COMPUTER MODELLING OF AC INTERFERENCE PROBLEMS FOR THE MOST COST-EFFECTIVE SOLUTIONS

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ABSTRACT

AC interference from high voltage power lines can constitute an electric shock hazard and a threat to equipment integrity during both normal operation conditions and fault conditions. Simplified analysis methods can lead to millions of dollars in excess expenses due directly to overdesign or resulting from the consequences of underdesign. This paper presents a cost-effective AC interference mitigation method, which is made possible by the power of presently existing computer software. The importance of the soil's multilayer soil structure in determining the performance of mitigation systems is discussed. This mitigation method is compared with other types of mitigation systems.

Keywords: AC Interference Mitigation, Induced Voltages, Electric Power Transmission Lines, Conductive Through-Earth Coupling from Towers and Poles, Gas, Oil, Water Pipelines

INTRODUCTION

A pipeline which shares a common corridor with AC transmission lines becomes energized by the magnetic and electric fields surrounding the power system in the air and soil. This AC interference can result in an electrical shock hazard for people touching the pipeline or metallic structures connected to the pipeline... or simply standing nearby; furthermore, damage to the pipeline's coating, insulating flanges, rectifiers or even direct damage to the pipeline's wall itself can occur.

This paper discusses recent advances made in mitigating electromagnetic interference generated by electric lines on neighbouring pipelines (oil, gas, water). It describes state-of-the-art analysis tools and mitigation techniques which effectively reduce AC interference to acceptable levels, while yielding tremendous cost savings compared to alternative methods.

HISTORICAL PERSPECTIVE

In 1976, EPRI and A.G.A. jointly funded a research project which resulted in the development of a hand calculator program to predict inductively induced voltages on pipelines parallel to power lines[1,2,3,4,5]. Further work was carried out later in a follow-on research program to develop computer software which can handle realistic rights-of-way in which pipelines and power lines are not always parallel[6]. Subsequent funding by EPRI and AAR focused on interference to railroad facilities[7,8] and a computer program called CORRIDOR, capable of predicting steady-state induced voltages on pipelines and railroad facilities was made available. In the late 80's, the ECCAPP (Electromagnetic and Conductive Coupling Analysis from Power lines to Pipelines) was developed to account for both inductive and conductive coupling during fault conditions, a problem which could not be investigated using the CORRIDOR program[9,10,11].

The preceding work focused mainly on the prediction of interference levels, but very little work was devoted to the development of sound and practical mitigation methods. Indeed, following the initial EPRI/A.G.A.- funded research work, a mitigation method called the "Cancellation Wire" technique was developed and presented as a highly effective approach to reduce inductive interference. As explained later, it turned out that this method was not appropriate because it transferred dangerous voltages from one location to another. Furthermore, all this work considered the soil to be uniform and did not discuss the effects of soil inhomogeneity on the design of effective mitigation.

Significant work on economically sound and practical mitigation measures started with studies in the Saudi desert and culminated in the development of a highly efficient mitigation solution capable of achieving significant inductive and conductive interference reduction, while accounting for the true nature of the soil structure. This new method was implemented along the NYPA/Empire State Pipeline right-of-way in the state of New York[12].

INTERFERENCE MECHANISMS AND MITIGATION OBJECTIVES

Pipelines sharing a right-of-way with power lines may be subject to electrical interference due to both inductive and conductive effects. Magnetic induction (coupling) acts along the entire length of pipeline which is approximately parallel to the power line and can result in significant pipeline potentials even at relatively large separation distances. Conductive interference due to currents flowing in the soil is of particular concern at locations where the pipeline is close to transmission line structures which may inject large currents into the soil during power line fault conditions. Such structures include transmission line tower or pole foundations and substation grounding systems.

The effects of power system interference on pipelines are due to the relative voltage difference which is created between the pipeline metal and the local soil.

In terms of safety for personnel and the public, a potential shock hazard exists when someone touches an exposed part of the pipeline (such as a valve) while standing on soil which is at a different potential. The ***touch voltage*** to which a person would be subjected when standing near the pipeline and touching an exposed part of the pipeline is defined as the difference in potential between the pipeline metal and the earth surface above the pipeline. Similarly, the ***step voltage*** is the difference in potential between a person's feet, and is defined as the difference in earth surface potential between two points spaced 1 m (3.3 feet) apart.

Power line / pipeline interference can also result in damage to the pipeline and its coating. Excessive coating stress voltages (the difference between the pipe steel potential and local soil potential) can result in degradation or puncture of the coating, leading to accelerated corrosion. In the case of an extreme soil potential rise, the pipeline wall itself can be damaged or punctured.

Steady State or Load Conditions

"Steady state conditions" designates normal operating conditions of the electric power transmission system, which can vary from low to high load conditions. During such conditions, the currents flowing in the 3 phases of each circuit are relatively low in magnitude (compared to fault conditions) and their effects on nearby pipelines tend to cancel one another out. As a result, AC interference levels during load conditions result from incomplete cancellation between phases, due to the difference in the relative distance of each phase from the nearby pipelines and due to any unbalance in the currents the 3 phases carry.

Inductive interference is the dominant interference mechanism under normal power line conditions. Induced potentials on unmitigated pipelines can reach hundreds of volts at power line transposition locations or at locations where the pipeline and power line veer away from one another or cross each other. Induced steady-state pipeline potentials are more severe when the pipeline coating has a high electrical resistance. However, a high coating resistance is desirable from a cathodic protection standpoint, so reducing the coating resistance is not usually considered a viable solution.

In spite of the relatively low magnetic field levels during steady state conditions, induced voltages on an unprotected pipeline can reach hundreds of volts. Even with extensive grounding systems connected to the pipeline, pipeline potentials can be on the order of dozens of volts, with hundreds of amps flowing in the pipeline. This constitutes primarily a shock hazard, which can be transferred miles away from the parallel corridor.

Fault Conditions

Inductive Coupling. During single-phase-to-ground fault conditions on the power line (i.e., a single energized phase wire is shorted to a transmission line structure or substation grounding system), induced potentials in a pipeline with no mitigation system can reach thousands of volts, due to the intense magnetic field caused by the large current which may flow in the faulted wire. In AC inductive interference studies, it is important that power lines as far away as 300 m or more from the power line under study be given serious consideration.

Conductive Coupling. When a single-phase-to-ground fault occurs at a power line structure, the large fault current injected into the soil by the structure raises the local soil potential (see Figure 1). A pipeline located nearby, however, will typically remain at a relatively low potential, due to the resistance of its coating and grounding at points distant from the fault location. The pipeline potential rise will be particularly small for a pipeline with a high resistance coating. Therefore, the earth around the pipeline will be at a relatively high potential with respect to the pipeline steel potential.

Unless the pipeline is perpendicular to the power line, the pipeline will be simultaneously subject to both inductive and conductive interference. In most interference studies performed by the authors, the change in pipeline steel potential due to induction is essentially opposite in sign to the soil potential change due to conduction, therefore inductive and conductive effects add, producing even more severe coating stress voltages and touch voltages.

The magnitude of the conductive interference is strongly influenced by the soil structure: soil potentials, and therefore touch voltages, decrease with increasing distance away from the faulted structure, but the rate of decrease depends upon the soil structure, and especially on the soil layering characteristics, and thus can cause order of magnitude variations in interference levels from site to site.

Excessive touch voltages due to conductive interference can be reduced by either reducing earth surface potentials in the vicinity of the pipeline, or by raising the pipeline potential near the faulted structure. The most effective mitigation systems perform both of these actions simultaneously.

Transferred Voltages. Due to inductive and conductive coupling, considerable voltages can be transferred many kilometers beyond the end of a common corridor. As a result, it is necessary to properly study the entire pipeline system, as mitigation may be required, for instance, to protect valve sites which are far away from the transmission line exposure location.

Mitigation Objectives

The mitigation system must achieve the following objectives:

- During worst case power line load conditions, touch voltages at all exposed structures, such as valves, metering stations, and pig launchers/receivers, must be sufficiently low to minimize shock hazards to operating personnel and the public. NACE Standard RP0177-95[13] recommends a 15-volt touch voltage limit, based on the let-go current threshold for most men. This limit is also set forth in CSA Standard C22.3 No. 6-M91[14]. Note that this is the potential difference between two parts of the pipeline that can be contacted simultaneously and are at different potentials (e.g., the voltage difference across an insulating flange) or between the pipeline and the earth surface within reach of the exposed structure. The actual potential of the pipeline with respect to a remote point can be quite high, so long as the earth potential is also high: i.e., within 15 volts of the pipeline potential. This nuance is important as it means that mitigation systems need not lower pipeline potentials to 15 volts, provided that they transfer a sufficient percentage of the pipeline's potential to the local soil.
- During fault conditions, as for steady state conditions, touch and step voltages at all exposed structures must be sufficiently low to mitigate shock hazards. ANSI/IEEE Standard 80-1986[15] provides safety criteria based on the heart fibrillation current threshold, derived from empirical work performed by Dalziel and others. For a 0.5-second fault

duration, the touch and step voltage safety limits, while different for significant surface soil resistivities, both approach 164 volts for a 50 kg subject as the soil resistivity approaches zero and no protective layer such as crushed rock or asphalt is installed over the earth. The safety limits increase as the fault duration decreases and the surface material resistivity increases. An international standard[16,17], published by the International Electrotechnical Commission (IEC), provides alternative safety criteria. Unlike the ANSI/IEEE standard, which assumes a constant 1000-ohm body resistance, the IEC standard accounts for variations in body resistance as a function of applied voltage. The fibrillation current versus time curves provided by the IEC standard are based on research performed since Dalziel's work and result in substantially different values for certain fault durations, as shown in the comparison done in one CEA study[18]. For example, for a 0.5-second fault duration, the touch voltage limit derived from the IEC standard is 113 volts, for a very low resistivity soil, as compared to 164 volts for ANSI/IEEE Standard 80.

Special precautions must be taken by maintenance personnel when excavating portions of the pipeline to ensure safety in case of a fault.

- Also during fault conditions, coating stress voltages must be maintained sufficiently low to prevent arcing through coating holidays. This typically occurs for coating stress voltages on the order of 3 - 5 kV or higher for modern coatings such as fusion bonded epoxy[19]. For bitumen coatings, glow arcing can occur for voltages as low as 1 kV[20]. This arcing can damage not only the coating but also the pipeline's steel wall itself[21]. Indeed, in severe cases, the pipeline can rupture as a result[22].

- Achieve the preceding objectives, while minimizing the cost of the mitigation system. One key element here includes taking advantage of the soil's multilayer structure to achieve good control of earth gradients without necessarily installing extensive grounding systems to bring pipeline potentials down to very low levels. In general, the more detail is included in the model used to perform the study, the more the mitigation system can be fine-tuned, as conservative assumptions, required in the absence of data, can be avoided.

In addition to the above considerations, current research[23] indicates that corrosion can be caused directly by AC interference on pipelines whose measured CP levels are satisfactory according to current standards, particularly when the AC leakage current density is on the order of 20 A/m^2.

METHODOLOGY FOR A COMPLETE AC INTERFERENCE / MITIGATION STUDY

This section presents an analysis/design methodology which, in the authors' experience, produces effective mitigation, as confirmed by recent measurements[24], at a fraction of the cost of alternative methods.

Soil Resistivity Measurements - A Key Element

Soil resistivity measurements must be made at representative locations throughout the common pipeline/transmission line right-of-way in order to characterize the soil structure as a function of depth, to significant depths, everywhere. Touch voltages, step voltages and coating stress voltages associated with the pipeline and resulting from fault currents injected into the earth by nearby electric power system structures are highly sensitive not only to the average soil resistivity at any location, but also to the relative thicknesses and resistivities of the soil layers present at that location. Order of magnitude errors in computed interference levels can result[12], if the soil structure is not adequately measured, resulting in excessive mitigation costs or underdesigned systems, with the latter entailing possible exposure to expensive safety or equipment integrity problems. The performance of mitigation systems, such as gradient control grids and gradient control wires, is also dependent on a good knowledge of detailed soil characteristics down to significant depths.

Soil resistivity measurements are carried out using the Wenner 4-pin method up to electrode spacings on the order of 100 m or more, for typical applications. Measurement sites should be selected at regular intervals along the right-of-way and include strategic locations such as exposed pipeline appurtenances, sites where power lines structures are especially close to the pipeline, and sites where inductive interference levels are expected to be most severe. Precautions must be taken to permit detection and elimination of induced ac noise and noise from stray earth currents in the measurements. Furthermore, measurement traverses should be located and oriented such as to minimize interference from nearby bare buried metallic structures (such as water pipes and grounding systems).

Equivalent soil structures must be derived from the soil resistivity measurement data with enough accuracy to allow prediction of interference effects from power system structures buried in those soils and prediction of the performance of mitigation systems. Often, three or more soil layers must be modelled in order to characterize a soil structure accurately. In interpreting the soil resistivity measurements, possible distortions arising from inductive coupling between the measurement leads must be considered and so must the burial depth of the measurement electrodes or pins for short electrode spacings[25].

Interference Analysis and Mitigation Design Process

Inductive Interference Study. All conductors in or close to the right-of-way of interest should be modelled by computer in order to accurately determine interference effects resulting from magnetic induction. Conductors of interest include phase conductors and non-energized conductors (e.g., static wires, neutral wires, continuous counterpoises) of the electric power system, coated pipelines, and long bare buried conductors such as water pipes, which can have a significant effect on interference levels, including considerable mitigating action. All significant deviations of these conductors and phase transpositions should be modelled, since voltage peaks will occur in the pipelines at these locations.

For maximum emergency load conditions, accounting for the maximum expected load unbalance, touch voltages (typically equal to the pipeline potentials when the coating resistance is high and no mitigation is present) are computed throughout the entire length of interest of the pipelines.

Usually (but not always), the worst case fault location for a given pipeline section is the power system structure closest to that section of pipeline. In order to protect a pipeline adequately, it is necessary to model faults at representative locations throughout its length of exposure to the transmission line (e.g., every 10% or more) in order to determine the worst case interference levels everywhere. For each fault, the following values are computed:

1. induced pipeline potentials (and coating stress voltages) throughout the pipeline length of exposure, touch voltages at exposed pipeline appurtenances, and transfer voltages to locations outside the exposure zone.
2. GPR of the faulted transmission line structure and neighbouring structures (required for the conductive interference study).
3. distribution of total fault current between the power system static wires (or neutral wires) and the faulted structure. This must be done to avoid overly conservative (by an order of magnitude in some cases) conductive and inductive interference predictions. Note that static wires can carry a significant percentage of the total fault current *throughout* the pipeline parallelism in such a way as to cancel part of the magnetic field generated by the faulted phase conductors.

Conductive Interference Study. Because soil characteristics can change considerably from one part of a right-of-way to another, and because the current distribution between a faulted structure and the static wires (or neutrals) can also vary considerably from one location to another, it is important to model representative towers or poles throughout the pipeline/transmission line collocation zone in order to determine worst case conductive interference effects on each portion of the pipeline of interest.

The foundations of each representative structure (i.e., tower or pole) are modelled in the multilayer soil structure characterizing the surrounding area. Each structure is then energized to the GPR computed in the inductive interference analysis at that structure during a fault at that structure (accounting for the fact that most of the fault current is normally diverted away from that structure by the static wires), and earth potentials are computed as a function of distance away from the structure up to the pipeline position. If the distance between the pipeline and the nearest structure is not very small, then it may be necessary to include the effects of several structures in the calculation. Extensive bare buried metallic structures close to the pipeline, such as water pipes, may have a significant impact on the results and should be modelled. The grounding systems of substations close to the pipeline(s) of interest must be studied in the same manner as the towers/poles.

Note that this calculation is very sensitive to the layering of the soil[12]. Calculating conductive interference levels based on uniform soil models can lead to order-of-magnitude errors when the soil has a multilayer structure, thus requiring expensive conservatism, i.e., high mitigation costs. Similarly, a satisfactory equivalent two-layer soil model may be impossible to find. Three or more soil layers must often be modelled in order to achieve satisfactory results.

Mitigation Design. Mitigation typically consists of gradient control grids at exposed pipeline appurtenances, to eliminate electrical shock hazards, and gradient control wires (other mitigation methods are typically less effective and more expensive, as described in the following section) along the pipeline to prevent excessive gradients from damaging the pipeline's coating and possibly the pipeline's steel wall. Designing safe and cost-efficient gradient control grids and gradient control wire systems requires computer modelling of these conductor systems in the soil structures obtained from detailed measurements at these locations. Touch and step voltages associated with gradient control grids are highly sensitive to the characteristics of the soil layers: structures with three or more layers are often required for satisfactory results.

The same is true of the gradient control performance of the gradient control wires: the effectiveness of gradient control wires in reducing coating stress voltages varies considerably as a function of the soil structure. It is different for inductive and conductive interference, which must be studied separately and then combined together, as the magnitudes of inductive and conductive effects are typically additive.

Furthermore, the frequency of interconnection required between the gradient control wires and the pipeline is very much a function of soil structure and resistivity, lower top soil resistivities requiring more frequent connections to offset the higher voltage drops along the gradient control wire conductors.

MITIGATION METHODS

Overview

In the past, various types of mitigation strategies have been employed, but many have been found to be either ineffective or very expensive or even hazardous. The following subsections describe three types of mitigation system, beginning with two older (non-recommended) methods, i.e., lumped grounding and cancellation wires, and ending with the preferred method, i.e., gradient control wires.

Note that in addition to these methods, all of which involve some form of pipeline grounding, the following are additional measures which can be considered to reduce AC interference levels in an effective manner, although all but the first represent options which may often not be available :

1. Bonding across insulating flanges through solid state isolator/surge protectors, which maintain DC isolation, while establishing AC continuity for reduction of touch and stress voltages across these flanges.
2. Bonding to substation/plant grounding systems through solid state isolator/surge protectors. This measure may be expedient for pipelines running beneath or feeding power plants or substations, but requires careful analysis to ensure that dangerous potentials are not transferred to remote locations.
3. Increased separation distance between the pipeline and the nearby power lines. Note that while conductive interference levels drop off in an inverse proportion to the separation distance for uniform soils, inductive interference levels drop off much more slowly. For example, a recent CIGRÉ guide[26] suggests that pipelines within a zone of influence extending 200 $\sqrt{\rho}$ meters (i.e., 2 km, for a 100 ohm-m soil) from the power line be studied, where ρ is the equivalent soil resistivity (including deeper layers) in ohm-m.
4. Installation of continuous, low-impedance, overhead ground wires on the power line structures, bonded to the structures. This measure considerably reduces conductive interference levels, as the total available fault current is distributed among neighbouring structures, rather than being injected into the earth by a single structure. Furthermore, current flowing in the overhead ground wires can mitigate inductive interference levels considerably. The addition of overhead ground wires, however, will often be out of the question, once the power line has been built.
5. Judicious selection of the conductor phase sequence on double circuit lines can reduce interference levels substantially during load conditions (but not during fault conditions).
6. Increased insulator BIL ratings on power line structures that are especially close to pipelines (e.g., at pipeline crossings) will reduce the likelihood of a fault at these structures.

Note also that all of the methods which follow require engineering calculations specific to the voltage levels, soil structures and other particularities of the system under study. For example, gradient control mats are sometimes routinely specified for exposed pipeline structures, without any verification that their performance is satisfactory. As a result, although they will certainly lower touch voltages, there is no guarantee that they will lower touch and step voltages to safe levels. In fact, ***the gradient control grids may actually increase the safety hazard*** if they lower voltages from a range in which thermal damage to body tissue is likely (resulting in hospitalization for burns) and death from ventricular fibrillation less likely, to a range in which thermal damage does not occur, but ventricular fibrillation is most likely.

Lumped Grounding or "Brute Force Method"

The conceptually simplest manner of lowering AC interference levels in a pipeline is to connect the pipeline to a low impedance grounding system. If the impedance is made low enough, then the pipeline potential at the connection point can be decreased to any level desired. Unfortunately, achieving the low impedances required to achieve acceptable levels can require grounding systems of daunting proportions. For example, in a 100 ohm-m uniform soil, a 50 m long vertical rod will achieve a ground impedance of 3 ohms; to achieve an impedance of 0.3 ohms, six 100 m long vertical rods spaced 100 m apart and connected by a bare horizontal conductor are required; to achieve 0.1 ohms, a 400 m x 800 m array of fifteen 300 m vertical rods are required. If the soil resistivity increases to 1000 ohm-m (not uncommon), then the dimensions of these systems must increase tenfold! Furthermore, these must be installed at multiple locations. These impedances are those determined from one early exploratory study performed by the authors to determine mitigation requirements for one parallel corridor they encountered (see Section 8.2 for further details). Clearly, this mitigation strategy can be both impractical and exhorbitantly expensive.

On the other hand, in areas where soil resistivities are very low (e.g., resistivities on the order of 10 ohm-m or lower) this method can result in satisfactory protection systems, although such soil resistivities are more the exception than the rule. Unfortunately, when the multilayered structure of the soil is not accounted for in the mitigation design process, this is the only mitigation method, strictly speaking, which can assure sufficient protection.

Cancellation Wires

The Cancellation Wire technique[6], which was developed in the late 80's as part of a series of EPRI/A.G.A. research projects, is a seemingly elegant method of mitigating pipeline voltages which, however, suffers from several serious problems. The technique consists of burying long wires parallel to the transmission line, often on the side opposite to the pipeline, or continuing along the transmission line right-of-way beyond points where the pipeline deviates out of the common right-of-way. Thus, the wires themselves are subject to interference from the transmission line. However, by carefully locating each wire, the voltages induced on it are out-of-phase with the voltages induced on the pipeline. Then, by connecting one end of the wire to the pipe, the out-of-phase voltages on the wire will cancel the voltages induced on the pipeline. The other end of the wire is left free.

Problems with the technique include:

- It is only designed to mitigate magnetically induced voltages, and does not address potentially damaging conductive interference during fault conditions. It may even worsen induced voltages for certain fault locations.

- The wire can export excessive potentials to its free end, which is often on the other side of the power line right-of-way, where high potentials may not be expected and can represent a safety hazard.

- The cancellation wire often crosses beneath the power line and thus increases exposure of the pipeline to virtually direct energization from a fallen line or, during fault conditions, from unknown grounding system components or metallic debris.

- This mitigation scheme also often requires the purchase or leasing of additional land outside the pipeline right-of-way, which can represent a significant added cost.

Gradient Control Wires

Recent advances in interference control have resulted in the gradient control wire method. Gradient control wires typically consist of one or more bare zinc conductors in backfill, buried parallel and near to the pipeline, and regularly connected to it (see Figures 2 and 3). They are a highly effective means of mitigating excessive pipeline potentials due to both inductive and conductive interference. Gradient control wires accomplish their task by "evening out" pipeline and soil potential differences.

In the case of inductive interference, gradient control wires provide additional grounding for the pipeline, thus decreasing the induced pipe potential rise. At the same time, they raise local earth potentials, resulting in sharply lower touch and coating stress voltages (see Figure 2 for a typical touch voltage profile running across the pipe). In the case of conductive interference, gradient control wires dampen the soil potential rise in the neighborhood of the pipe. At the same time, pipe potentials are raised. Again, this results in reduced touch and stress voltages (see Figure 1, which corresponds to the mitigation system shown in Figure 2).

When the gradient control wires are made of zinc, they are anodic with respect to the pipeline and thus minimize their impact an any impressed current CP system connected to the pipeline and may even supplement it at some locations.

Gradient Control Wire Performance. Figures 2 and 3 illustrate typical gradient control wire installations. In Figure 3, a plot of touch voltage along a traverse perpendicular to the pipeline is superimposed on a schematic diagram of the pipeline and wire installation. The gradient control wires can also be placed at the bottom of the pipeline trench and raise local earth potentials, thus limiting touch, step, and coating stress voltages to a fraction of the pipeline potential with respect to remote earth. The touch voltages are expressed as a percentage of the pipeline potential rise.

As Figure 3 shows, touch voltages near the pipeline, i.e., the difference in potential between the pipeline steel and local earth, are approximately 14% of the pipe potential rise. This means that near the pipeline, earth surface potentials are raised to approximately 86% of the pipeline potential. The 14% touch voltage also represents the maximum possible coating stress voltage, while step voltages will be even lower.

The performance of gradient control wires is a function of the soil layering characteristics of the location where they are buried. Table 1 lists touch voltages, as a percentage of the pipeline potential with respect to remote earth, for a representative sample of soil structures encountered along an ANR Pipeline Company (Detroit, Michigan) right-of-way in New York State. The table also shows the ground resistance per unit length of gradient control wire. The following observations can be made based on Table 1:

1. The effectiveness of the gradient control wires in raising local soil potentials and reducing touch voltages varies by more than an order of magnitude as a function of soil structure: touch voltages vary from 2.4% to 67% of the pipeline GPR in the right-of-way studied.
2. Touch voltage as a percentage of pipeline GPR varies independently of gradient control wire ground resistance per unit length: i.e., an increase in touch voltage due to a change in the soil structure may be accompanied by either an increase or a decrease in the gradient control wire ground resistance.
3. The gradient control wires are most effective at reducing touch voltages when they are located in a low resistivity soil layer, with high resistivity soil below (e.g., first table entry). They are least effective when located in a high resistivity layer, with a low resistivity soil below (e.g., last table entry). Thus, touch voltages are a function of the ratios of the resistivities in adjacent soil layers. In fact, touch voltages, expressed as a percentage of the pipeline GPR, are not influenced by the absolute resistivities of the soil layers, but only by their relative resistivities and thicknesses.
4. The mitigating wire ground resistance per unit length is directly proportional to the soil resistivity for any given set of layer thicknesses and resistivity ratios.

From the above discussion, it can be seen that a good knowledge of the soil structure is crucial in predicting the performance of a gradient control wire system and saving money on mitigation.

Gradient Control Grids. In a similar way, rectangular or circular grids of gradient control wires can be used to achieve safety at exposed pipeline appurtenances. The spacing of the conductors, the distance they must extend beyond the outermost exposed structures (often a perimeter fence), the depth required of the perimeter skirt (at progressively greater depth, to control step voltages) and the resistivity of the earth surface covering layer (such as crushed rock, if required) must be determined based on the interference levels encountered, soil structure and proximity gradient distortion effects caused by nearby transmission line structures or, to a lesser degree, nearby non-energized buried metallic structures.

SOFTWARE TOOLS

Under the auspices of EPRI/A.G.A.(PRC), software was developed during the 1980's to analyze interference problems and design mitigation for pipelines, railways and other utilities sharing common corridors with AC power lines, as the occurrence of common rights-of-way became more and more frequent, as described in Section 3. Initially, steady state power line conditions were the primary concern and only magnetic coupling was considered. It was subsequently recognized that fault conditions could result in serious damage to pipelines and safety hazards and the conductive interference component was therefore included.

These early analysis tools were however limited in several ways, which have been overcome by more recent developments by Dawalibi et al[27,28,29,30,31,32]. Some of these are listed below:

1. Multilayer Soil Structures. Whereas earlier software was limited to modelling buried metallic structures (e.g., tower/pole foundations or mitigation conductors) in homogeneous soils, these structures can now be modelled in stratified soils with any number of horizontal layers[27,29]. This allows the designer to account for the effects, for example, of a surface layer of low resistivity soil overlying a layer of rock, below which is located the water table. As discussed above, this kind of situation can result in order-of-magnitude errors in computed conductive interference levels when a uniform soil equivalent is used in the modelling (typically based on shallow soil resistivity readings). Modelling of multilayer soil structures allows adequate protection to be designed against arc burns or coating damage resulting from faults on nearby transmission line structures. In other situations, a deep, low resistivity soil layer can reduce the required extent, and therefore cost, of mitigation.

2. More Complex Corridors. While many power line/pipeline corridors consist of one pipeline extending from point A to point B, with exposure to one set of transmission lines at one voltage, many corridors are considerably more complex. Several pipelines may exist in the corridor, interconnected at one or more locations; pipeline taps may exist, which branch out of the main corridor, following another set of transmission lines or one (or more) circuits of the transmission lines in the main corridor, which also branch out of the main corridor. The transmission lines may have intermediate substations within, or close to, the main corridor. The pipelines under study may be connected directly or indirectly to the electric power system neutral or ground system: e.g., gas pipelines supplying a power plant and connected (deliberately, through DC-blocking devices) to the grounding system of the electric power system; pipelines continuous with a pumping or compressor station ground, which is connected to the electric power system neutral. These situations can now be accurately modelled with existing software. Accurate predictions allow cost reductions in mitigation, since major conservative simplifying assumptions need not be made.

3. Integrated Inductive/Conductive Modelling. While earlier software was based on the assumption of essentially parallel facilities, cases arise in practise in which both the electric power lines and the pipelines follow curved paths which intersect one another, diverge, reconverge, etc., making them difficult to model accurately. Recently developed software does away with the parallel assumption and accounts for inductive and conductive effects between any given conductor segment and all other segments (both buried and aboveground) modelled[30,31,32].

4. Lightning and Transients. The new generation of software[30,31,32] can model high-frequency transients in the time domain, accurately accounting for the eletromagnetic interactions of a system of aboveground and buried conductors. As a result, the response of a pipeline to a lightning strike or other types of transients on a nearby transmission line can be computed. This is a new area of research, which is currently being explored, as described in Section 9 of this paper[33].

TYPICAL RESULTS

Empire State Pipeline: Gradient Control Wires Versus Cancellation Wires

Study Overview. In one landmark study, SES modeled a 700,000 foot corridor shared by the proposed Empire State Pipeline (ANR Pipeline Company) and two New York Power Authority (NYPA) 345 kV transmission lines. The model consisted of the transmission line phase and static wires, and the buried pipeline. The right-of-way was modeled under worst-case steady-state conditions, with a maximum load current of 2000 A per phase.

Interference Levels. During worst case steady state conditions, predicted voltage peaks ranged from 100-250 V at transmission line phase transpositions and locations where the pipeline deviates from the transmission line right-of-way.

Mitigation Design. When pairs of gradient control wires are installed parallel to the pipeline at locations with high interference levels, the induced potentials on the pipe were reduced, to less than 70 volts throughout the right-of-way, due to the additional grounding provided by the wires. With respect to local earth, the gradient control wires reduce touch voltages to less than 15 volts at all locations where they are installed.

While the gradient control wires provide effective mitigation, reducing pipeline potentials over almost all of the pipeline length, additional protection in the form of gradient control grids was required at exposed appurtenances such as valve sites. These grids raise local earth potentials in the same way as the gradient control wires do.

Mitigation Cost Savings. In this mitigation study, the cost of mitigation for approximately 160 miles of exposed pipelines was estimated to be on the order of $ 30-40 million for a cancellation-wire based system, and about $ 10-12 million if gradient control wires were used according to a uniform soil model design approach. The cost was reduced to less than $ 2 million with the implementation of a gradient control wire system based on computer modelling of realistic multilayer soil structures.

Another Example: Lumped Grounding Versus Gradient Control Wires

In another study, involving interference caused by power lines on gas and oil pipelines in Saudi Arabia, it was possible to compare the cost of lumped grounding versus gradient control wires. In this case, the two parties involved required that AC interference levels be reduced such that touch voltages even on buried, normally inaccessible parts of the affected pipelines be maintained below the limits determined in accordance with the ANSI/IEEE Standard 80 methodology. Furthermore, it was required that no protection be attributed to the high resistivity surface sand, which would otherwise have increased the touch and step voltage limits about tenfold or more at some locations.

This study involved a total of sixteen 380 kV and 230 kV transmission line circuits influencing 19 pipelines and 6 communications cables in a desert environment. It was necessary to model all simultaneously in order to compute induced voltages during load conditions, because of the interconnectedness of the system. Several pipelines were directly bonded to the grounding systems (or structures continuous with the grounding systems) of the generating plants associated with the 5 substations involved. The transmission line right-of-way system had a total length of over 200 km, with various transmission lines entering one common corridor and then veering off along independent corridors with some pipelines. Some of the pipelines were interconnected at crossings.

Initially, based on limited soil resistivity measurements, it was estimated that mitigation costs based on the lumped grounding method would be on the order of $US 50 million. Following detailed soil resistivity measurements, which required the use of special procedures and equipment to filter out 60 Hz noise and drive sufficient current in the high resistivity surface sand, it was possible to design site-specific gradient control systems, which reduced the estimated cost of mitigation to approximately $US 4 million.

CURRENT AND FUTURE RESEARCH WORK

As indicated earlier, research at present is centered on studies which are now possible for the first time, as a result of the development of a new generation of software[30,31,32], which can model simultaneously aboveground and buried structures, accounting for magnetic (inductive), resistive (conductive) and capacitive (electrostatic) coupling. Transients, such as switching surges, lightning strikes and faults can be analyzed in both the frequency and the time domains.

Figure 4 for example, shows the current distribution in a transmission line tower and nearby fence during a fault at the tower, accounting for both inductive and conductive coupling between the faulted transmission line and the fence. Figure 5 shows the time domain response of a 1.8 km section of aboveground aqueduct to induction from transmission line shield wires centered 60 m away (laterally) which have been struck by lightning with a peak amplitude of 30 kA.

This research will make it possible to verify and improve present mitigation design techniques, based on a more accurate assessment of the interactions of power lines and pipelines, particularly for close proximities at which the inductive and conductive components have significant influences on one another.

CONCLUSIONS

The following important conclusions can be drawn from the preceding discussion:

- AC interference in pipelines can represent a significant safety hazard and threat to equipment integrity.
- Some mitigation approaches that are still widely used can result in incomplete protection and considerably more expensive mitigation.
- Gradient control wires constitute the most cost-effective known mitigation solution.

- Modelling of the soil's multilayer structure is required for an accurate assessment of interference levels and of mitigation requirements; inadequate protection or overdesign or both can occur otherwise, at different locations along a given pipeline.
- Detailed soil resistivity measurements, from surface layers to deep layers, are a must in order to determine the soil's multilayer structure.

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TABLE 1
PERFORMANCE OF CONTROL WIRE PAIRS IN DIFFERENT SOIL STRUCTURES

Soil Structure			Maximum Touch Voltage Over Wire Pair (%GPR)	Ground Resistance per Unit Length of Wire Pair (ohm-ft)
Layer No.*	Resistivity (ohm-m)	Thickness (ft)		
1 2 3	48.7 14.9 350.5	0.66 7.83 infinite	2.4	1074.2
1 2 3	178.9 150.9 86.8	0.83 10.00 infinite	26.0	883.9
1 2 3	330.0 1050.8 37.8	1.33 6.16 infinite	67.2	1845.4

* Layer 1 is top layer, Layer 2 is next layer down, and so on.

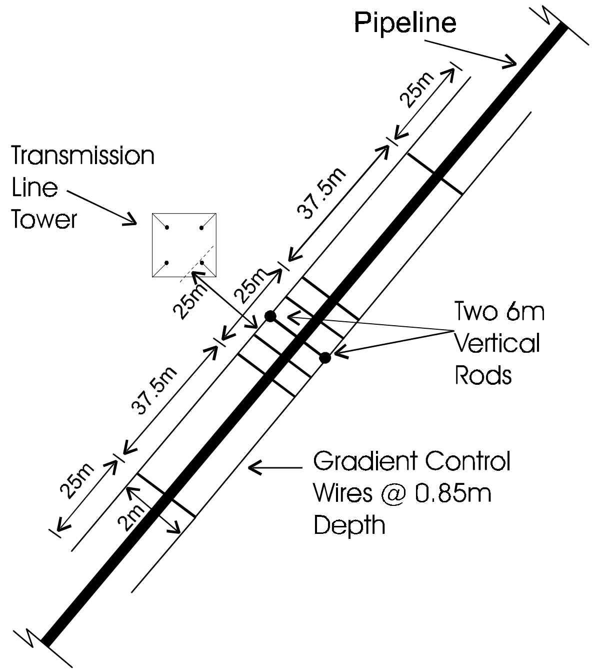

Figure 2 – Gradient Control Wire System on Pipeline Near Transmission Line Tower – Plan View

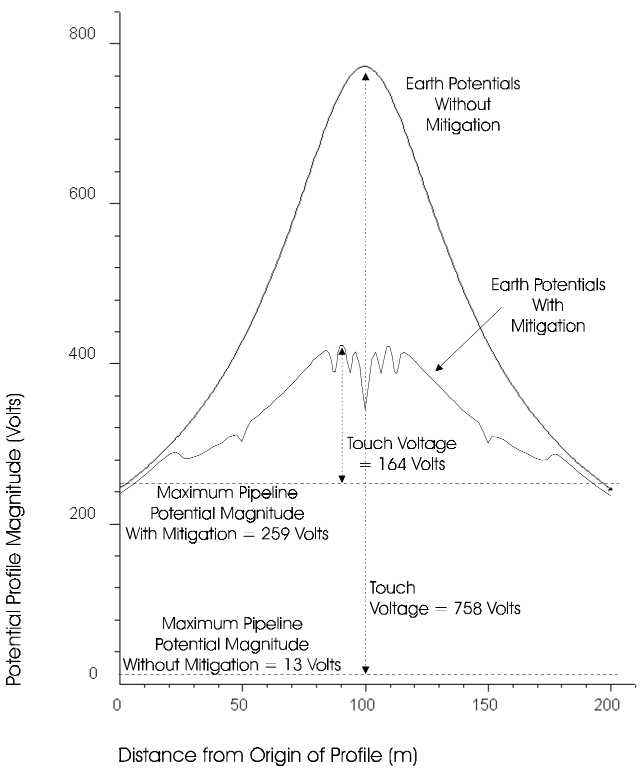

Figure 1 - Earth Surface Potentials and Touch Voltages Along Profile Directly Over Pipeline Center Line, During Fault on Nearby Transmission Line Tower (see Figure 2) : With and Without Mitigation

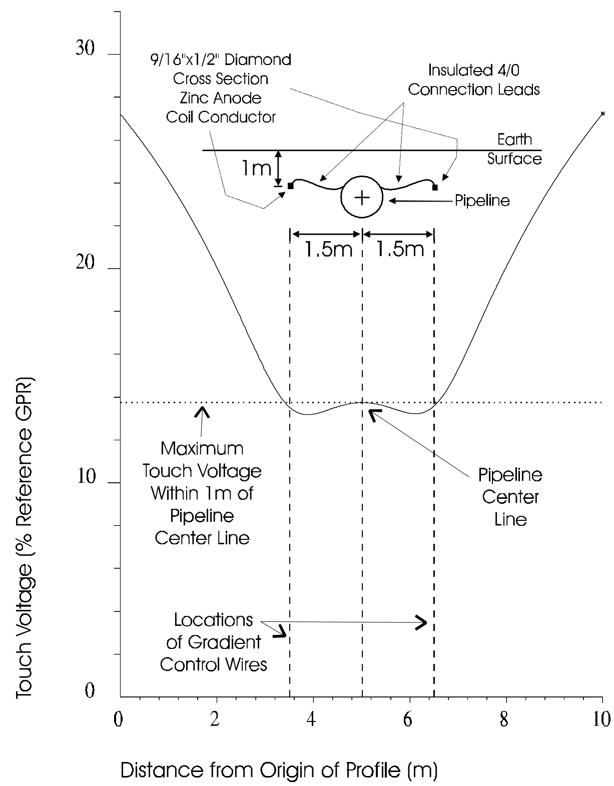

Figure 3 – Effectiveness of Gradient Control Wires Against Magnetically Induced AC Interference : Touch Voltages Along Profile Perpendicular to Pipeline, as a Percentage of Pipeline Potential Rise Measured With Respect to Remote Earth

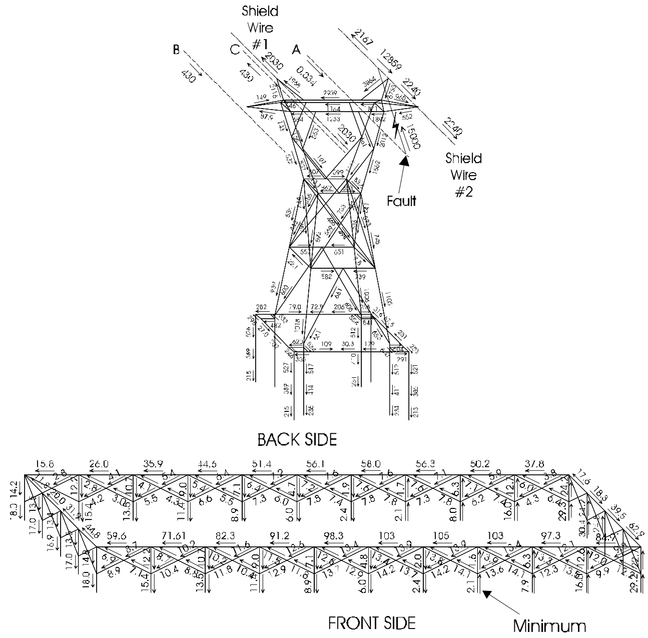

Figure 4 – Current Distribution in a Tower and Nearby Fence During a Phase-to-Ground Fault Condition

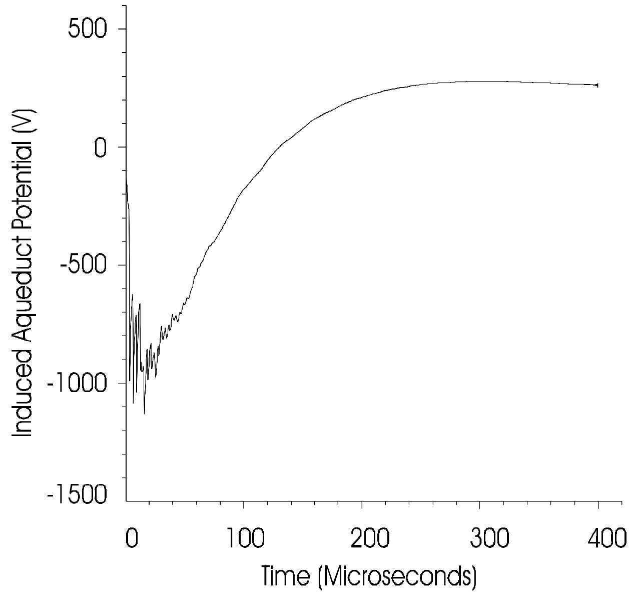

Figure 5 – Time Domain Potential Rise of Aboveground Aqueduct (60 meter separation distance, 30 ohm-m soil resistivity)