the safety problem associated with the neutral wire on wye lines.

The single mode voltage that develops between phase and neutral wires is also a problem because many of the devices and systems on wye lines are connected between phase and neutral wires. This is often referred as the flicker problem, because its most visible manifestation is in the light flickering that it can cause for an incandescent light bulb.

The safety problem is by far the most extensive and the most serious problem. The voltage on the neutral is typically around 3 to 10 V. For lines close to and parallel to the antenna wires, these voltages can reach into the 20 to 50 V range, with a few instances of voltages up to or even greater than 100 V. Of course all line facilities, such as guy wires, transformer enclosures, switch gears, etc. will also have these voltages, by conduction from this neutral wire to which they are connected to. The voltage will also be conducted inside the residence and most other services by virtue of the neutral interconnection at the service transformer, mandated by standard construction (NESC). Furthermore, these voltage are conducted to other utility systems also interconnected to this neutral wire. These include telephone, cable TV, and municipal water systems. These other utilities have or represent extensive grounded conductor systems, which on their own would pick up ELF ground conductor voltages. However, the power line neutral wire remains the most serious and dominant problem, because it is often the longest, most continuous, and most effective conductors among these utilities. Breaks or gaps exist either accidentally, intentionally, or because of the working of the system, in most of these other utilities. The interconnection among these utilities creates a super maze of grounded conductors across many utility systems and large geographical areas, representing a pervasive treat.

The safety problems in connection with neutral wires are confined to line worker only because the line neutral wire is usually located out of reach of the general population. On overhead power lines, the neutral wire is usually at least 12 ft up in the air, and on underground lines it is similarly not directly accessible. The presence of few volts on the line neutral conductor should not be a threat or surprise to a line worker. They are aware of the presence of such voltages on any deenergized wire by the mere phenomenon of induction from active wires on the same pole. What may be surprising to line workers is the fact that merely grounding will not eliminate these voltages. Furthermore, it would be also a surprise to a line worker to see a voltage above 10 V on a normal customer service drop neutral wire.

There are no sure ways to eliminate or reduced the ELF voltage on primary neutral wires. One obvious technique would be to change the line from wye to delta, or other hybrid systems that in essence eliminate the multigrounded neutral, or threat it as an energized conductor. Few treatments like these have been tried (typically in hardship cases where the neutral wire had 100 V and more). An approach of limited effectiveness is to improve the line grounding. Techniques employed include putting a standard ground rod at every pole along the line, the use of counterpoise, and the use of deep ground rods. The latter has proven to be particularly cost effective and long lasting. The effects of improved grounding are to reduce the overall level of voltages on the line neutral, but it will not completely eliminate it. Furthermore, this approach has shrinking marginal returns, where the additional benefits in voltage reduction get smaller and smaller while the investments for improving grounding gets bigger at a fast escalating rate.

Another technique would be to create breaks in the power distribution line neutral wire. To safeguard the integrity and safety of the line, line transformers have to be used that create a mini substation, complete with special grounding, overcurrent protection, and other safety features. Overcurrent protection on the outgoing line are used to protect the line downstream and may even include undervoltage protection. Fuses and other overcurrent devices are used on the incoming line to open the circuits in case of a fault with the line transformers themselves. By creating a new return point for the line unbalance current to return to, and by appropriating the necessary safety guards, it is then possible to keep the incoming line neutral separated and isolated from the outgoing line neutral. An important consideration is cost. The expenditure for such an installation is a function of the line load at the point that neutral segmentation is chosen, and these costs can escalate nonlinearly with load size. These costs and safety considerations limit the number of such installations on the same line. Fortunately, most lines involved in the ELF interference problem are rural lines, which make this technique a viable one. It has been tried at least in one instance in Michigan.

Another approach, tried in Wisconsin, is to treat the neutral conductor as an energized conductor. It is a relatively simple procedure in single phase lines. In a manner similar to the one discussed above for the case of neutral wire segmentation, a line transformer is used to convert the line at a selected point on the line. One side of the line transformer output line is grounded, hence the name “unigrounded.” The line transformer is fused at the input and provided with output overcurrent and undervoltage protection at the output. This is a viable solution is simple situations, although it results in hybrid designs requiring special attention in operation and maintenance.

Another approach still is to attempt to cancel the ELF signal on the neutral wire. Shield wires principles can be used for passive cancellation. If not capable of eradicating the problem, it should be able to reduce substantively the ELF voltage on neutral conductors. This technique can be valuable as a special use on limited sections of a line to reduce very high levels of ELF voltages on the neutrals. Active neutral wire mitigation is another measure along this approach. It would purposefully inject on the neutral wire or another parallel conductor coupled into the neutral, a signal equal to but in opposite phase of the natural ELF signal on the neutral wire for the purpose of canceling it. Neither of these techniques has been investigated further.

The voltage on the line neutral wire may still be relatively high and objectionable after some of these line modification techniques are implemented. This leads to touch voltage, step voltage, and a host of related electrical safety problems in and around consumer facilities and distribution facilities along roadways, as discussed before. Residential customers are a prime concern because the line neutral voltage is carried onto the residential grounding system, and thence to the rest of the residential infrastructures such as potable water plumbing, hydronic heating systems, and aluminum siding. Power line facilities located along roadways and easily accessible to passerby, such as guy wires, are also of concern. The approach of last resort to deal with these problems is to isolate, using safe and approved techniques, with the goal of preventing the conduction of the line neutral voltage to the facility or structure intended to be safeguarded. Where this is not possible, insulation is used as well as redesigning that puts the facility out of reach or eliminates the situation altogether.

The most common mitigation technique for residential services on lines with multigrounded neutral wires is to isolate the customer neutral from the line neutral in accordance with NESC rule 97.D.2. This requires that the transformer be factory-predisposed to isolate the secondary from the primary neutral. Guy wires are similarly treated with insulators high up on the guy, which prevent the voltage from being transmitted to the lower portion of the guy and the anchor. Ground wires are instead replaced with insulated wires and covered with plastic moldings at the ground level. The service transformer enclosure (also at the line neutral voltage) is considered safe up on the pole where it is out of reach of the general population.

Ground level transformers, on underground lines, require specialized treatment. First of all, jacketed cables have to be used underground near the transformer site to insulate the concentric neutral from earth . If a selfenclosed pad mounted transformer is used, it has to be modified at the factory to allow for the isolation of the incoming line neutral from the transformer enclosure. Another approach is to use a pole-top transformer mounted on a pad and enclosed within a metallic enclosure isolated from the line neutral, or a plastic enclosure. The latter is a particularly expensive treatment, because of the extra parts and the need to provide double door safety for high voltage live-wire operation. The self enclosed design is by comparison much simpler in design and much less expensive. However, the pole-top transformers mounted on a pad within and insulated enclosure can provide increased safety over selfenclosed pad-mounted transformers. In case of a transformer internal failure, the ability of clearing the problem by a fuse ahead of the transformer is dependent on sufficient fault current to flow. The line neutral is isolated from the transformer enclosure in the case of the selfenclosed transformer, which would limit the flow of this fault current. This is not the case for the pole-top transformer mounted on a pad. The neutral isolator becomes then a key link in the circuit, to resolve possible internal transformer failures. This is possibly a role that goes beyond what was intended in the NESC code where the neutral isolation practice was allowed for.

Other devices along a power line that may need treatment include the gears to operate pole-top line switches, and ground based enclosures on underground lines, such as junction boxes and pad-mounted line switches. Here too arrangements are worked to keep the line neutral from being connected to the metallic hardware or enclosures at ground level, to protect passerby from touch voltages. Facilities such as street light harms (when mounted on wooden poles) and other control devices for the power line can usually be located high on the pole to remain bonded to the line neutral and still be out of reach to the general population.

Another special concern along a power distribution line, referenced earlier, is the grounding electrode for the line neutral and the possibility of related step voltages. A typical power line grounding electrode is a copper-clad steel rod (5/8 in. in diameter and 8 ft. long) installed vertically in the ground with its top end flush with the ground. The ground rod will be elevated in potential compared to the earth it is buried in, because of the ELF voltage on the neutral wire to which it is connected to. ELF signal current will flow through this ground rod between the neutral wire and earth, setting up an electric potential gradient as one moves away from the ground rod. This gives rise to step and touch voltages that can be objectionable.

The problem is resolved simply by driving the rod deeper in the earth, so that its top end will be buried below the earth surface enough to preclude surface step potentials (typically a foot or more). An insulated wire, covered with molding at ground level, is used along the pole to connect the line neutral to the ground rod. The insulated wire is required below grade also, to extend the neutral connection wire to the ground rod now buried deeper. Special care is needed to insure that the construction does not results in exposed metallic parts below grade above the top of the ground rod (i.e., splicing bolts). This is why engineers will specify typically a splice-free wire from the top of the ground rod to a point high on top of the pole.

Any other grounding system on the power line has to be buried deep to provide protection from these voltage problems. Counterpoises, for example, are buried 12 to 18 inches deep. The approach has proven very effective, although there have been noteworthy issues associated with this construction, as we will see later.

The other major ELF interference problem for wye power distribution lines is flicker. This is a single mode voltage that develops between the phase and neutral wire on power line distribution conductors. As explained earlier it is typically small, around 1 V for a 120V service, but enough to cause some nuisance problems such as light flicker. It is affected in part by the grounding effectiveness of the line neutral, and will change in response to changes in the line neutral grounding effectiveness. Trying to reduce the line neutral voltage by improving the line grounding, as a mitigation measure for example, will cause the flicker voltage to rise. Flicker voltage will vary with variations in the ELF voltage on phase wires as well. The phase wire voltage is the common mode voltage and, as explained earlier, it is subject to line imbalances. The continuous and random changes in customer load over a network is a source for such imbalance.

Flicker voltage is primarily a nuisance problem. It is however a very expensive problem to fix. An obvious technique to eliminate this voltage problem is to change the line from wye to delta. This would have the added benefit of eliminating the safety voltage problems as well. There are some concerns in using delta, as explained earlier. Some power engineers see it as a move backward to an outdated mode. Furthermore, it is a very expensive remedy in that the line would have to be redesigned and rebuilt extensively. A more convenient solution, less expensive as well, is to change service transformers form the type that is connected phase to neutral to the type that is connected phase to phase. This allows for the mitigation to blend into the power line design, because while the line design remains the same throughout the network, the service transformer can be changed over only on taps and in areas where it is needed for mitigation purposes. This is a solution that completely precludes the problem by eradicating it.

There are other solutions that tend to provide relief for the problem, as compared to eradicating the problem. Raising the level of distribution voltage (voltage uprating) will cause a drop in the flicker voltage level because of in increase in the service transformer step-down ratio. Service transformers are used typically near where the service takes place to drop the voltage from the line level, many thousands of volts, to the standard residential service voltage of 120/240 V. The voltage step-down ratio is 20 for a 2.4 kV line, 60 for a 7.2 kV line, and 120 for a 14.5 kV line. The ELF voltage on the phase wire, which contributes to the flicker voltage, is the same independently of the 60-HZ voltage that the line is operated at, but will be reduced by the same step-down ration. Raising the operating voltage from 2.4 to 7.2 kV will likely cause flicker voltages to drop by a factor of 3, while raising the operating voltage from 2.4 to 14.5 kV will likely drop flicker by a factor of 6. Voltage uprating are also expensive because it requires changing the insulation level on the line (new poles and new insulators) as well as replacing service transformers. It is a worthwhile consideration when this measure is part of a company plan to upgrade the line.

Another technique of limited effectiveness is the use of isolation transformers. This is basically a parochial solution that uses a line transformer connected phase to phase to the source so as to see the common mode voltage, which cancels out inside the transformer. Its effectiveness is limited by the fact that the ELF voltage will start building up again on the outgoing lines. The section of line between the transformer location, where the ELF voltage is zeroed, and the point further down the line where the voltage rises above the objectionable level is where the benefit occurs. This works very well if the isolation transformer is located near the end of a line where the voltage is less than the unobjectionable range, or where the line follows a path away from the antenna so that it does not pick any more ELF voltage.

The line after the isolation transformer is not affected and remains unchanged, which has some appeal to power engineers. It is also an ideal solution for single phase taps. A drawback is that the line often has to be upgraded from single phase to double phase up to the point where the isolation transformer is installed, to provide the common mode voltage. Balance on the feed line for the transformer is a consideration to assure a good cancellation inside the isolation transformer. This has been a very popular mitigation technique. It is preferred in areas where the interference effects are modest and where the need for line upgrade are minimal.

Another technique is a to utilize a line transformer connected to give phase reversal, hence the name phase reversal transformer. This transformer is more effective than an isolation transformer because rather than zero the ELF signal at a certain point on the line and then let it naturally rise again, the phase reversal transformer flips the polarity of the ELF signal so that from that point on it cancels with the ELF signal picked up naturally further down the line. In essence, it is more efficient than the isolation transformer, because rather than zeroing the ELF voltage, it turns it around and makes it work to cancel more voltage down the line. In so doing it extends the mitigation along a line. It has further the advantage on not requiring two phase feed. So, altogether is a lesser expensive solution. This technique has been tried a few time in Wisconsin, but has fallen in disuse because of some problems. For instance, the phase inversion cause a drastic change in the 60Hz operational current flow with significant noise induction problems on telephone lines. In the end, like isolation transformers, phase reversal transformers have limited effectiveness and can be used only for localized relief.

The isolation transformer can be used for area wide solution of flicker problem. The line is redesigned along a different philosophy. The main line trunk, typically multiphase, is reserved for multiphase customers and as a feed to a host of isolation transformers which serve and control a limited geographical area.. It is as if the service network were fragmented into smaller, single-phase, local networks and then each one of them were hooked to a power distribution bus through an isolation transformer. The main line purpose then becomes to feed the isolation transformers which in turn feed the subnetworks; it is, therefore, referred to as the express feed system. This approach makes possible to use isolation transformers, a device of limited effectiveness, to resolve the interference problem for an entire network. Its effectiveness and practicality compared to other approaches depends also on the extent and intensity of ELF interference. It leaves the end portions of the distribution system intact, the taps and the service transformers, and for this reason is preferred by some power engineers. It has been used in Michigan.