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Estimating AC Mitigation Requirements for Pipelines Installed in High Voltage AC Corridors: Fault Conditions

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ABSTRACT

A previous paper[1] has addressed the question of estimating mitigation requirements for pipelines installed in high voltage AC corridors, such as to maintain induced voltages at acceptable levels during normal operating conditions on the power system. This paper addresses the more difficult problem of estimating what mitigation is required to maintain pipeline coating stress voltages within acceptable limits during fault conditions on the power system. The difficulty of this undertaking arises primarily from the fact that AC interference during fault conditions includes not only induction, but also voltages transferred through earth to the pipeline location from power line poles or towers near which the fault has occurred: as a result, the analysis is more complex and the mitigation requirements are influenced by a greater number of factors. Furthermore, since the goal is to minimize the voltage difference between the earth and the pipeline steel, the interaction between the earth and bare mitigation wire buried next to the pipeline and connected thereto must be considered. This paper shows how factors such as soil resistivity, soil layering, length of parallelism, proximity of pipeline to transmission line, fault current levels, transmission line static wire type, transmission line structure grounding and coating resistance determine mitigation requirements.

Keywords: AC mitigation, induced voltages, grounding pipelines, coating stress voltages, power line fault conditions, computer modeling, cost estimates

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 system design studies[1-21]. A previous paper[1] has provided a means to estimate the degree of grounding required to mitigate this AC interference during balanced load conditions on a nearby power line, as a function of various parameters of the system under study. The present paper provides a means to estimate mitigation requirements during fault (i.e., short-circuit) conditions on the power line: in particular, for protection of the pipeline coating and steel, again as a function of various system parameters. It is felt that this paper, in conjunction with the previous one, will prove to be a valuable cost estimation tool for mitigation required in joint-use corridors.

METHODOLOGY

This study is based on computer modeling of a parallel pipeline and high voltage transmission line. Figures 1-3 illustrate the joint-use corridor, transmission line and pipeline modeled as a base case, whose parameters were varied throughout the study. As Figure 1 shows, the base case corridor is 8 km (5 miles) long, contains one horizontally-configured transmission line and a 61 cm (24 inch) diameter pipeline, and provides a clearance of 9.1 m (30 ft) between the pipeline and the nearest tower leg. Further details on the system modeled are provided in the next section.

First, it was established that the worst case transmission line fault (i.e., short-circuit) location within the parallel corridor was midway along the corridor (spot checks were carried out throughout the study, in order to ensure that this was the case). Next, it was established that once a certain minimum length of parallel corridor was reached, mitigation requirements per unit length of pipeline, during fault conditions, did not change significantly: 8 km (5 miles) was found to be a suitable length of corridor to represent longer lengths. Next, several system parameters were targeted for study. The following list was obtained:

1. <u>Length of parallel corridor</u>: varied from 3.2 – 16.1 km (2 – 10 miles)

2. <u>Pipeline coating resistance</u>: varied from 2,787 – 74,324 Ω - m^2 (30,000 – 800,000 Ω - ft^2)

3. <u>Transmission line shield wires</u>: one 66 mm^2 (3/8") EHS Class A galvanized steel (far side from pipeline), versus two of these, versus one of these and one 64 mm^2/528 optical fiber shield wire (far side from pipeline)

4. <u>Clearance between pipeline and tower footings</u> (or pole ground rod, when such is modeled): 4.57 – 30.48 m (15 –100 ft)

5. <u>Soil resistivity</u>: 25 – 1,000 Ω-m

6. <u>Soil layering</u>: 100 Ω-m top layer, 1000 Ω-m bottom layer, top layer varying from 0.76 – 6.71 m (2.5 – 22 ft) thickness; also 1000 Ω-m top layer, 100 Ω-m bottom layer, top layer varying from 1.83 – 6.71 m (6 – 22 ft) thickness

7. <u>Transmission line structure grounding</u>: single 10 ft ground rod versus four 20 ft tower footings

8. <u>Fault current level</u>: 2.5 – 10 kA (from both ends of the transmission line, simultaneously)

9. <u>Proportion of total fault current from each end of line</u>: 50%/50% - 100%/0%.

Each case studied represents a variation of a single parameter from its base case value, in order to best evaluate the influence of that parameter. For each parameter variation, a series of 6 fault simulations were carried out, with different lengths of zinc ribbon anode grounding the pipeline at each transmission line structure location: none, 12.6 m, 25.2 m, 50.3 m, 101 m, 201 m (41.25 ft, 82.5 ft, 165 ft, 330 ft, and 660 ft, respectively). Except where indicated otherwise, each length of zinc ribbon anode was modeled parallel to the pipeline, at the bottom of the pipeline trench, on the side of the pipeline closest to the transmission line structure, and centered with respect to the transmission line structure (see Figs. 2-3). After the runs were complete, the one satisfying the design criterion of 3 kV maximum coating stress voltage with the shortest length of zinc ribbon anode was selected and reported.

Note that 3 kV represents a conservative coating stress voltage limit for fusion bonded epoxy (FBE) and polyethylene (PE) pipeline coatings. Presently, limits in the range of 3 kV – 5 kV are typically used. These represent the point at which damage to the coating begins, due to arcing through coating holidays. At higher levels, direct damage to the pipeline wall can occur during the arcing.

The computed coating stress voltage includes not only the voltage transferred to the pipeline steel by magnetic field induction, but also the earth potential rise incurred by the nearby faulted tower (or pole) injecting fault current into the earth. Limiting the coating stress voltage to acceptable levels is often the factor that drives the cost of the pipeline AC mitigation, particularly for long parallel corridors. The results presented in this paper therefore do not include zinc ribbon anode required to build gradient control grids for exposed pipeline structures (such as valve sites) or to attenuate pipeline potentials after the pipeline leaves the parallel corridor.

The software used for the computer modeling[1] is highly accurate, as it solves Maxwell's equations directly, without simplifying assumptions of any importance made for 60 Hz calculations, other than the usual conductor segmentation used by all numerical methods. The field theory approach used in this paper 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 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 methods are described in References 22 and 23 and their references.

COMPUTER MODEL DETAILS

Figures 1-3 illustrate the base case used in the parametric analysis. Figure 1 shows a plan view of the entire joint-use corridor. A 61 cm (24 inch) pipeline runs parallel to a transmission line for a distance of 8 km (5 miles). The clearance between the pipeline and the nearest tower footing is 9.1 m (30 ft). The tower footings are 6.25 m (20.5 ft) apart, 1.95 m (6.4 ft) in diameter, and 6.1 m (20 ft) long (see Figure 3). The transmission line consists of a single horizontal circuit (see Figure 2), with two 66 mm2 (3/8") extra high strength, Class A galvanized, steel wires. Short-circuits (i.e., faults) are modeled between the phase closest to the pipeline (i.e., Phase C, the worst case) and the tower, which is connected to the two shield wires and the tower foundations. The span length (i.e., spacing between transmission line towers) is 201 m (660 ft). Beyond the parallel corridor, at each end, the pipeline continues for 16 km (10 miles) and the transmission line for 2 km (6,600 ft), at right angles to one another. The current flowing into the transmission line's faulted phase, at each of its extremities, is modeled as originating from a remote point; the transmission line shield wires are terminated by an equivalent ground impedance, representing an infinitely long line, at the tenth tower away from the parallel corridor; only magnetic field induction between the shield wires and the faulted phase are not modeled beyond the 2 km point, a small approximation.

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[1] HIFREQ™ module of the CDEGS™ software package, by Safe Engineering Services & technologies ltd. (SES).

Although the transmission line circuit configuration is horizontal, similar results are expected for vertical configurations, since only one phase, the faulted phase, and the shield wires have the dominant effect on the pipeline.

Key parameters of the base case system, which varied in the other simulations, were set as follows:

Soil Structure:	uniform 100 Ω-m soil
Clearance Between Pipeline and Power Line Structure:	9.1 m (30 ft)
Pipeline Coating Resistance:	30,937 Ω-m^2 (333,000 ohm-ft^2)
Length of Parallel Corridor:	8.05 km (5 miles)
Fault Current Level (from Both Sides, Simultaneously):	5 kA
Power Line Shield Wires:	two 66 mm^2 (3/8") EHS Class A galvanized steel wires
Power Line Structure Grounding:	see Figures 2 and 3

Other system parameters that were not varied in this study were set as follows:

Power Line Span Length:	201 m (660 ft)
Pipeline burial depth (depth of cover):	0.91 m (3 ft)
Pipeline diameter:	61 cm (24 inches)
Pipeline wall thickness:	12.7 mm (0.5 inch)
Pipeline wall resistivity (relative to annealed copper):	10
Pipeline wall permeability (relative to free space):	300
Mitigation wire depth:	1.52 m (5 ft)
Mitigation wire equivalent circular diameter:	15.2 mm (0.59 inch)
Mitigation wire resistivity (relative to annealed copper):	3.42
Mitigation wire permeability (relative to free space):	1.0

System attributes associated with parameters that did change in this study are as follows:

Optical fiber shield wire geometric mean radius:	0.52 cm (0.21 in)
Optical fiber shield wire AC resistance:	0.5424 Ω/km (0.8729 Ω/mi)

In the base case, two steel shield wires were present. In one variant, the shield wire closest to the pipeline is absent (this is the worst case as far as shield wires are concerned); another case was run with the shield wire furthest from the pipeline replaced by an optical fiber shield wire (this is the worst case location for this more conductive shield wire).

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.

Table 1, which presents the detailed results of this study, also indicates all of the parameter values simulated in this study. The values studied span a wide range of situations, albeit with only one parameter varying at a time, with one exception. On the other hand, the base case is fairly representative of typical situations, with a conservative bent, except perhaps for the soil characteristics, which can vary greatly. The results pertaining to the soil characteristics are therefore of particular interest. It should be noted that tower (and pole, in the case of the single ground rod) grounding have not been enhanced in the high resistivity soils to maintain structure ground resistances less than, say, 25 Ω. Such enhancements, made, for example, by connecting buried counterpoise (bare copper wires, running horizontally away from the structure) to the structure, can increase coating stress voltages. On the other hand, high soil resistivities do not always mean that counterpoise has been installed to maintain structure ground resistances at low values. To flag situations modeled in which counterpoise might normally be installed, Table 1 indicates the structure ground resistances for the cases in which soil characteristics or structure grounding changes.

RESULTS OF PARAMETRIC ANALYSIS

Table 1 presents the results of the study. In the first column, the parameter under consideration is listed, along with the base case setting of that parameter. In the second column, each value to which the parameter was set during the study is listed. The third column lists the maximum coating stress voltage occurring anywhere along the length of the pipeline, for the worst case fault location, with the required mitigation installed. The fourth column lists the maximum coating stress voltage occurring with no mitigation installed. The fifth column indicates what length of zinc ribbon anode is required near each transmission line tower in order to reduce coating stress voltages to less than 3 kV. The last column indicates what tower or pole ground resistance resulted from each soil structure for the tower or pole modeled.

Although the greatest coating stress voltages occur at the center of the corridor, for faults occurring there, coating stress voltages and therefore mitigation requirements are on the same order throughout the corridor. Figure 4, which shows coating stress voltages as a function of distance along the entire corridor, for six representative fault locations, illustrates this point. The scenario depicted here is the base case, with 25.1 m (82.5 ft) of zinc ribbon anode connected to the pipeline near each transmission line tower and centered with respect to each tower. The worst case fault location, with the exception of each end tower, is the central tower of the parallel corridor and this is the fault location chosen for the entire study. Coating stress voltages are highest close to the center of the corridor and near the ends.

Figure 5 shows how zinc ribbon anodes alter coating stress voltages on the pipeline, in the vicinity of a faulted tower. In this case, the 1000 Ω-m uniform soil scenario is used as an example. As can be seen, the zinc ribbon anode dramatically reduces coating stress voltages to a fraction of their pre-mitigation values, throughout the length of the anode, and also reduces coating stress voltages elsewhere. It can also be seen here that a single anode is not always enough: in this case, two are required, one on either side of the pipeline.

Figure 6 summarizes in graphical form much of what is presented in Table 1. In particular, for each of 8 key parameters studied, it shows to what degree variations in the parameter influence the required zinc ribbon anode required on the pipeline near each transmission line structure. Figure 6 also provides an indication of the degree of uniformity in the maximum coating stress voltages achieved by the final mitigation of any group of parameter values: ideally, for optimally designed mitigation, all of the maximum coating stress voltages would be slightly under 3 kV. However, since the study was limited in the number of mitigation scenarios it could examine, there are some maximum coating stress voltages that are considerably under 3 kV.

Referring to Table 1 and Figure 6, let us examine the importance of each parameter.

Pipeline Coating Resistance. While pipeline coating resistance does influence coating stress voltages when no mitigation is installed, it has a small impact on mitigation requirements.

Transmission Line Structure Grounding. In the 100 Ω-m uniform soil studied as a base case, the transmission line structure grounding makes a noticeable difference in pre-mitigation coating stress voltages and an even greater difference in mitigation requirements. Indeed, the 3 m (10 ft) ground rod, typical of wood pole structures, results in only half as much mitigation as the lattice tower foundations and the very low resulting coating stress voltage (i.e., 1.5 kV) suggests that even less mitigation would have been satisfactory. As this example illustrates, the less transmission line structure grounding the better, at least as far as pipeline mitigation requirements are concerned.

Length of Parallel Corridor. While a very short parallel corridor can result in decreased mitigation requirements, a threshold length is reached at which further increases in corridor length do not significantly alter zinc ribbon anode requirements per unit corridor length. For the 100 Ω-m uniform soil studied as a base case,

8 km (5 miles) is already past this threshold: increasing the corridor length to 16 km (10 miles) has no impact on the mitigation required per span.

Clearance Between Pipeline and Transmission Line Structure. At first glance, clearance between the pipeline and transmission line tower legs does not appear to have a great impact on mitigation requirements: indeed, for the 100 Ω-m uniform soil studied as a base case, decreasing the spacing from 9.1 m (30 ft) to 4.6 m (10 ft) does not change the required zinc ribbon anode length and the maximum coating stress voltage rises only from 2.2 to 2.4 kV, with the mitigation installed. On the other hand, as the soil resistivity increases, the importance of the separation distance increases. For example, for a 400 Ω-m uniform soil, the required mitigation per span increases from 50.3 m (165 ft) of single zinc ribbon anode to a pair of 101 m (330 ft) anodes, a four-fold increase.

Fault Current Level. As is to be expected, mitigation requirements are strongly dependent upon fault current levels. For the 100 Ω-m uniform soil studied as a base case, mitigation requirements are proportional to the fault current. This appears to be particularly true of the 5 kA and 10 kA fault currents. For the 2.5 kA fault current, on the other hand, coating stress voltages without mitigation are just barely over the 3 kV limit, so mitigation can almost be dispensed with. Once the minimal mitigation of 12.6 m (41.3) per span is installed, coating stress voltages drop to 1.8 kV, suggesting that significantly less mitigation would still result in coating stress voltages less than the 3 kV limit.

Proportion of Total Fault Current From Each End of Line. In the main study, equal fault currents were injected into the faulted phase at each end of the transmission line, so as to converge on the fault location from both sides. Keeping the total fault current arriving at the fault location equal to 10 kA, but varying the respective proportion of the total arriving from both sides of the fault from 50%/50% to 100%/0%, it was found that this factor had a relatively small impact on mitigation requirements, at least for the fault occurring midway along the corridor. Coating stress voltages and the associated mitigation requirements do tend to increase gradually as the proportion of the total fault current arriving from one side increases.

Transmission Line Shield Wires. It is clear from this study that a highly conductive shield wire, such as an optical fiber ground wire, can easily reduce mitigation requirements by a factor of 2 – 4, compared with single or double 66 mm2 (3/8") EHS Class A galvanized steel wires. Although conductive shield wires can increase induced voltages during normal load conditions, they provide very important benefits during fault conditions.

Soil Resistivity. Not surprisingly, increasing soil resistivities lead to the need for greater lengths of zinc ribbon anode in order to achieve the required grounding. An increase in uniform soil resistivity from 25 Ω-m to 1000 Ω-m leads to an increase in the required mitigation from 12.6 m (41.3 ft) or less to 201 m (660 ft), the latter actually consisting of two 101 m (330 ft) conductors, one on either side of the pipeline.

Soil Layering. Not only do the average soil resistivities have a considerable impact on coating stress voltages and associated mitigation requirements, but the layering of the soil can also be quite important. This was seen during the study for the 100 Ω-m soil, 0.76 m (2.5 ft) thick, over 1000 Ω-m soil: this exposed the tower footings to a thin, yet conductive, soil layer, which transferred high electrical potentials from the faulted tower to the pipeline location, while the mitigation, located at the bottom of the pipeline trench, in high resistivity soil, was highly ineffectual. In this case, even a pair of continuous zinc ribbon anodes could not reduce pipeline coating stress voltages to acceptable levels. It was necessary to raise the zinc ribbon anodes into the low resistivity top layer, in order to obtain satisfactory protection.

CONCLUSIONS

By means of a parametric analysis made with computer software that provides a direct numerical solution of Maxwell's equations, the study reported in this paper has determined the mitigation required to reduce pipeline coating stress voltages to satisfactory levels during fault conditions, for a wide range of system parameter values. The relative importance of parameters such as the following has been demonstrated: pipeline coating resistance,

transmission line structure grounding, length of corridor shared by the transmission line and pipeline, clearance between the pipeline and the transmission line structures, fault current levels and distribution between both sides of the fault, transmission line shield wire type, soil resistivity, and soil layering. The results presented in this paper can be used to estimate mitigation requirements for many joint-use corridors.

This work can be expanded in the future to study the simultaneous variation of several parameters: in particular, it would be interesting to repeat this analysis for a higher base case soil resistivity. Other points of interest to explore would be the following: address the effects of tower counterpoise that might be present in high resistivity soils, show how mitigation requirements decrease when the coating stress voltage design limit increases, and examine what mitigation is required to decrease transferred potentials to meet touch voltage limits outside the parallel corridor.

ACKNOWLEDGEMENTS

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TABLE 1
DETAILED RESULTS OF PARAMETRIC ANALYSIS

Parameter (Default Value)	Value	Coating Stress Voltage, in kV		Required Mitigation, in m/span (ft/span)[2]	Tower/Pole Ground Resistance, in Ω
		With Mitigation	Without Mitigation		
Base Case	N/A	2.2	6.4	25.1 (82.5)	2.8
Coating Resistance (31,000 Ω-m^2 /333,000 Ω-ft^2)	2,787 Ω-m^2 (30,000 Ω-ft^2)	2.8	4.5	12.6 (41.3)	2.8
	9,291 Ω-m^2 (100,000 Ω-ft^2)	2.2	5.6	25.1 (82.5)	2.8
	74,324 Ω-m^2 (800,000 Ω-ft^2)	2.3	7.0	25.1 (82.5)	2.8
Tower/Pole Grounding (6 m/ 20 ft tower footings)	Single 3.05 (10 ft) ground rod	1.5	4.1	12.6 (41.3)	33.0
Corridor Length (8.05 km/ 5 mi)	3.2 km (2 mi)	2.8	4.6	12.6 (41.3)	2.8
	16.1 km (10 mi)	2.2	8.9	25.1 (82.5)	2.8
Separation Distance (9.1 m/ 30 ft)	4.57 m (15 ft)	2.4	7.8	25.1 (82.5)	2.8
	30.48 m (100 ft)	2.3	4.3	12.6 (41.3)	2.8
Fault Current[3] (5 kA)	2.5 kA	1.8	3.2	12.6 (41.3)	2.8
	10 kA		12.9	50.3 (165)	2.8
Fault Current Split[4] (50%/50%)	100% / 0%	3.2/1.9	9.1	25.1/50.3 (82.5/165)	2.8
	90% / 10%	2.8	8.5	25.1 (82.5)	2.8
	80% / 20%	2.6	7.9	25.1 (82.5)	2.8
	70% / 30%	2.4	6.5	25.1 (82.5)	2.8
	60% / 40%	2.4	6.5	25.1 (82.5)	2.8
Shield Wires (2 steel wires)	1 steel wire	2.0	7.7	50.3 (165)	2.8
	1 steel & 1 optical fiber	1.8	4.2	12.6 (41.3)	2.8
Soil Resistivity[5] (100 Ω-m)	25 Ω-m	1.5	4.5	12.6 (41.3)	0.7
	400 Ω-m	3.0	10.1	50.3 (165)	11.2
	1,000 Ω-m	2.8	13.9	2 x 101 (2 x 330)[6]	28.3
Separation Distance and Soil Resistivity	4.57 m (15 ft) 400 Ω-m	2.8	13.2	2 x 101 (2 x 330)[6]	11.2
Soil Layering[7] (Uniform Soil)	100 Ω-m/ 1000 Ω-m/ 0.76 m (2.5 ft)	2.1	13.0	50.3 (165)[8]	19.6
	100 Ω-m/1000 Ω-m/ 1.83 m (6 ft)	1.8	12.9	50.3 (165)	14.1
	100 Ω-m/ 1000 Ω-m/ 6.71 m (22 ft)	2.2	11.6	50.3 (165)	6.7

[2] Each span is 201 m (660 ft) long
[3] Equal current from both sides
[4] Proportion from each side of the fault
[5] Uniform soil
[6] Two zinc ribbon anodes required, one on either side of the pipeline
[7] Top layer resistivity/bottom layer resistivity/top layer thickness
[8] Here, it was necessary to place the zinc ribbon anode in the top soil layer, which is more conductive, at a depth of 2 ft

	1000 Ω-m/ 100 Ω-m/ 1.83 m (6 ft)	3.0	6.3	201 (660)	3.2
	1000 Ω-m/ 100 Ω-m/6.71 m (22 ft)	2.4	5.9	50.3 (165)	15.2

NOT TO SCALE
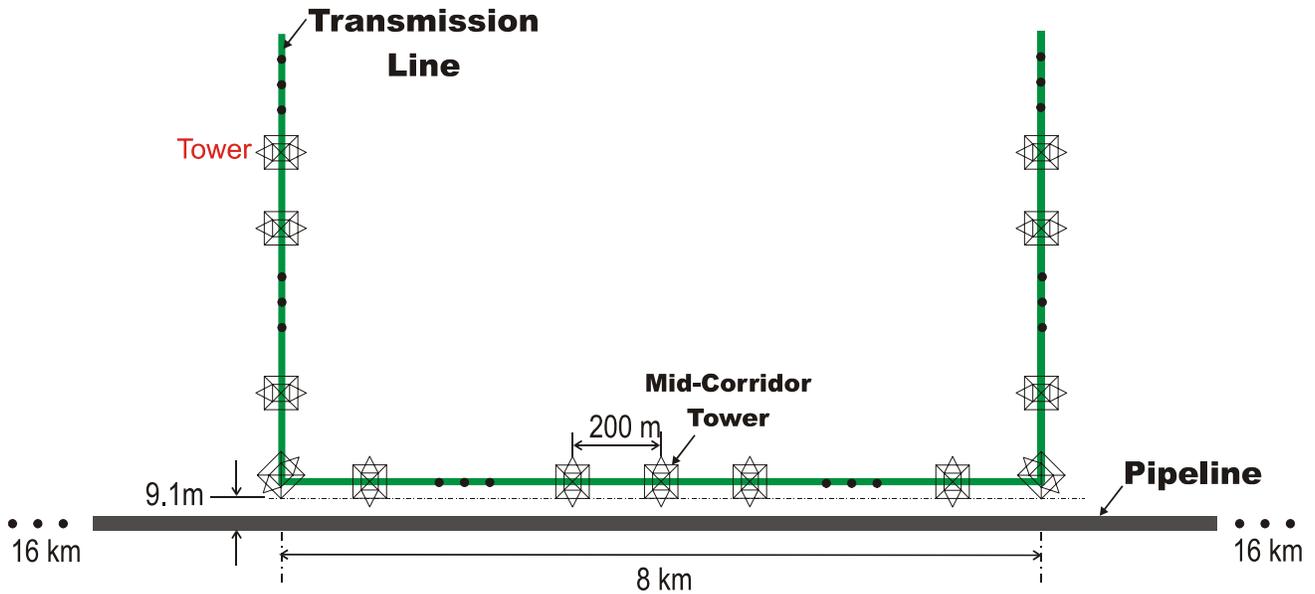
Figure 1.   Base Case Transmission Line/Pipeline Corridor Studied: Plan View
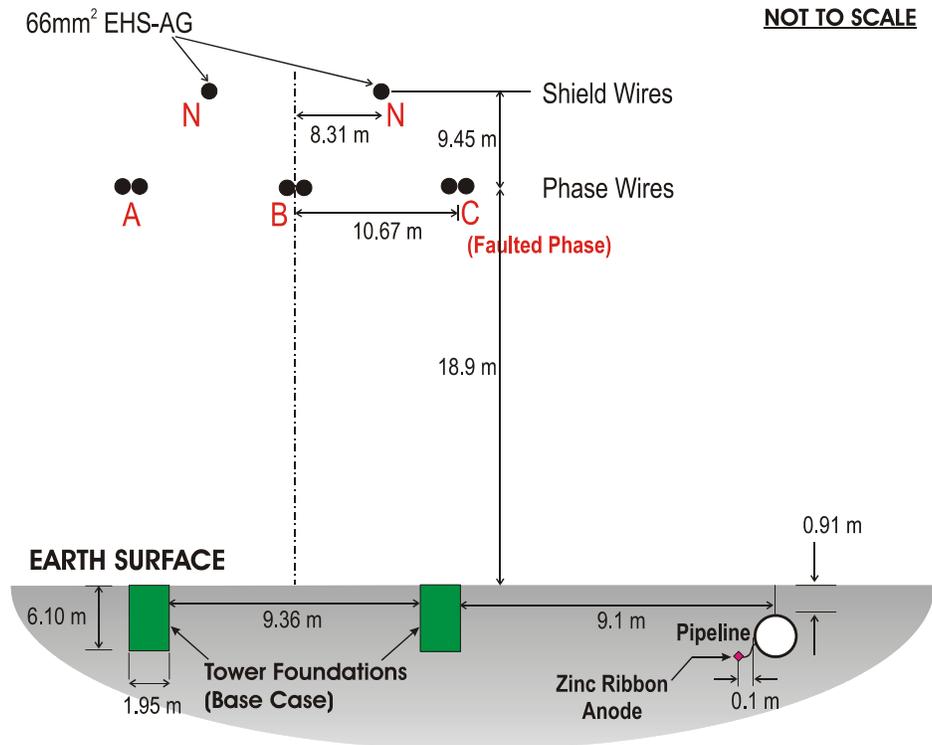
Figure 2.   Base Case Transmission Line/Pipeline Corridor: Cross Section

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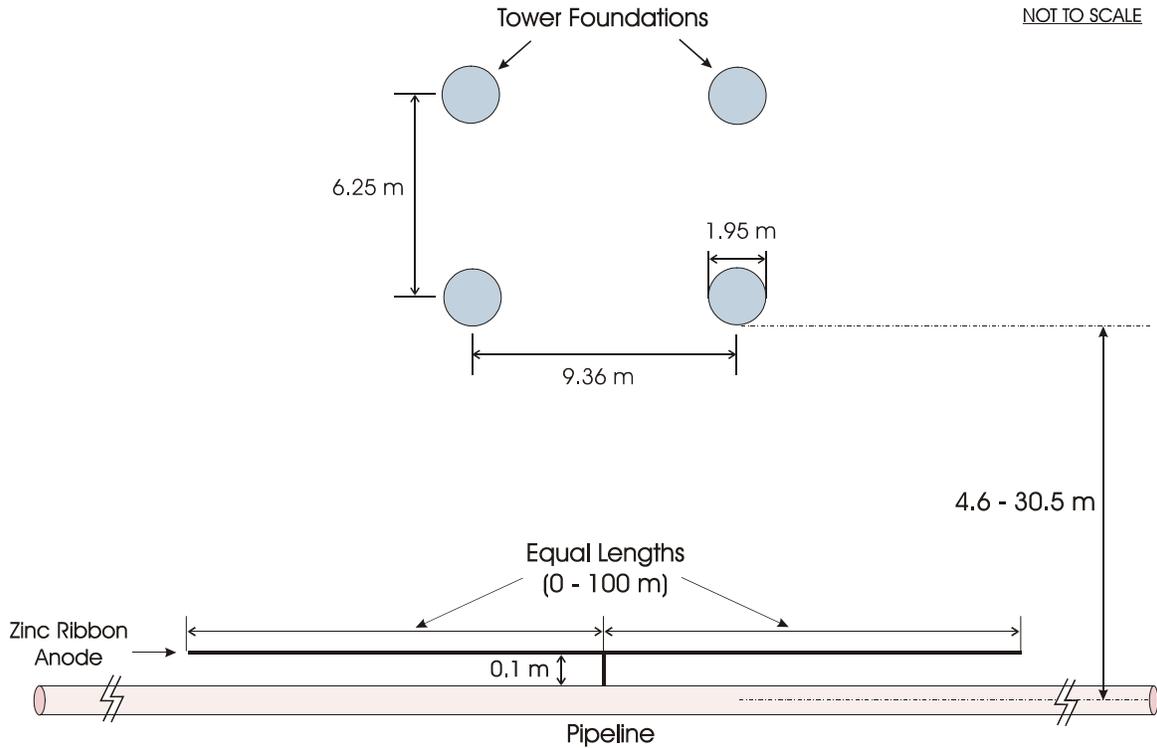
Figure 3.   Plan View of Tower Footings, as Modeled, and Nearby Mitigated Pipeline
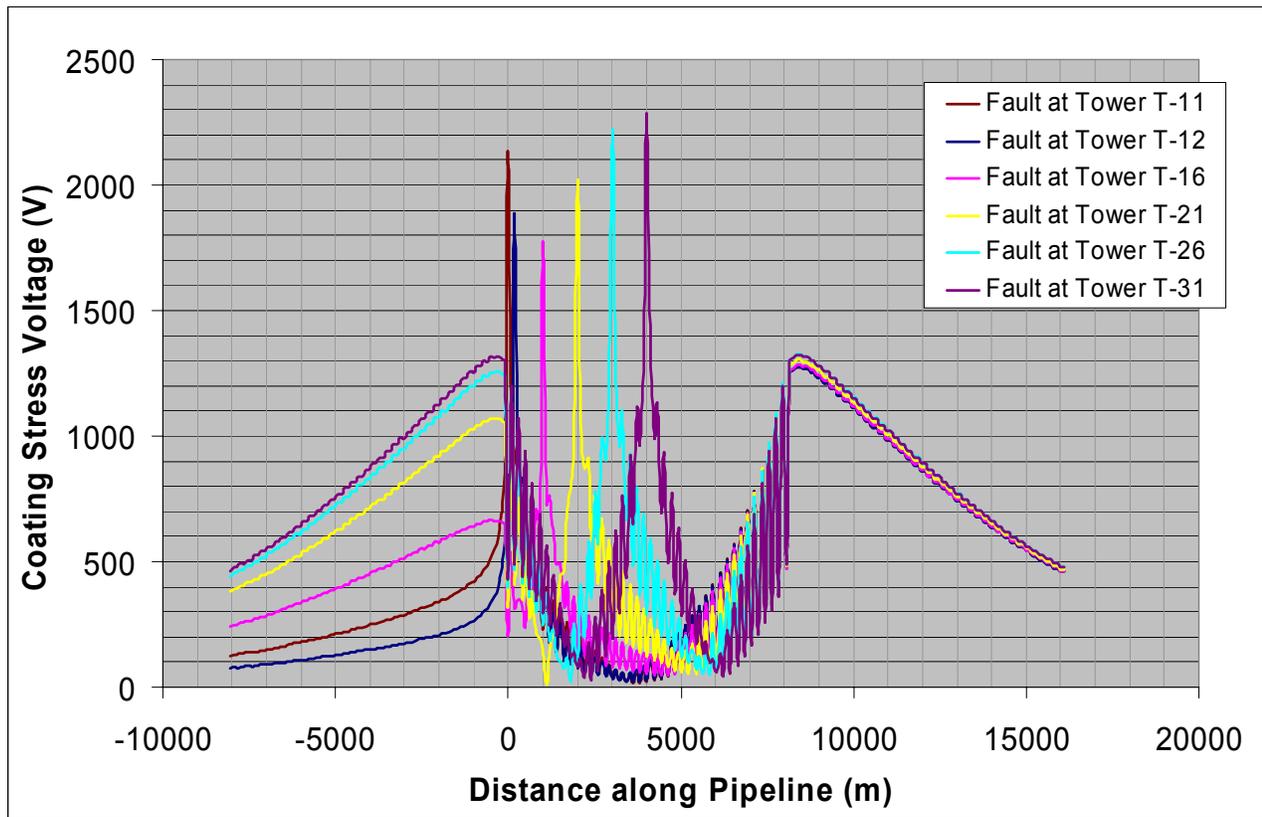
Figure 4.   Coating Stress Voltages along Entire Corridor as a Function of Fault Location: base case with required mitigation (i.e., 25.1 m of zinc anode ribbon per 201 m span of transmission line)
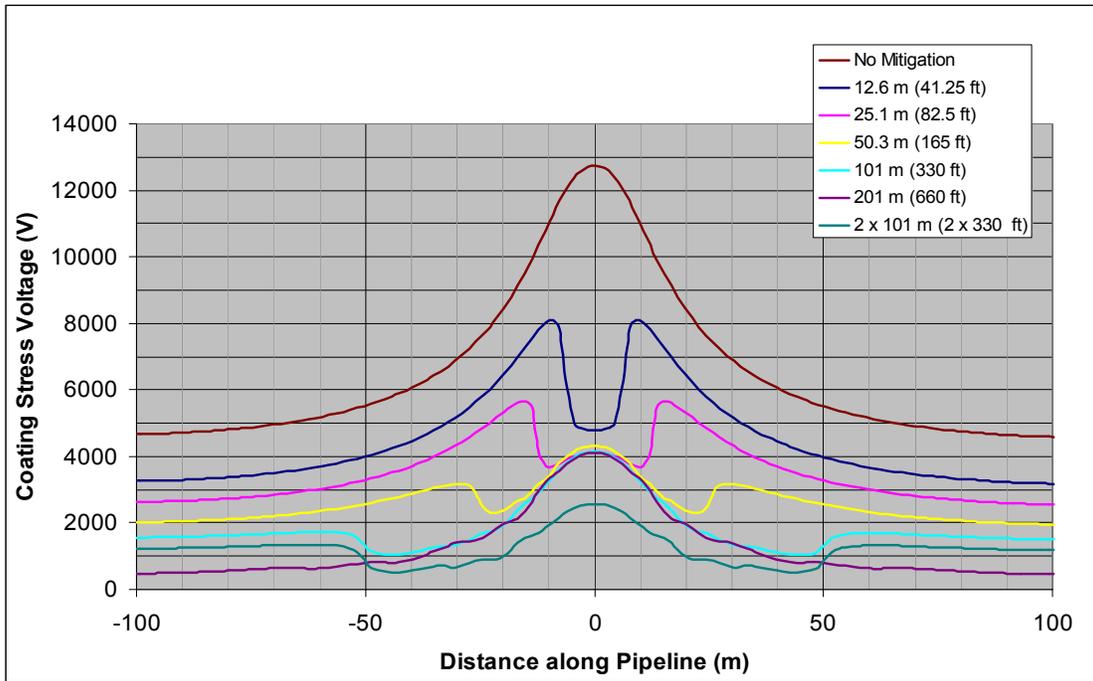
Figure 5. Effect of Zinc Ribbon Anode Length upon Coating Stress Voltages along Section of Pipeline Closest to Faulted Tower: 1000 Ω-m uniform soil
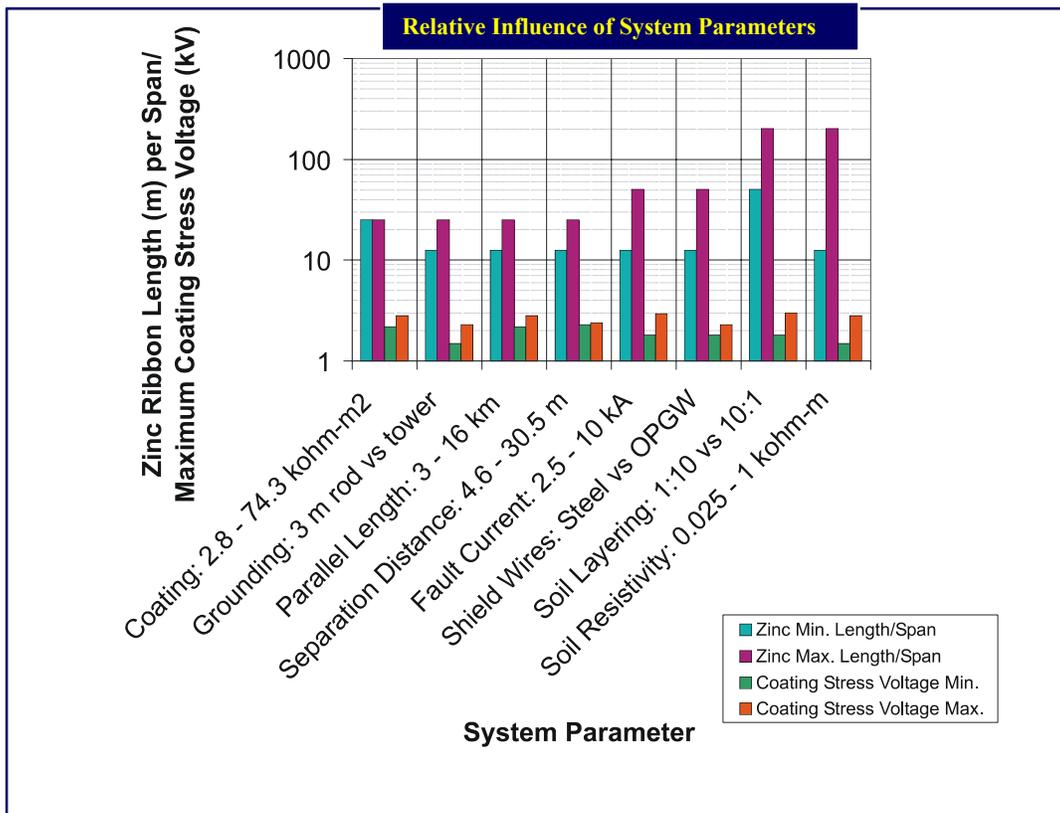
Figure 6. Relative Sensitivity of Coating Stress Voltages (with Mitigation Installed) and Required Mitigation Wire Length to Key System Parameter Values