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Increasing the Cost-Effectiveness of AC Interference Mitigation Designs with Integrated Electromagnetic Field Modeling

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ABSTRACT

The electricity transmission, gas transmission, and railway industries have developed various methods for the calculation of voltages induced in infrastructure following power line corridors. These tools are typically based on simplified topologies and assumptions that make the implementation of the required algorithms more tractable and data entry screens more alluring. On the other hand, such an approach suffers from reduced accuracy, due to the required simplifying assumptions, and furthermore excludes the possibility of studying complex systems for which the designer is unable to determine what simplifying approximations are the most appropriate. In the absence of confidence in his or her calculations, the designer tends to be overly conservative, resulting in excessive mitigation. This situation arises in particular when the system includes buried components whose through-earth coupling interactions are significant. This paper illustrates this point with a case study and parametric analysis, showing how a calculation based on integrated electromagnetic field modeling results in a more accurate assessment of interference levels and therefore more suitable mitigation.

Keywords: AC interference mitigation, through-earth coupling, pipeline coating stress voltages, power line fault conditions, computer modeling, software

INTRODUCTION

When a pipeline runs more or less parallel to a high voltage power line for a significant distance, considerable voltages can be transferred to the pipeline under both normal power line operating conditions and short-circuit conditions on the power line. These voltages can represent an electrical shock hazard for personnel and the public. They can also threaten the integrity of cathodic protection equipment, the pipeline coating, and the pipeline steel, particularly during short-circuit conditions. Many references describe this phenomenon, indicate how it can be mitigated effectively and describe computer modeling tools that can be used to carry out accurate analysis and mitigation design for standard studies[1-21]. Such earlier papers have focused on a first order approximation of the interactions between power lines and pipelines. It is assumed, of course, that the power line has a determining influence on the voltages and currents associated with the pipeline, but it is also assumed that the pipeline has a negligible impact on the currents and voltages associated with the power line, particularly as far as through-earth coupling is concerned. In most cases, this is a fair approximation, but there are situations in which this can lead to significant error and therefore either underdesigned or overdesigned protection for the pipeline, with direct consequences on safety and cost. This is particularly true during a phase-to-ground fault on a high voltage transmission line tower which has strong through-earth coupling with a nearby pipeline. This paper discusses this point, illustrating it with a case study.

The fundamental assumption that a transmission line is uninfluenced by a parallel pipeline is violated to a greater or lesser degree during a fault condition at a tower that is close to the pipeline, if the pipeline is grounded both nearby and remotely. This is typically the case, since the pipeline most needs protection near the tower, in order to minimize coating stress voltages, and periodic grounding over the length of the pipeline is frequently required. Although the pipeline grounding, which often consists of one or two gradient control wires (see Figures 1 and 2, for example), is not directly connected to the tower, it nevertheless intercepts current flowing through the earth from the tower, carrying it away from the vicinity of the tower more effectively than the earth alone, thereby reducing the effective ground resistance of the tower. Furthermore, inductive coupling between the transmission line and the pipeline usually results in the pipeline drawing current from the earth near the tower, in order to expel it into the earth at a location where the inductive exposure between the transmission line and pipeline changes. This also reduces the effective tower ground resistance, in the sense that it reduces the potential rise of the tower per unit current injected into the earth by the tower. This means that the presence of the pipeline will cause the tower to inject more current into the ground, during fault conditions, than would be the case in the absence of the pipeline. The influence of the pipeline on the tower will vary as a function of a number of variables: the extent of the tower's own grounding, the proximity and extent of the pipeline's grounding, the soil structure, and the level of induced voltages in the pipeline.

METHODOLOGY

This study is performed by means of computer simulations, which compare predicted system performance both with and without adjustments made to account for the influence of the pipeline on the transmission line. Two types of simulations will be performed: first, the influence of a pipeline grounding system on a single transmission line tower will be examined for a number of key parameter settings; next, the interactions of a complete interacting pipeline and transmission line system will be examined for one example case.

Two software packages[(1)] will be used in this analysis. The first, which automatically accounts for all interactions between the pipeline and transmission line, is highly accurate, as it solves Maxwell's equations directly, without simplifying assumptions of any importance made for 60 Hertz (Hz) calculations, other than the usual conductor segmentation used by all numerical methods. Other methods may neglect end effects by using formulae applicable to infinitely long conductors; they may also ignore through-earth interactions between different ground electrodes. This field theory approach is an extension to low frequencies of the moment method used in antenna theory. By solving Maxwell's electromagnetic field equations, the method allows the computation of the current distribution (as well as the charge or leakage current distribution) in a network consisting of both

[(1)] MultiFields™ and Right-of-Way Pro™ software packages, by Safe Engineering Services & technologies ltd. (SES).

aboveground and buried conductors with arbitrary orientations. The scalar potentials and electromagnetic fields are thus obtained. The effect of a uniform or layered earth of arbitrary resistivity, permittivity and permeability is completely taken into account by the use of the full Sommerfeld integrals for the computation of the electromagnetic fields. The details of the method are described in References 22 and 23 and their references. Reference 24 presents field tests confirming the accuracy of this method.

The second software package, based on a circuit-model/moment method approach, makes the approximation that the pipeline has a negligible effect on the transmission line, at least as far as through-earth coupling is concerned, unless it is applied in an iterative manner. This software calculates line parameters for the conductor system as a first step[14]. It then builds a circuit model, with these line parameters and with user-specified ground impedances, which is resolved using the double-sided elimination method[25]. In the second step, the software rapidly computes voltage and current distributions in the transmission system and pipeline. In the third step, a moment method is used to represent power system grounds and the pipeline system, with power system ground injection currents and induced electromotive force (emf) values in the pipeline from parallel overhead conductors, accounting for conductor longitudinal impedances, to determine through-earth interactions between these buried conductors[14, 23]. Without iteration, this method does not account for the impact of through-earth interactions on power system ground current injections determined in the second step. While this method, without iteration, is adequate in many applications, it can result in overdesign or underdesign in particular situations that will be described in this paper. As will be seen, better accuracy results from restarting the process with adjusted power system ground impedance values; however, this can be a tiresome chore if performed manually, as each effective tower ground impedance value is different, as a function of its distance from the fault location, its proximity to a source substation or power plant, its proximity to the end of a joint-use corridor, and other factors.

COMPUTER MODEL DETAILS

Part I: Parametric Analysis - Through-Earth Coupling Between Tower and Pipeline Grounding

In the first part of this study, the impact of the following parameters on the apparent ground resistance of a transmission line tower is examined:

1. Soil structure
2. Tower grounding
3. Separation distance between tower and pipeline grounding

Figures 1 and 2 show the base case analyzed. The attributes are as follows:

Soil structure:	100 ohm-m top layer, 4.6 m thick; 1,000 ohm-m bottom layer
Tower grounding:	foundations and counterpoise both contribute to grounding. Foundations are 1.95 m x 6.10 m reinforced concrete cylinders, located at the vertices of a 6.26 m x 9.36 m rectangle. Counterpoise is #4/0 AWG copper, buried 0.5 m deep, extending 4.6 m away from the two tower legs closest to the pipeline, parallel to the pipeline. See Figure 2.
Pipeline grounding:	0.015 m diameter anode ribbon, 201 m long, centered at the tower location and connected to the pipeline at that location
Separation distance:	4.17 m from center of tower leg to ribbon anode
Pipeline energization:	no emf or direct energization (such an energization would tend to increase through-earth coupling effects).

A number of scenarios have been studied and are listed in Table 1. A nominal current of 1000 A is injected into the grounding system of the tower and the resulting ground potential rise (GPR) is calculated, both with and without the nearby pipeline ribbon anode present. The GPR is then divided by the injected current in order to obtain the nominal tower ground resistance, with and without the ribbon anode. A percent error is then obtained by comparing the two ground resistance values. With this information, the reader can judge what situations require that through-earth coupling be given more careful treatment. As will be seen, close proximity of a tower to the pipeline and a relatively thin low resistivity top soil layer over a high resistivity bottom layer require particular attention.

Part II: Case Study – Comparison of Field Approach With Circuit/Moment Method Approach

In the second part of this study, a complete interacting transmission line and pipeline system, has been modeled, using both the highly accurate field approach and the circuit/moment-method approach. In the latter case, results from a first run are presented and compared with results obtained from a second run, in which the apparent power line ground impedance values have been adjusted in accordance with the results of the first run of the moment method model (more specifically, the ground potential rise values of each tower ground and plant ground are divided by the earth injection currents computed for each in the first run and substituted into the circuit model created for the joint-use corridor). As will be seen, an iterative application of the circuit/moment-method can considerably improve accuracy.

Figure 3 presents a schematic plan view of the system under study, which can be described as follows:

- In a 4 km corridor, a high voltage, horizontally configured, transmission line runs parallel to a 0.61 m diameter gas pipeline, with a separation distance of 4.6 m between the pipeline center line and the center of the nearest tower footings (see Figures 1 and 2);
- The transmission line runs between a power plant at the west end and a substation at the east end, with the power plant located within 100 m beyond the west end of the joint-use corridor and the substation 1 km beyond the east end of the corridor.
- At the west end of the corridor, the pipeline veers away from the power line at an angle of 90 degrees and runs along the east side of power plant, with a clearance of 7.6 m, and its electrical continuity interrupted 30 m short of the north end of the plant. At the east end of the corridor, the pipeline also veers away from the transmission line at an angle of 90 degrees and continues 1 km, at which point its electrical continuity is interrupted.
- The ribbon anode associated with the pipeline runs the entire length of the pipeline, on the side closest to the power system grounds.
- A phase-to-ground fault is modeled on the phase closest to the pipeline at a transmission line tower located 2 km east of the power plant, midway along the joint-use corridor. Fault current contributions are as follows:
  - From the power plant: 10 kilo Amperes (kA)
  - From the substation: 5 kA
- Soil structure:
  - Top layer resistivity: 500 ohm-m
  - Top layer thickness: 7.6 m
  - Bottom layer resistivity: 5000 ohm-m
- Pipeline coating resistance: 30,937 Ω-m^2 (333,000 ohm-ft^2)
- Power line shield wires: two 66 mm^2 (3/8") EHS Class A galvanized steel wires
- Power line structure grounding: see Figures 1 and 2
- Power line span length: 201 m
- Pipeline burial depth (depth of cover): 0.91 m
- Pipeline diameter: 61 cm
- Pipeline wall thickness: 12.7 mm
- Pipeline wall resistivity (relative to annealed copper): 10
- Pipeline wall permeability (relative to free space): 300
- Pipeline ribbon anode depth: 1.52 m
- Pipeline ribbon anode equivalent circular diameter: 15.2 mm
- Ribbon anode resistivity (relative to annealed copper): 3.42
- Ribbon anode permeability (relative to free space): 1.0

For each computer simulation run, the stress voltage on the pipeline coating is computed throughout the entire length of the parallel corridor. The stress voltage is defined as the voltage between the pipeline steel and the earth immediately outside the coating. In this study, earth potentials were computed at the 12 o'clock, 3 o'clock, 6 o'clock, and 9 o'clock locations around the perimeter of the pipeline, in order to determine the maximum value (these locations have proven to be adequate).

RESULTS

Part I: Parametric Analysis - Through-Earth Coupling between Tower and Pipeline Grounding

Table 1 shows that the influence of the pipeline grounding on the tower ground resistance varies greatly from one scenario to another. The error that occurs when this influence is not considered ranges from 1.4 % to 49 %. The worst case soil is the one in which a low resistivity top layer, extending to a depth of 2.3 m and therefore in contact with the tower counterpoise, the pipeline grounding and part of the 6.1 m tower foundations, has its effectiveness in transferring earth currents from the tower to the pipeline enhanced by a high resistivity bottom layer. In this soil, neglecting the influence of the pipeline grounding results in an error of 33%, for the base case studied. Doubling the thickness of this low resistivity soil layer decreases the error to 28%. Doubling it again decreases the error to 20%. Increasing the thickness to infinity (this is the uniform soil) decreases the error to 11%. When the soil layer, in which the pipeline grounding is located, is considerably higher in resistivity than the soil layer in which the bottom portion of the tower foundations are located, the error drops to 1.4%. Soil layering is therefore a key consideration.

For the worst case soil, changing the tower-pipe clearance also has an important impact, as is to be expected. A clearance of only 2.3 m results in a 49% error in the tower ground resistance. If the influence of the pipeline grounding is not taken into consideration, this error drops to 33% for a clearance of 4.6 m and 19% for a 9.1 m clearance.

The tower counterpoise does not appear to make much difference. The error resulting from neglecting the pipeline grounding varies from 32% with no counterpoise to 36% with two 13.7 m lengths of counterpoise.

As can be seen, for the percent error to exceed 11 %, the soil structure must be rather unfavorable (i.e., a low resistivity top layer over a high resistivity bottom layer) and the pipeline distance from the tower relatively small. Note, however, that during fault conditions, the pipeline is not merely a passive element. Induced voltages from the overhead conductors will cause the pipeline to drain variable levels of current from the earth and therefore amplify or reduce its impact on the effective tower ground impedance. This will be seen in Part II of this paper, in which a joint-use corridor will be studied, based on a configuration similar to the base case presented in this Part I parametric analysis.

Part II: Case Study – Comparison of Field Approach With Circuit/Moment Method Approach

Figure 4 presents the pipeline coating stress voltages computed using the accurate field-approach method, as a function of distance from the extremity of the pipeline closest to the power plant. As this figure shows, coating stress voltage peaks occur periodically, along most of the length of the pipeline. These occur at the tower locations within the joint-use corridor. Figure 5 presents the values calculated at each of the peaks. The maximum coating stress voltage, not surprisingly, occurs at the fault location. A value of 5.62 kV has been calculated.

Figure 5 presents the pipeline coating stress voltage peak values computed near each tower location by the first pass through the circuit /moment method and compares them with those computed by the field-approach method. A similar pattern of peaks is seen as for the field-approach method, except that the values are considerably lower. The maximum value here is only 3.62 kV. This is partly a consequence of the use of a tower ground resistance of 30.6 ohms in the circuit model, obtained from the modeling of a lone tower with its two 4.6 m counterpoise conductors. As explained in the Part I discussion, this neglect of the pipeline grounding overestimates the effective ground resistance of the faulted tower. As a result, the circuit simulation underestimates the tower current flowing into the earth. The tower current is further underestimated because the effect of currents forced into the pipeline, from local earth, by magnetic field induction on the pipeline, is not taken into account. When the underestimated tower currents calculated by the circuit simulation are fed into the moment method simulation, which models the tower grounds, the pipeline and its grounds, and the power plant grounding system, pipeline coating stress voltages are underestimated by up to 36% or more as a result.

On the other hand, if a feedback loop is instituted, whereby the effective tower ground impedances obtained from the first pass through the process replace those used initially in the circuit model, then better results are obtained. As Figure 5 shows, this second pass through the circuit/moment method simulation results in significantly reduced error almost everywhere. The peak coating stress voltage has now increased to 5.44 kV, which is within about 3 % of the value computed with the highly accurate field approach method. The only significant differences remain at the ends of the joint-use corridor, at which the circuit/moment method significantly overestimates or underestimates coating stress voltages, even after a second pass. At the plant end of the corridor, the coating stress voltage is overestimated by about 55% at one tower location. This is primarily the result of a problem with the modeling of a tower ground impedance with a negative real part, as indicated below. Further investigation is required to explain the difference encountered at the substation end of the joint-use corridor, where coating stress voltages are underestimated as much after the second pass as after the first pass.

Figures 6 and 7 present the magnitudes and angles, respectively, of the tower ground impedances used in the first and second passes through the circuit model. The constant value of 30.6 ohms used for the first pass was simply calculated based on a single tower, with its two counterpoise conductors. The values used for the second pass were obtained by dividing the GPR (ground potential rise) of each tower, computed by the first moment method simulation, by the current flowing into the ground from that tower. As can be seen, every tower has a different effective ground impedance, partly as a result of through-soil interactions with neighboring towers, the plant ground or the substation ground, all of which are injecting different currents into the earth. This is also a result of interactions with different portions of the pipeline, whose potential rise varies throughout the entire joint-use corridor. It can also be seen that Tower 5 has an impedance with a negative real part (i.e., a phase angle of -160 degrees). This is unphysical (and therefore not possible to model); therefore the real part was set to zero in the circuit model, which results in suboptimal accuracy at that location, but permits accurate results to be obtained at adjacent locations.

Similar treatment has been given to the plant ground impedance, which is $6.28 \angle 0.36° \, \Omega$ in the first circuit simulation and $2.52 \angle 4.77° \, \Omega$ in the second pass through the process, based on the results of the first moment method simulation.

It can be seen that the actual maximum pipeline coating stress voltage exceeds the acceptable range of 3,000 – 5,000 V for fusion bond epoxy and polyethylene coatings. A second gradient control wire would therefore be required for adequate protection, at least near some of the towers. This prediction is obtained from the second pass through the circuit model/moment method approach, but not from the single pass. It is therefore important to perform such studies in an iterative manner, when close proximity and unfavorable soil structures characterize the system under study. Alternatively, a direct field approach method can be used, for greater accuracy, especially at the ends of the joint-use corridor, the disadvantage being greater run time. If neither of these approaches is adopted, then one can use a single-pass circuit model/moment method approach; but instead of assuming that currents injected into the ground are unchanged by the proximity of the pipeline grounding to the tower grounding, the pessimistic assumption is made that it is the potential rise of the tower grounds and the pipeline grounding that remain as computed by the circuit simulation. This, however, results in unrealistically large currents flowing through the earth and could therefore yield significantly overdesigned systems.

CONCLUSIONS

This paper has demonstrated that for adverse soil conditions (i.e., low resistivity at pipeline depth over a high resistivity layer below that) and close proximity of a pipeline to a high voltage transmission line, considerable error can occur if the influence of the pipeline grounding on the power line structures is not taken into account, for power line fault conditions. Indeed, the case study presented in this paper shows that pipeline coating stress voltages can be underestimated by as much as 36 % or more, if the pipeline is neglected when calculating the current injected into the earth by each power line tower or pole. This error is generated not only by the low impedance path presented by the pipeline grounding to current flowing out of the tower or pole, but also by the influence of the pipeline grounding on local earth potentials due to energization of the pipeline by magnetic field induction from the overhead transmission line. This error is typical of a once-through circuit /moment-method approach, in which estimated tower ground resistances are used to calculate the fault current distribution in the transmission line structures using a circuit model, after which pipeline coating stress voltages are calculated with a moment method, based on the tower earth currents determined by the circuit model. It has been demonstrated by this paper, however, that considerably more accurate results can be obtained by iterating the computation process, using effective tower ground impedances obtained from the moment method and running the circuit model a second time to obtain more accurate tower earth currents. In this case, the error in the maximum computed pipeline coating stress voltage drops from 36 % to 3 %. Further refinements, however, are required for better accuracy at smaller voltage peaks occurring at the ends of the joint-use corridor.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial and technical resources provided by Safe Engineering Services & technologies ltd. for this research work.

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TABLE 1
DETAILED RESULTS OF PART I PARAMETRIC ANALYSIS

Scenario			Tower Ground Resistance (ohms)		Percent Error
Tower Counterpoise	Tower-Pipe Clearance (m)	Soil Structure	Without Coupling	With Coupling	
Two 4.6 m lengths	4.6	100 ohm-m uniform	2.79	2.51	11
		100 ohm-m, 4.57 m top layer 1,000 ohm-m bottom layer	8.34	6.50	28
		1,000 ohm-m, 4.57 m top layer 100 ohm-m bottom layer	4.07	4.02	1.4
		100 ohm-m, 9 m top layer 1,000 ohm-m bottom layer	5.72	4.77	20
		100 ohm-m, 2.3 m top layer 1,000 ohm-m bottom layer	12.08	9.06	33
	2.3		12.08	8.13	49
	9.1		12.08	10.19	19
None	4.6		12.35	9.34	32
Two 13.7 m lengths	4.6		10.38	7.65	36

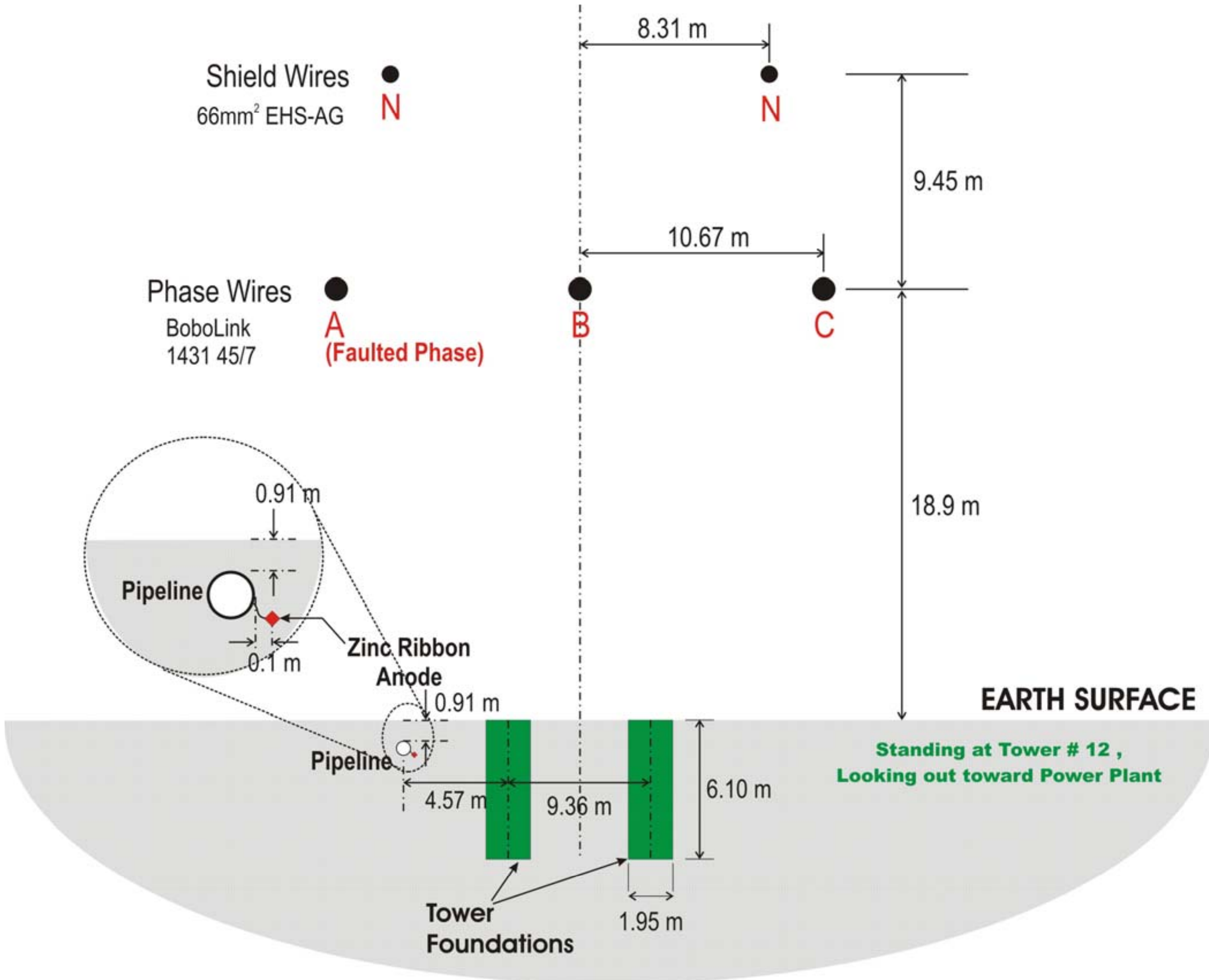

Figure 1. Nearby Pipeline and Transmission Line Tower Grounding: Cross Section

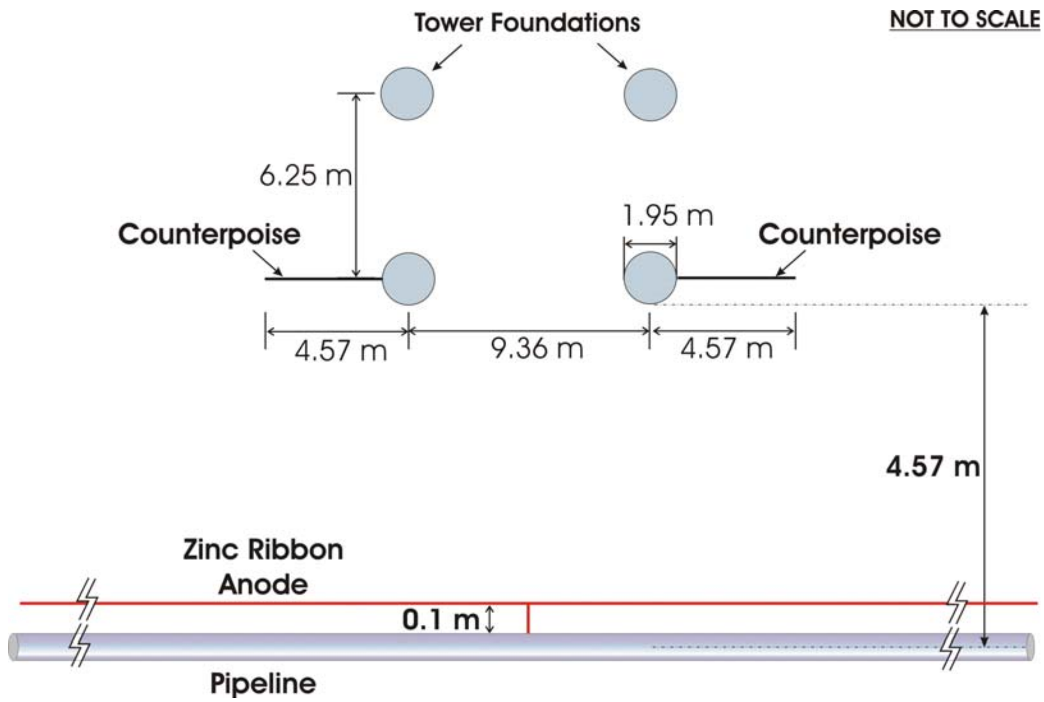

Figure 2. Nearby Pipeline and Transmission Line Tower Grounding: Plan View

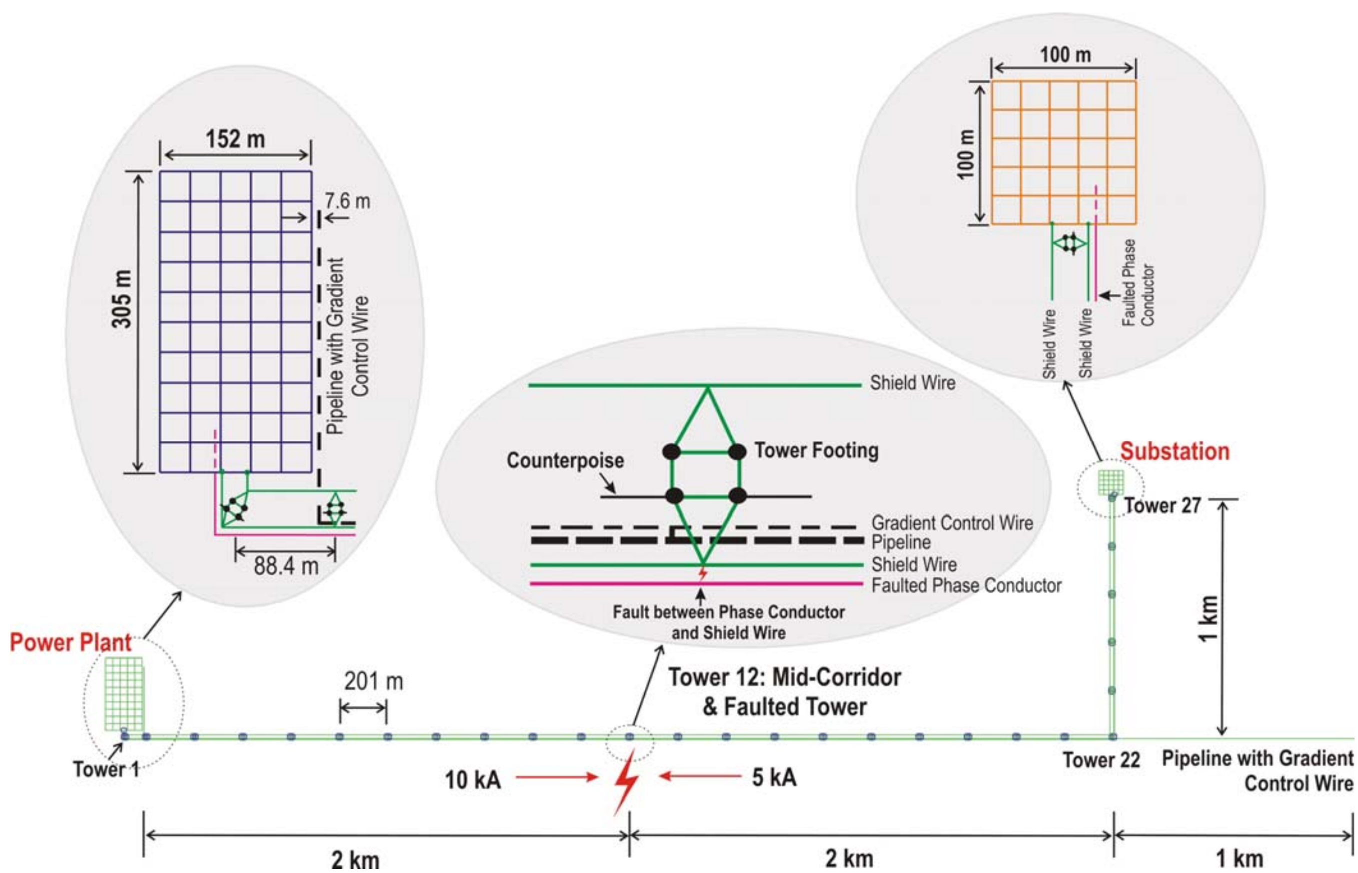

Figure 3. Schematic of Transmission Line/Pipeline Corridor Studied

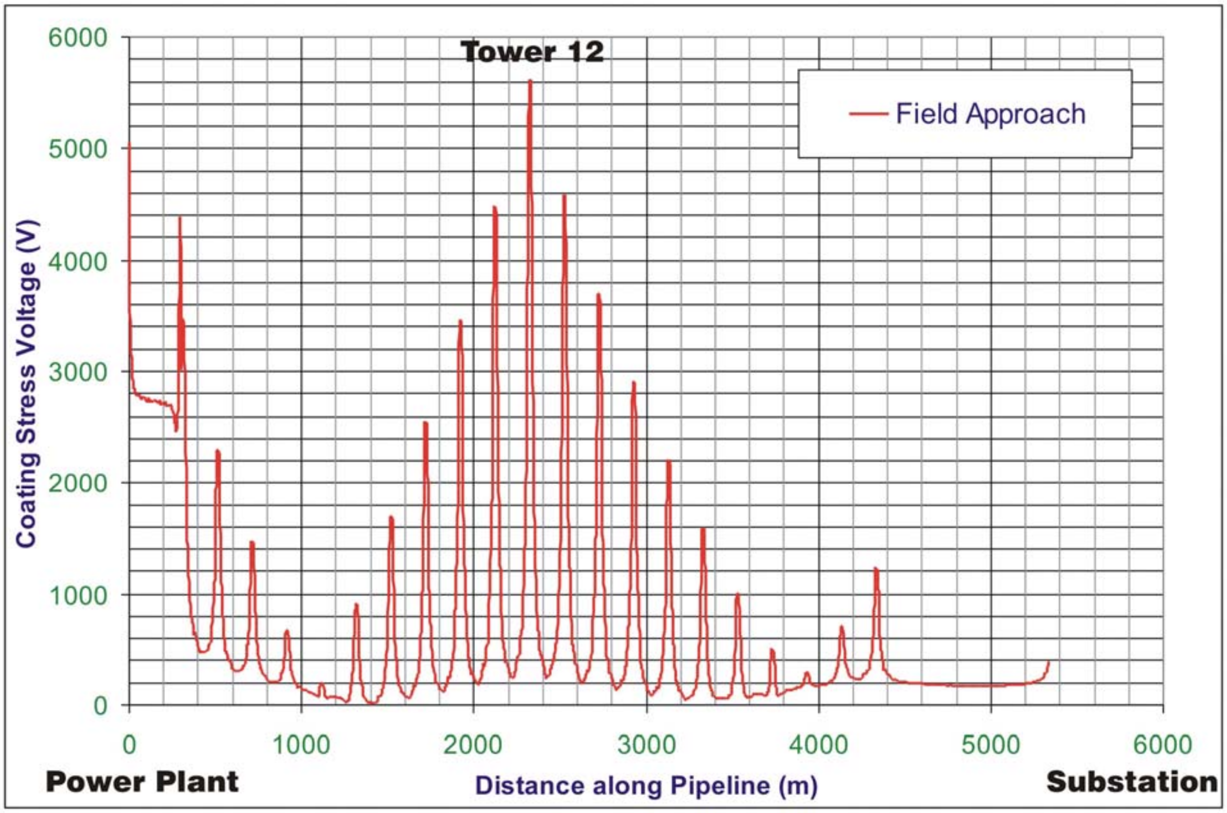

Figure 4. Pipeline Coating Stress Voltages along Joint Use Corridor: Accurate Results from Field Approach

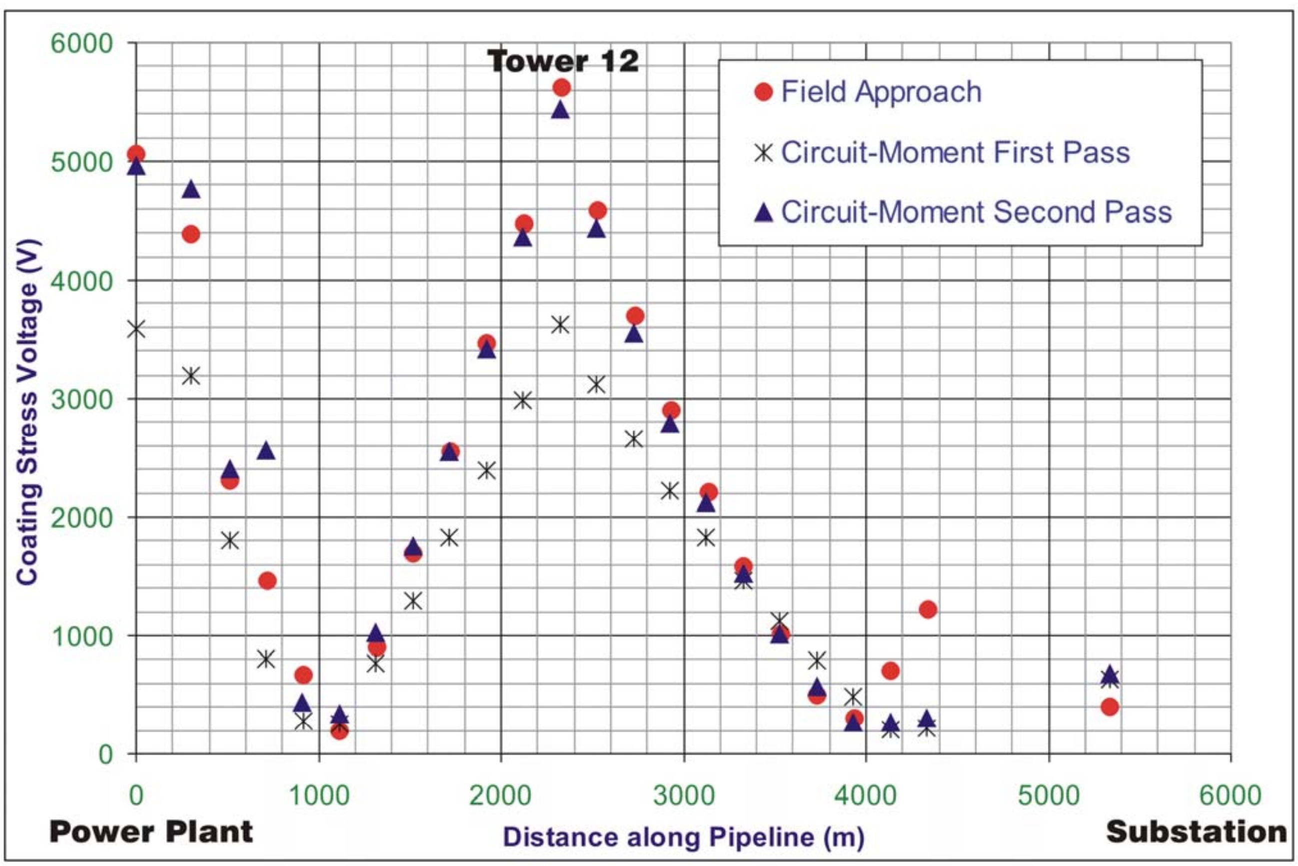

Figure 5. Pipeline Coating Stress Voltage Peaks Near Tower Locations: Comparison of Methods

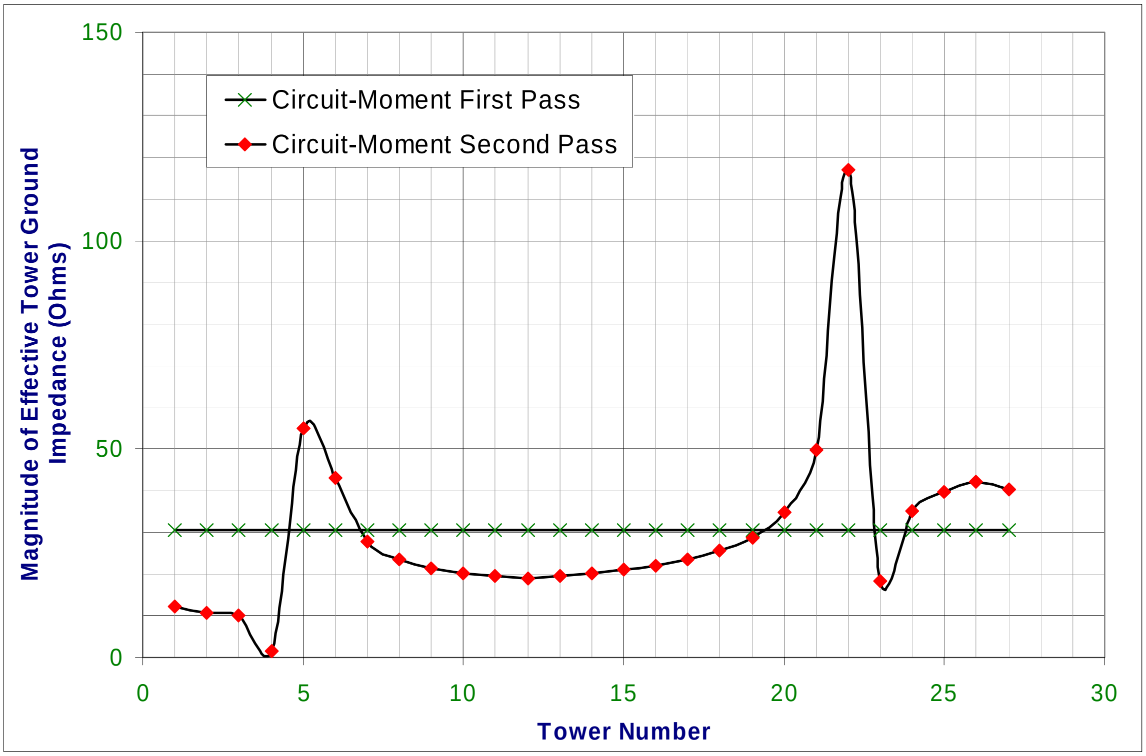

Figure 6. Effective Tower Ground Impedances Used in First and Second Passes through Circuit-Moment Method Simulations: Magnitude

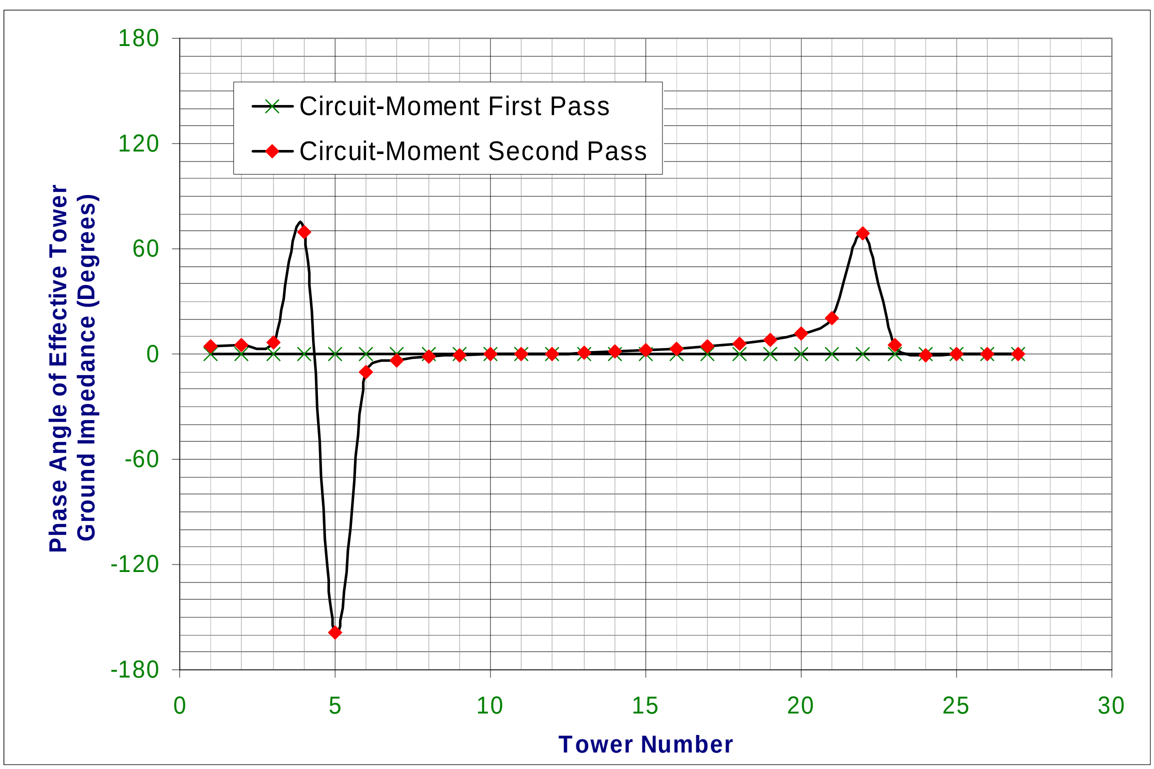

Figure 7. Effective Tower Ground Impedances Used in First and Second Passes through Circuit-Moment Method Simulations: Phase Angle