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MITIGATION OF BURIED PIPELINE VOLTAGES DUE TO 60 Hz AC INDUCTIVE COUPLING

PART I - DESIGN OF JOINT RIGHTS-OF-WAY

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Abstract - Useful mitigation techniques are presented for the reduction of voltages induced on gas transmission pipelines by 60 Hz ac power transmission lines sharing a joint right-of-way. Part I describes how a joint pipeline/power line corridor can be designed to minimize inductive coupling. This allows installation of the utilities with significantly reduced requirements for pipeline voltage mitigation using grounding techniques.

INTRODUCTION

Since January 1976, IIT Research Institute has been funded jointly by the Electric Power Research Institute and the American Gas Association to consolidate known data concerning the effects of voltages induced on gas transmission pipelines by 60 Hz ac power transmission lines sharing a joint right-of-way. The goal of the study is the writing of a tutorial handbook that can be used by field personnel to predict the induced pipeline voltages and institute measures to mitigate against accompanying effects.

This paper, in two parts, presents the mitigation method developed by IITRI for the induced voltages on pipelines. The approach applies the electrical transmission line theory presented in a previous paper[1] to locate and quantize pipeline voltage peaks and then determine the effects of installing various mitigation systems. The approach developed has been proven in field tests and is applicable to realistic pipeline-ac power line corridors.

Review of the Consequences of Inductive Coupling

Voltages and currents can be induced on a buried or above-ground pipeline by the coupling of the electromagnetic fields generated by a nearby ac power line. The following pipeline and personnel hazards can be presented due to this coupling mode.

1. The induced ac voltage can enhance the corrosion of a non-protected pipeline by an electrochemical effect.[2]

2. Cathodic protection devices, communications equipment, and other types of electronic equipment associated with monitoring the pipeline behavior can be upset by high levels of induced ac voltage.

3. A pipeline worker accidentally grounding the pipe through his body faces the hazard of electric shock due to steady current flow, if contact with the pipe is not broken. Injury or death can result if the current is large enough.

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Useful Mitigation Techniques

The following is a listing of the various mitigation techniques which can be employed to reduce 60 Hz ac inductive coupling to a pipeline system consisting of arbitrary buried and above-ground sections:

1. Design of a joint pipeline/power line corridor for minimum inductive coupling;

2. Pipeline grounding methods;

3. Use of insulating devices; and

4. Use of pipeline extensions.

Of the above techniques, the first was recently derived from the basic distributed-source theory of Reference 1. This technique, discussed in Part 1 of this paper, is most easily applied before the joint corridor is built, i.e., during the design stage, when some flexibility of utility positions and features is available.

The remaining techniques have been used in the past to mitigate existing induced voltage problems. Part II of this paper will discuss the optimization of these methods consistent with the developed theory of Reference 1.

It should be emphasized that the inductive coupling mitigation concepts to be discussed in Parts I and II of this paper have been verified by field tests. These tests involved Southern California Gas Company Line 235, a 34-inch diameter gas transmission pipeline extending from Newberry to Needles, California. This pipeline shares a right-of-way with a Southern California Edison Company 525 kV ac power transmission line for 54 miles and is subject to considerable electromagnetic induction. The illustrative examples to be discussed are taken directly from the results of the Mojave field tests.

REMOVAL OF ELECTRICAL OR GEOMETRIC DISCONTINUITIES FROM A JOINT-USE RIGHT-OF-WAY

Design Goals

As demonstrated in Reference 1, distinct voltage peaks on a buried pipeline due to inductive coupling should appear at widely spaced electrical or physical discontinuities of the pipeline, and at abrupt changes of the longitudinal driving electric field at the pipeline location. The pipeline discontinuities include insulators and junctions, transitions between long burial runs in low and high resistivity soil, and transitions between long burial runs with low and high resistivity pipe coatings. The field discontinuities include magnitude and phase changes occurring over long runs due to either changes in separation between the pipeline and the power line, phase transpositions of the power line, or the entrance of additional power lines into the joint corridor. It is concluded that, to prevent pipeline voltage peaks, a joint-use right-of-way should be designed to have the maximum possible degree of constancy of internal geometry and electrical characteristics of the individual utilities.

The optimum electromagnetic design of a joint right-of-way for minimum inductive coupling can be summarized concisely by listing the following six design goals for the right-of-way:

1. Avoid any changes of separation between individual utilities.

2. Avoid the use of pipeline insulating joints or junctions. If an insulating joint is necessary, place a low-ac-impedance cell across it.

3. Avoid changes in pipeline coating quality that are manifested over multi-mile lengths. Similarly, avoid the combination of long above-ground and buried sections in a single pipeline run.

4. Avoid the use of power line phase transpositions or phase changes in substations. Similarly avoid changes in the configuration of the phase conductors and lightning shield wires.

5. Avoid the entry of additional utilities to the right-of-way at intermediate points.

6. Use power line phase sequencing yielding the lowest value of longitudinal driving electric field.

The latter design goal is more fully developed in the section on electric field reduction within the right-of-way.

Case History: Effect of Right-of-Way Discontinuities

The following discussion concerning the joint-use corridor extending from Newberry to Needles, California, will illustrate many of the basic corridor design principles just summarized.

The Southern California Edison 525 kV electric power transmission line meets the Southern California Gas Company 34-inch diameter gas pipeline at pipeline milepost 47 (47 miles west of Needles, California) and leaves it at milepost 101.7, as shown in Figure 1a. The power line has a horizontal configuration with a full clockwise (phase-sense) transposition at milepost 68 and single-point-grounded lightning shield wires. During the test period, an average loading of 700 amperes was reported for each phase conductor. No other power lines, pipelines, or long conductors share the right-of-way.

Measurements performed during the test indicated an average earth resistivity of 400 ohm-meter. Based upon furnished data, a value of 700 $k\Omega\text{-}ft^2$ was assumed as the average pipeline coating resistivity. Using these values as data for a pipeline-characteristics calculator program,[1] the pipeline propagation constant, γ, was computed as $(0.115 + j0.096)\ km^{-1} = 0.15\underline{/40^o}\ km^{-1}$; and the pipeline characteristic impedance, Z_o, was computed as $(2.9 + j2.4)$ ohms $= 3.8\underline{/40^o}$ ohms.

In Reference 1, it was shown that separably-calculable pipeline voltage peaks could be expected at all discontinuities of a pipeline-power line geometry spaced by more than $2/\mathrm{Real}(\gamma)$ meters along the pipeline. Using the computed value of γ, all geometry discontinuities spaced by more than $(2/0.115)$ km = 17.4 km ≃ 10 miles were assumed to be locations of separable induced voltage peaks. These discontinuities included

1. Milepost 101.7 (near end of pipeline approach section);

2. Milepost 89 (separation change);

3. Milepost 78 (separation change);

4. Milepost 68 (power line phase transposition);

5. Milepost 54 (separation change); and

6. Milepost 47 (near end of pipeline departure section

The pipeline voltages at these mileposts were predicted by applying Equation 28 of Reference 1. The predicted and measured voltage peaks are summarized in Table 1.

Table I

Mojave Desert Pipeline Voltage Peaks

Milepost	Predicted Voltage (volts)	Measured Voltage (volts)
101.7	46.3	46
89	54.0	53
78	31.1	34
68	54.8	54
54	11.4	11
47	31.2	25

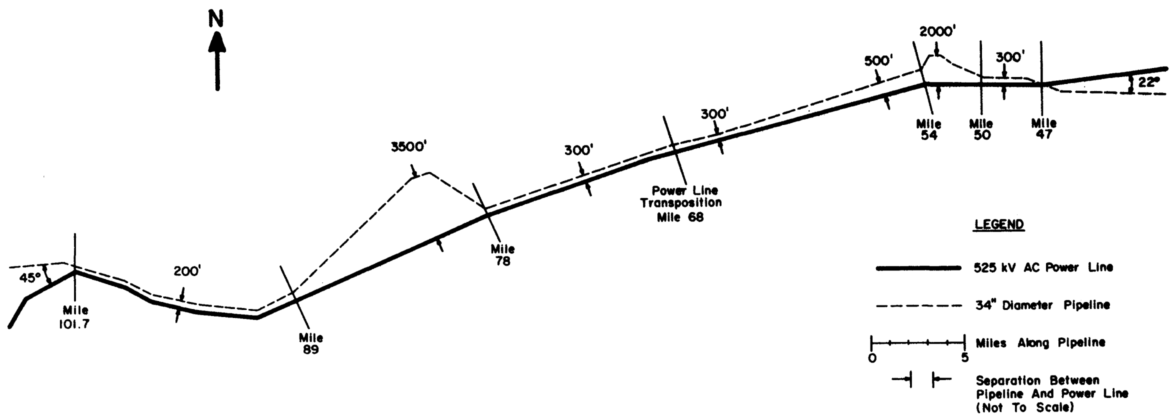
Figure 1b plots both the measured ac voltage profile of the Mojave pipeline and the predicted voltage peaks. The solid curve represents voltages measured during the field test; the dashed curve is a set of data (normalized to 700 amperes power line current) obtained by a Southern California Gas Company survey. From this figure, it is apparent that the pipeline voltage peaks did occur at the points of discontinuity of the joint right-of-way, and did have the predicted amplitudes. This agreement with the analysis confirms the right-of-way design goals of this section in optimizing a given joint-use corridor for minimum inductive coupling.

REDUCTION OF THE LONGITUDINAL DRIVING ELECTRIC FIELD WITHIN A JOINT-USE RIGHT-OF-WAY

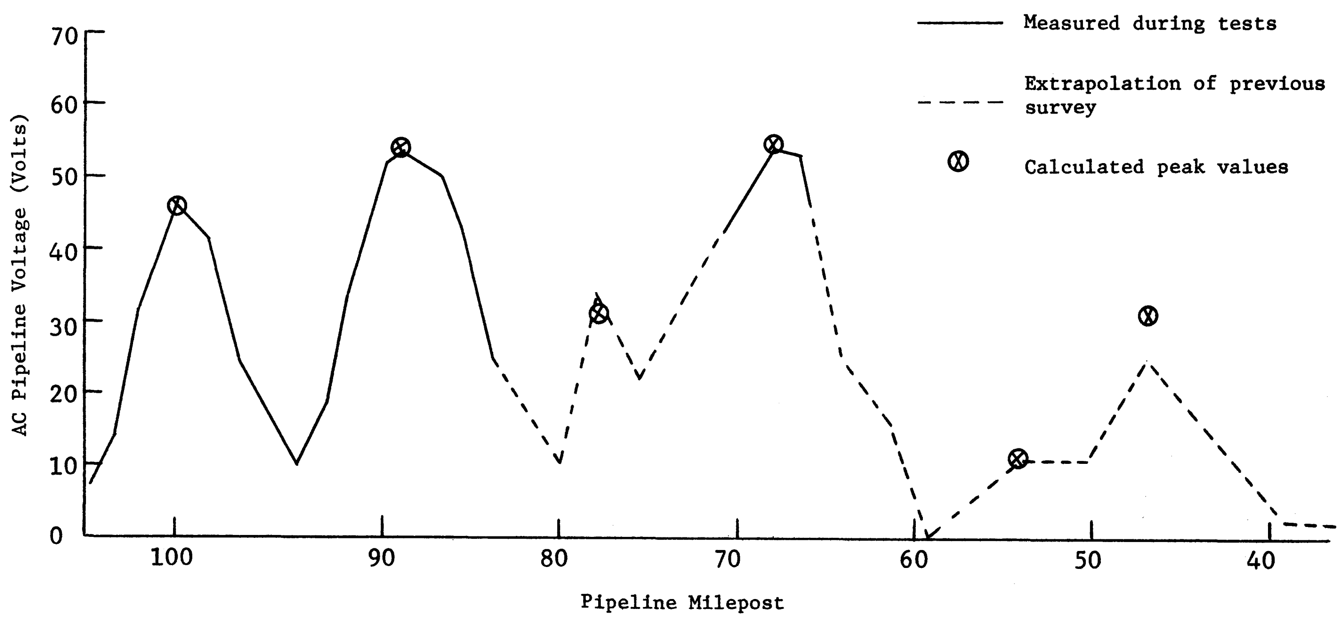
For purposes of inductive coupling mitigation, a power line would ideally be designed to generate only a minimal, but constant, longitudinal driving electric field at the location of the adjacent pipeline. (This field results from current flow through the power line conductors, and is not the same as the electrostatic field, which results from the potential of the power line conductors with respect to ground.) To strengthen this concept, computer analyses were performed to investigate the effect of power line conductor phasing and shielding upon the driving electric field profile. This section summarizes the results of these analyses.

Optimized Phase Sequencing

For certain ac power line configurations, it is possible to minimize the driving electric field within the right-of-way by proper sequencing of the phase conductors.[4,5] The effectiveness of such phase sequencing has been studied for three common power line geometries. The results indicate that for certain geometries and proper phase conductor sequencing, the induced electric field levels can be significantly reduced. This technique is especially appropriate for vertically stacked circuits, particularly the double circuit configuration.



(a) Pipeline-Power Line Geometry



(b) Pipeline Induced-Voltage Profile

Figure 1 MOJAVE DESERT JOINT-USE CORRIDOR CASE HISTORY

The analysis of this mitigation technique was accomplished in two basic steps. First, for a given power line geometry, Carson's infinite series approach and linear circuit analysis were combined to determine the induced currents in the lightning shield wires. The mutual interaction between these wires was included in the analysis, requiring the solution of simultaneous equations. Second, using superposition theory and Carson's infinite series, the field contribution from each current-carrying wire was computed and summed to provide the total longitudinal electric field at arbitrary distances from the power line. In all cases, the Carson mutual impedances were calculated to better than 0.1% accuracy. These steps were then repeated for each geometry and conductor phasing examined.

<u>The Single Horizontal Circuit.</u> The first power line geometry considered is that shown in Figure 2, the single horizontal circuit with two multiple-grounded lightning shield wires. There are six possible phase sequences for this geometry, separable into two categories -- clockwise (cw) and counterclockwise (ccw) sequences. Referring to the phase conductors from left to right in Figure 2, and letting "A" denote the

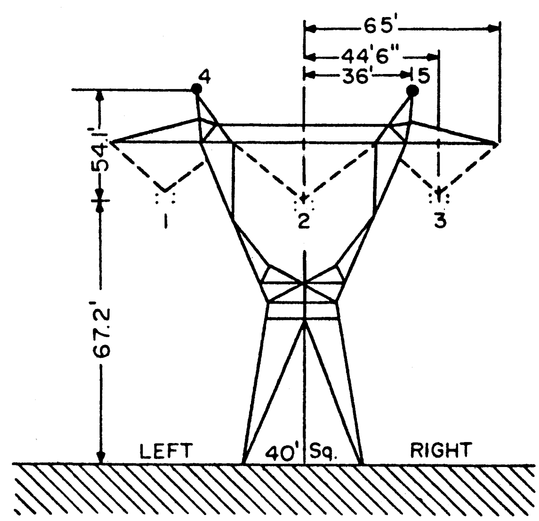


Figure 2 HORIZONTAL POWER LINE GEOMETRY

0^o phase, "B" denote the $+120^o$ phase, and "C" denote the -120^o phase, we have

cw sequences	ccw sequences
ABC	ACB
BCA	CBA
CAB	BAC

At a fixed observation point, p, on one side of the power line, it can be shown that all three cw sequences produce the same longitudinal electric field magnitude, $E_{cw}(p)$; and all three ccw sequences produce the field magnitude, $E_{ccw}(p)$; However, $E_{ccw}(p)$ does not equal $E_{cw}(p)$, in general. This difference can be exploited to obtain a field reduction at the pipeline location through proper choice of either a cw or ccw sequence. For example, Table II lists values of the electric field computed to the right of the power line of Figure 2, assuming an earth resistivity of 33.3 Ω-m and equal phase currents of 100 amperes per conductor.

Table II

Choice of CW or CCW Sequence For Balanced Horizontal Circuit

Distance From Center Phase (feet)	$\lvert E_{ccw}\rvert$ (V/km)	$\lvert E_{cw}\rvert$ (V/km)	Mitigation Advantage of CW Sequence (percent)
0	2.25	2.25	0.0
50	5.21	5.02	3.6
100	4.90	4.72	3.9
150	3.68	3.51	4.6
200	2.87	2.71	5.6
250	2.32	2.18	6.0
300	1.95	1.81	7.2
350	1.67	1.55	7.2
400	1.46	1.34	8.2
450	1.29	1.18	8.5
500	1.15	1.05	8.7

From the table, it is seen that the driving electric field exposure levels can be reduced by as much as 9 percent simply by choosing the proper phase sequence. Since the voltage induced on the pipeline is directly proportional to the electric field, it, too, can be reduced by this same percentage. However, if the sky wires are not continuous and periodically grounded as assumed in the above analysis, then there is no significant advantage of one phase sequence over another.

The Single Vertical Circuit. The second geometry considered is that shown in Figure 3, the single vertical circuit with two multiple-grounded lightning shield wires. Similar to the single horizontal circuit, this configuration has six possible phase combinations separable into the cw and ccw sequences. Referring to the phase conductors from top to bottom in Figure 3, the phase combinations ABC, BCA and CAB are again defined as clockwise, while ACB, CBA and BAC are defined as counterclockwise.

At a fixed observation point, p, on one side of the power line, it can be shown that all three cw sequences produce the same longitudinal electric field magnitude, $E_{cw}(p)$, while all three ccw sequences produce the field magnitude, $E_{ccw}(p)$, not equal to $E_{cw}(p)$. Again, the difference in fields can be exploited to obtain mitigation. Table III lists values of the electric field computed to the right of the power line of

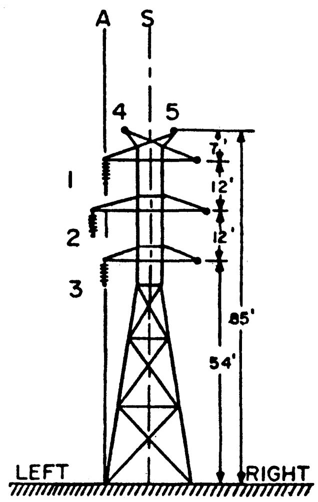


Figure 3 SINGLE CIRCUIT VERTICAL GEOMETRY

Figure 3, assuming an earth resistivity of 33.3 Ωm and equal phase currents of 100 amperes per conductor. From the table, it is seen that the electric field exposure levels, and thus, induced pipeline voltages, can be reduced by as much as 15 percent simply by choosing the proper phase sequence. However, if the skywires are not continuous and periodically grounded as assumed in the above analysis, then there is no significant advantage of one phase sequence over another.

Table III

Choice of CW or CCW Sequence For Balanced Vertical Circuit

Distance From Center Phase (feet)	$\lvert E_{ccw}\rvert$ (V/km)	$\lvert E_{cw}\rvert$ (V/km)	Mitigation Advantage of CCW Sequence (percent)
0	4.61	4.83	4.6
50	2.20	2.41	8.7
100	1.14	1.32	13.6
150	0.80	0.95	15.8
200	0.64	0.76	15.8
250	0.55	0.64	14.1
300	0.48	0.56	14.3
350	0.43	0.50	14.0
400	0.39	0.45	13.3
450	0.36	0.41	12.2
500	0.33	0.38	13.2

The Double Vertical Circuit. The third geometry considered is that shown in Figure 4, the double vertical circuit with two multiple-grounded lightning shield wires. Assuming a balanced current flow, there is a total of 36 possible phase sequences for this configuration. Of this number, there are five separate sets of phase combinations, as shown in Table IV: the center point symmetric; the full roll; the partial roll; (upper); the partial roll (lower); and the center line symmetric. For each set, the electric field magnitude is approximately constant for the distinct phase sequences which comprise the set. However, significant differences exist in the field magnitudes generated by separate sets. These differences can be exploited to obtain mitigation of pipeline voltages.

Table IV

Possible Phase Sequences for a Double Vertical Circuit

1. Center-Point Symmetric

A C / B B / C A	A B / C C / B A	B C / A A / C B

and the 3 right-to-left mirror images;

2. Full Roll

A B / B C / C A	A B / C A / B C	B C / A B / C A	B C / C A / A B	C A / A B / B C	C A / B C / A B

and the 6 right-to-left mirror images;

3. Partial Roll (Upper)

A B / B A / C — C	A C / C A / B — B	B C / C B / A — A

and the 3 right-to-left mirror images;

4. Partial Roll Lower

A — A / B C / C B	B — B / A C / C A	C — C / A B / B A

and the 3 right-to-left mirror images;

5. Center Line Symmetric

A — A	A — A	B — B	B — B	C — C	C — C
B — B	C — C	A — A	C — C	A — A	B — B
C — C	B — B	C — C	A — A	B — B	A — A

For example, Table V lists values of the longitudinal electric field computed to the right of the power line of Figure 4, assuming an earth resistivity of 33.3 Ωm, and equal phase currents of 100 amperes per conductor. From the table, it is seen that the electric field levels, and thus, induced pipeline voltages, can be reduced by as much as 60 to 90% over the right-of-way by choosing the center point symmetric phasing instead of any of the others. This reduction is significant when it is realized that it is solely a result of power line phasing. No special or unorthodox procedures or equipment are required of either the electric power or gas utility to achieve this reduction. It is a consequence of the physical interaction of the induced electric field from all of the power line conductors.

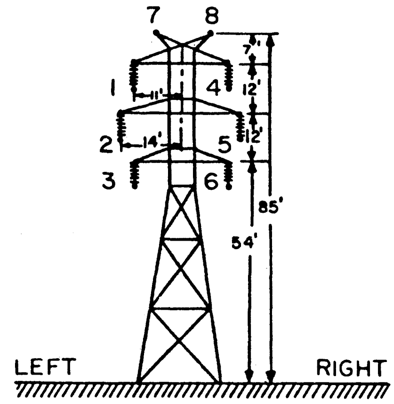


Figure 4 DOUBLE VERTICAL CIRCUIT GEOMETRY

Installation of an Auxiliary Grounded Shield Wire

A second possible electric field reduction technique is the usage of an auxiliary grounded shield wire installed between the power line towers.[4] The purpose of this shield wire is to induce an additional component of longitudinal electric field 180 degrees out of phase with the existing field, causing field cancellation. This cancellation can occur only when the current induced in the auxiliary wire is of a favorable magnitude and phase. The desirable parameters for the induced current are attained through the proper positioning of the wire relative to the tower-mounted phase conductors and lightning shield wires.

The effectiveness of this technique has been studied for three common power line geometries. The results indicate that the extra grounded shield wire can provide a substantial reduction of the longitudinal electric field for vertical circuits. However its mitigation effect can be sensitive to the loading conditions of the power line which limits the usefulness of this technique.

The computer program developed previously for calculation of the longitudinal electric field was modified for this analysis to include the effects of the auxiliary shield wire. By making this calculation with and without

Table V

Choice of Phase Sequence for the Balanced Double Vertical Circuit of Figure 4

Distance From Center Line (feet)	Longitudinal Electric Field Magnitude (V/km)					Mitigation Advantage of Center-point Symmetric Phasing
	Center Point Symmetric	Full-Roll	Partial-Roll (upper)	Partial-Roll (lower)	Center-Line Symmetric	
0	0.7	4.3	8.0	7.35	9.1	85 - 90%
100	0.3	0.9	1.9	2.2	2.5	65 - 90%
200	0.2	0.5	1.0	1.25	1.4	65 - 85%
300	0.15	0.4	0.75	0.9	1.0	60 - 85%
400	0.15	0.35	0.6	0.75	0.85	60 - 85%
500	0.1	0.3	0.5	0.65	0.7	60 - 85%

Best Phasing ⟷ Worst Phasing

the presence of the auxiliary shield wire, it was possible to evaluate the effectiveness of this mitigation technique. This procedure was then repeated for each power line geometry and conductor phasing examined.

The Single Horizontal Circuit. The first geometry considered is that shown in Figure 2, the single horizontal circuit with two multiple-grounded lightning shield wires. (The optimum phasing of this circuit was discussed previously.) A single, auxiliary grounded shield wire was assumed to exist in various vertical planes defined within the bounds of the tower structure. The wire was then assumed to be located at different heights within each plane. A comparison of the original longitudinal electric field to the field with the auxiliary wire present could then be made.

Figure 5 illustrates the effect of placing a grounded auxiliary shield wire at the outer right edge of the power line towers (65 feet to the right of the center line), as observed at two points: (1) 200 feet to the right of the center line; and (2) 200 feet to the left of the center line. For this example, an earth resistivity of 33.3 Ωm was assumed, along with balanced phase conductor currents. From the figure, it is seen that the maximum field reduction, about 25%, occurs to the right of the power line for a shield wire height of 48 feet. However, an equivalent field increase is seen to occur to the left of the power line.

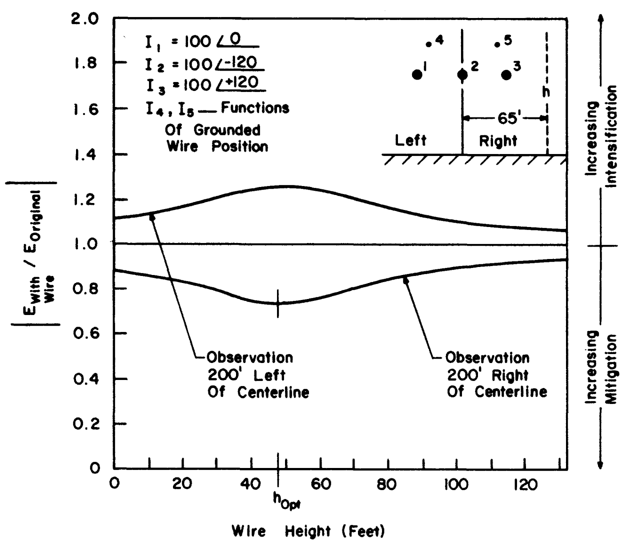


Figure 5 EFFECT OF A GROUNDED AUXILIARY SHIELD WIRE AS A FUNCTION OF HEIGHT FOR THE SINGLE-CIRCUIT HORIZONTAL CONFIGURATION

Modeling of the auxiliary shield wires in several other vertical planes gave results similar to those of Figure 6. Mitigation greater than 25% could be obtained only if the auxiliary wire was assumed to be within six feet of a phase conductor. Under these circumstances, a field reduction of about 50% was possible. However, this placement is unrealistic if the insulation characteristics of the power line are to be preserved.

Overall, a grounded auxiliary shield wire can be expected to provide about a 25% reduction in the longitudinal electric field on one side of a single horizontal circuit power line. This reduction is accompanied by a corresponding increase of the field level on the opposite side of the power line. The most favorable heights for the auxiliary wire are approximately the same as the phase conductor height, thus placing the practicality of this technique in question.

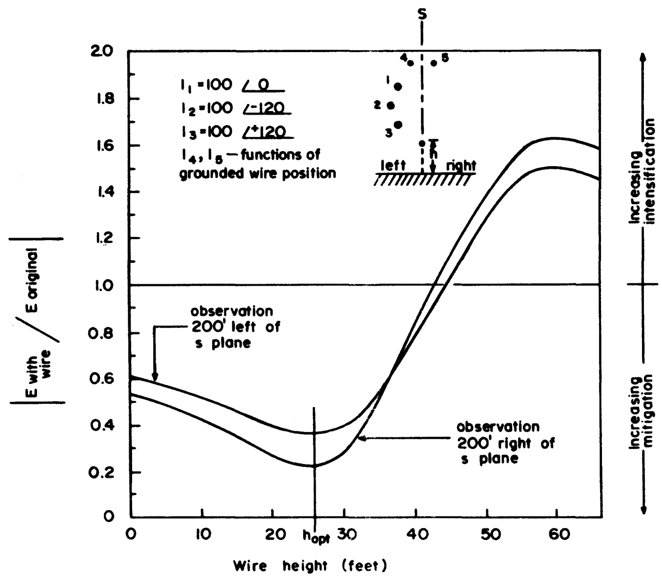
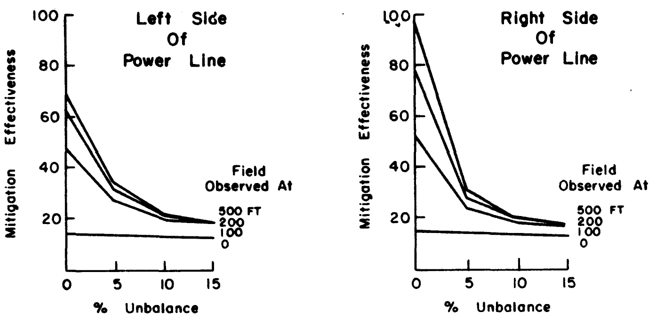


Figure 6 EFFECT OF A GROUNDED AUXILIARY SHIELD WIRE AS A FUNCTION OF HEIGHT FOR THE SINGLE-CIRCUIT VERTICAL CONFIGURATION

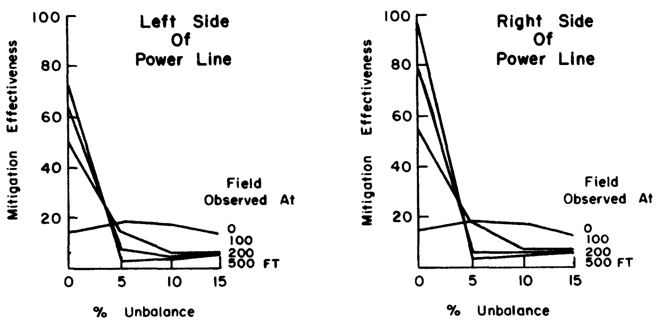
The Single Vertical Circuit. The second geometry considered is that shown in Figure 3, the single vertical circuit with two multiple-grounded lightning shield wires. (The optimum phasing of this circuit was discussed previously.) A single, auxiliary grounded shield wire was assumed to exist in the vertical plane S as shown in the figure. The total longitudinal electric field was computed for the wire at different heights within the plane and compared to the results of the power line without the auxiliary shield wire.

Figure 6 illustrates the effect of the auxiliary shield wire as observed at two points: (1) 200 feet to the right of the S plane; and (2) 200 feet to the left of the S plane. For this example, an earth resistivity of 33.3 Ωm was assumed, along with balanced phase conductor currents. From the figure, it is seen that the maximum field reduction is about 75% to the right of the power line, and about 60% to the left of the power line, for an optimum shield wire height of 26 feet. Above this height, the effectiveness of the wire in reducing the electric field diminishes to the point where all mitigation properties are lost. A wire located still higher carries current with a phase characteristic resembling that of the lightning shield wire currents, and accordingly, tends to reinforce the existing longitudinal electric field.

To illustrate the sensitivity of this mitigation technique to phase current unbalance, several simple situations were considered. Figure 7 presents the results of this analysis. The geometry of Figure 3 was employed with a base current of 100 amperes. The center phase conductor current was assumed to be constant for all of the calculations There was an assumed 0, ±5, ±10, and ±15 percent phase unbalance between the currents in the outer phase conductors relative to the center phase current. The effectiveness of the grounded wire in reducing the electric field was determined at four perpendicular separation distances: 0, 100, 200, and 500 feet on either side of the power line. The mitigation wire was assumed to be located at the optimum height of 26 feet as determined from Figure 6 for balanced phase currents. Figure 7a presents the results for both sides



(a) Largest Current In Lowest Phase Conductor



(b) Largest Current In Highest Phase Conductor

Figure 7 SENSITIVITY OF GROUNDED AUXILIARY SHIELD WIRE METHOD TO POWER LINE CURRENT UNBALANCE (SINGLE VERTICAL CIRCUIT)

of the power line when the largest current is in the lowest phase conductor, and Figure 7b when the largest current is in the highest phase conductor. It is believed that most power line loading characteristics fall within the current unbalances assumed here.

Two conclusions can be drawn from Figure 7. First, the effectiveness of the grounded auxiliary shield wire is sensitive to the balance of the phase currents. Small unbalances can cause a marked deterioration in the degree of mitigation provided by the grounded wire. For power lines having time-dependent current unbalances, it would be difficult to design a wire placement achieving a satisfactory mitigation at all times of the day.

It is also seen that the ability of the grounded wire to reduce the electric field is a function of the separation distance between the power line and the field observation point. For balanced currents, the mitigation technique becomes less effective as the observation point approaches the power line. But once even a small amount of unbalance is experienced, the effectiveness of the technique is reduced to 20% or less for all separation distances.

The Double Vertical Circuit. The third geometry considered is that shown in Figure 4, the double vertical circuit with two multiple-grounded lightning shield wires. (The optimum phasing of this circuit was discussed previously.) A single auxiliary grounded shield wire was assumed to exist in the center plane of the power line. The total longitudinal electric field was computed for the wire at different heights within the plane and compared to the results for the power line without the auxiliary shield wire.

Computations indicated that, when optimally placed, the grounded wire could reduce the longitudinal electric field by more than 50% for each of the phase sequences of Table IV. A maximum mitigation greater than 95% was found for the center-point symmetric configuration.

Although this reduction in the electric field is significant, the mitigation effect can deteriorate with just a small current unbalance, similar to the single vertical circuit case. Four simple current-unbalance combinations were considered for the center-point symmetric configuration, assuming a $\pm$ 5% current variation about the center phase conductors and a base current of 100 amperes. The four possible current combinations were then analyzed with the grounded wire located at the optimum height of 43 feet, with the results shown in Table VI. It is seen that a mitigation effectiveness of more than 95% for the balanced phase currents case can completely disappear for only a small perturbation of the phase currents.

Table VI

Effect of Current Unbalance on Performance of Grounded Auxiliary Wire for a Center Point Symmetric, Double Vertical Circuit

Phase Currents			Reduction in Electric Field (%) Left of Power Line	Right of Power Line
100	100	Nominal Currents		
100	100		68	> 95
100	100			
105	105			
100	100		85	70
95	95			
95	95			
100	100		-14 (increase)	74
105	105			
95	105			
100	100		17	17
105	95			
105	95			
100	100		2	1
95	105			

The computed sensitivity of the grounded auxiliary shield wire technique to phase current unbalances implies that it probably is not practical to implement in the field. Therefore, the chief recommended technique for reduction of a power line's longitudinal electric field is the selection of the optimum conductor phasing, as discussed in the previous section.

CONCLUSIONS

This paper has presented a new mitigation approach for the voltages induced on gas transmission pipelines by 60 Hz ac power lines sharing a joint right-of-way. This mitigation approach involves the optimum design of a joint right-of-way for minimum inductive coupling, and is based upon the distributed-source analysis of Reference 1. It is concluded that, to prevent pipeline voltage peaks, a joint-use right-of-way should be designed to: avoid any changes of separation between individual utilities; avoid pipeline insulating joints; avoid changes in pipeline coating quality; avoid the use of power line phase transpositions; and avoid any other geometric or electrical discontinuities of utilities sharing the right-of-way. This mitigation approach is most easily applied during the design stage of a joint-use corridor when the exact positions and features of each utility are somewhat flexible.

The paper treats as part of this approach the problem of minimization of the longitudinal, driving electric field due to the power line. It is concluded that, while optimum power line phasing is useful for field reduction, the use of an auxiliary grounded shield wire produces a mitigation effect that is overly sensitive to normal fluctuations of the phase conductor currents.

[1] A. Taflove and J. Dabkowski, "Prediction Method for Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling. Part 1 -- Analysis," Paper No. F78698-3, presented at the IEEE PES Summer Meeting, Los Angeles, California, 16-21 July, 1978.

[2] W.H. Bruckner, The Effects of 60 Hz Alternating Currents on the Corrosion of Steels and Other Metals Buried in Soil. Engineering Experiment Station Bulletin 470, University of Illinois, Urbana, Illinois, November 1964.

[3] C. F. Dalziel, "Electrical Shock Hazard," IEEE Spectrum, Vol. 9, No. 2, February 1972, pp 41-50.

[4] A.H. Manders, G.A. Hofkens, and H. Schoenmakers "Inductive Interference of the Signal and Protection System of the Netherlands Railways by High Voltage Overhead Lines Running Parallel With the Railway," Paper No. 36-02 presented at CIGRE, Paris, France, August 1974.

[5] G. R. Elek and B. E. Rokas, "A Case of Inductive Coordination," IEEE Trans. Power App. Systems, Vol. PAS-96, May/June 1977, pp. 834-840.

For Combined discussion see page 1822

MITIGATION OF BURIED PIPELINE VOLTAGES DUE TO 60 Hz AC INDUCTIVE COUPLING PART II -- PIPELINE GROUNDING METHODS

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Abstract - This paper presents useful mitigation techniques for the reduction of voltages induced on gas transmission pipelines by 60 Hz ac power transmission lines sharing a joint right-of-way. Part II describes how pipeline grounding methods can be implemented to reduce pipeline voltage peaks after installation of the utilities on the joint right-of-way. The use of properly-designed grounding systems permits the maximum mitigation of pipeline voltages at minimum cost.

INTRODUCTION

Even if a joint power line/pipeline right-of-way is designed using the approach of Part I of this paper, induced voltage peaks can appear on the pipeline at unavoidable discontinuities such as entry and exit points to the right-of-way. Part II discusses methods for mitigating these remaining voltage peaks using pipeline grounding methods optimized according to the distributed source analysis of References 1 and 2. These mitigation methods allow highly predictable and useful pipeline voltage reductions.

PIPELINE GROUNDING REQUIREMENTS

The most effective location for a grounding installation on a buried pipeline is at a point where the induced voltage is maximum. A good ground established at such a point serves to null the local exponential voltage distribution. However, the mitigating effects of this ground installation are negligible at an adjacent voltage peak located more than 2/Real(γ) m away, where γ is the propagation constant of a buried pipeline. Therefore, a ground should be established at each induced voltage maximum.

To effectively reduce the induced ac potential on a long buried pipeline of Thevenin source impedance, Z_θ, by connecting the mitigating, grounding impedance, Z_m, the condition

$$|Z_m| < |Z_\theta| \simeq 2 \text{ ohms} \tag{1a}$$

must be achieved. Grounding impedances exceeding $|Z_\theta|$ are essentially useless for mitigation in this case. Grounding impedances much less than $|Z_\theta|$ reduce the local pipeline voltage by

$$\% \text{ reduction} = 100 \left(1 - \left|\frac{Z_m}{Z_\theta}\right|\right) \quad . \tag{1b}$$

The grounding requirement of Eq. 1a is much more demanding than that for mitigation of electrostatic coupling to an above-ground pipeline. The combination of possibly high values of pipe source voltage, V_θ, and low values of pipe source impedance, Z_θ, serves to create shock hazards. Using the equivalent circuit of Figure 1, the shock current, I_w, through the worker can be shown to equal

$$I_w = \frac{V_\theta}{Z_\theta + Z_w \left(1 + \frac{Z_\theta}{Z_m}\right)} \tag{2}$$

where Z_w is the impedance of the current path through the worker, and $Z_\theta << Z_w$. Mitigation of I_w requires values of Z_m significantly less than Z_θ. This is much more stringent than the mitigation requirement for electrostatic coupling shock hazards on above-ground pipelines which is that Z_m must be significantly less than Z_w for best effect.

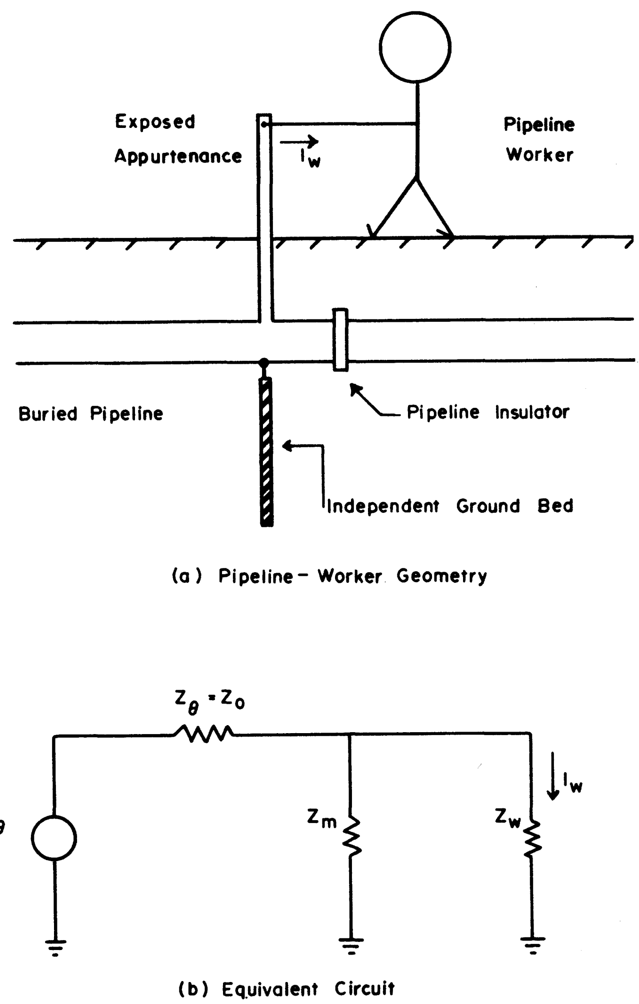

Figure 1 MITIGATION OF EM SHOCK HAZARDS BY PIPELINE GROUNDING

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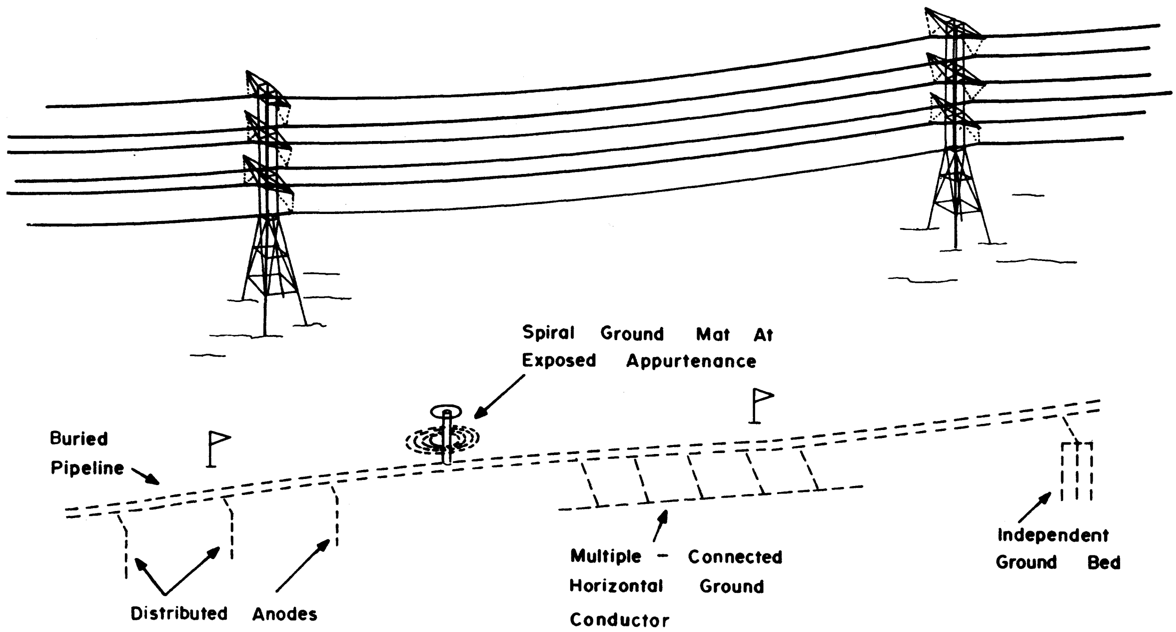


Figure 2 APPLICATION OF GROUNDING TECHNIQUES FOR MITIGATION OF ELECTROMAGNETIC COUPLING TO A BURIED PIPELINE

PIPELINE GROUNDING METHODS

As shown in Figure 2, the pipeline and personnel hazards due to inductive coupling to a buried pipeline can be mitigated by grounding the pipe using either independent ground beds, distributed anodes, or horizontal ground wires, and by installing ground mats at points of possible human contact. In particular, two general types of independent grounding systems, namely vertical anodes and horizontal conductors (including casings), have found extensive use in realizing the low-impedance grounds required. The following sections summarize the characteristics of the various low-impedance grounding systems, and review the use of grounding mats and bonds to the power-line ground system.

Vertical Anodes

A vertical anode grounding system can be realized with either a single deep anode or several distributed anodes. One possible single deep anode system consists of a steel casing containing cathodic protection type anodes in a carbonaceous backfill.[3] Here, the bottom portion of the steel casing which contains the anode and backfill can be below the normal water table, allowing a low impedance ground to be obtained quite easily.

A vertical ground rod and its surrounding earth form a lossy transmission line characterized by the propagation factor, γ_{rod}, and the characteristic impedance, Zo_{rod}. The ac grounding impedance, Z_{rod}, is simply the input impedance of this lossy transmission line. It is incorrect to assume that Z_{rod} is equal to the dc grounding resistance, R_{rod}. As will be shown below, the transmission line characteristics of a vertical ground rod significantly affect its performance.

For a vertical ground rod radius, a, the propagation factor is given by[4,5]

$$\gamma_{rod} = \sqrt{j\omega\mu_0(\sigma + j\omega\varepsilon)}\ m^{-1} \qquad (3)$$
$$\simeq 0.0154\cdot(1 + j)\cdot\sqrt{\sigma}\ m^{-1}, \text{ at 60 Hz}$$

where $\omega = 2\pi f$; $\mu_0 = 4\pi\cdot10^{-7}$ H/m; σ = soil conductivity in mhos/m; ε = soil permittivity in F/m; and $\sigma >> \omega\varepsilon$ is assumed. The characteristic impedance is given by[5]

$$Z_{o_{rod}} = \frac{1}{2\pi}\sqrt{\frac{\omega\mu_0}{2\sigma}}\left[(1+j)\cdot\ln\left(\frac{1.12}{a\sqrt{\omega\mu_0\sigma}}\right) + (1-j)\cdot\frac{\pi}{4}\right] \text{ ohms} \qquad (4)$$
$$= \frac{2.44\cdot10^{-3}}{\sqrt{\sigma}}\left[(1+j)\cdot\ln\left(\frac{51.6}{a\sqrt{\sigma}}\right) + (1-j)\frac{\pi}{4}\right] \text{ ohms at 60 Hz}$$

The ac grounding impedance of a single, electrically short vertical ground rod of radius, a, and length, L, is given by[5]

$$Z_{rod} = Z_{o_{rod}} \coth(\gamma_{rod}L) \simeq Z_{o_{rod}}/\gamma_{rod}L \text{ ohms} \qquad (5)$$
$$\simeq \frac{0.159}{\sigma L}\left[\ln\left(\frac{51.6}{a\sqrt{\sigma}}\right) - j\frac{\pi}{4}\right] \text{ ohms at 60 Hz}$$

where

$$a << L << \delta = \sqrt{\frac{2}{\omega\mu_0\sigma}} = \frac{64.9}{\sqrt{\sigma}} \text{ m = soil electrical skin depth} \qquad (6)$$

The ln term of Eq. 5 is usually of the order of 10, so that Z_{ac} is almost a pure resistance. For comparison, the dc resistance of the same ground rod is given by[4]

$$R_{rod} = \frac{0.159}{\sigma L}\left[\ln\left(\frac{4L}{a}\right) - 1\right] \text{ ohms} \qquad (7)$$

Equation 5 usually yields values of Z_{rod} larger than the values of R_{rod} obtained from Equation 7.

Multiple Vertical Anodes

The use of a single deep anode may be uneconomical in regions where the earth conductivity is low and buried rock strata make deep drilling difficult. In such cases, the use of multiple, short, distributed magnesium or zinc cathodic protection anodes may be indicated.[6]

A. For vertical anodes grouped together in a distinct bed (arranged on a straight line or circle) with the spacing between the rods equal to the length of the rods, the net ac grounding impedance is approximated by the following table (established for dc resistance).[4]

No. of Rods in Bed	Approximate Net ac Grounding Z
1	Z_{rod}
2	$0.58 \times Z_{rod}$
4	$0.36 \times Z_{rod}$
8	$0.20 \times Z_{rod}$
10	$0.16 \times Z_{rod}$
20	$0.09 \times Z_{rod}$
50	$0.04 \times Z_{rod}$

B. For vertical anodes distributed uniformly along a short (< 300 m) stretch of a buried pipeline, the ac grounding impedance is simply the grounding impedance of one anode divided by the total number of anodes.

C. For vertical anodes distributed uniformly along a lengthy (> 3 km) stretch of buried pipeline, Eq. 1b does not precisely describe the mitigation effect. Wave propagation effects within the grounded section must be taken into account. The value of the propagation constant, γ_m, of the pipeline section with anodes is estimated as

$$\gamma_m \simeq \gamma \sqrt{\frac{Y + Y_m}{Y}} \tag{8a}$$

where γ and Y are the propagation constant and admittance per km to remote earth, respectively, of the pipeline section before mitigation, and Y_m is the mitigating admittance per km provided by the distributed anodes. The reduction voltage is estimated as

$$\% \text{ reduction} \simeq 100 \left(1 - \left|\frac{\gamma}{\gamma_m}\right|\right) \tag{8b}$$

$$\simeq 100 \left(1 - \frac{1}{\sqrt{1 + \frac{Y_m}{Y}}}\right)$$

Equation 8b indicates that appreciable mitigation is obtained for this case only if the net mitigating admittance per km is much greater than Y, which is of the order of 0.1 mhos/km for a typical, moderately well insulated, buried pipeline.

Horizontal Conductors

A horizontal ground wire and its surrounding earth form a lossy transmission line characterized by the propagation factor, γ_{wire}, and the characteristic impedance, $Z_{o,wire}$. The ac grounding impedance, Z_{wire}, is simply the input impedance of this lossy transmission line. It is incorrect to assume that Z_{wire} is equal to the dc grounding resistance, R_{wire}. As will be shown below, the transmission line characteristics of a horizontal grounding wire significantly affect its performance.

Further, horizontal ground conductors can be subject to the same longitudinal driving electric field generated by the adjacent power line as the pipeline is exposed to. Therefore, ground wires can develop appreciable terminal voltages which must be accounted for in computations of the expected mitigation. Additional factors involve the effects of resistive and inductive coupling between long ground wires and the nearby pipeline. All of these factors are highly dependent upon the specific orientation of the ground wire relative to the power line and the pipeline. Reference will be made to Figure 3, which shows four possible types of horizontal ground wire installations, and to Figure 4, which shows the electrical equivalent circuit for each type of installation.*

Ground Wire Perpendicular to the Pipeline. This ground wire configuration, denoted as A in Figure 3, is the simplest to analyze because the perpendicular configuration serves to minimize inductive and conductive coupling between the wire, pipeline, and power line. In this configuration, the wire acts only as the grounding impedance, Z_{wire}, for the pipeline, as shown in Figure 4b. The overall mitigation effect is computed in three steps.

1. Determine the propagation constant, γ_{wire}, and characteristic impedance, $Z_{o_{wire}}$, of the ground wire. This may be done simply by applying the TI-59 calculator program "WIRE" which is documented in Reference 2. This program is suitable for wires of arbitrary electrical conductivity and permeability, and diameters up to one inch, for the full range of possible earth resistivities. The program achieves this degree of generality by solving Sunde's propagation-constant transcendental equation[4] for the case

$$Y_i = \infty \tag{9a}$$

and

$$Z_i = \frac{1}{\pi a^2 \sigma}\left[1 + \frac{1}{48}\left(\frac{a}{\delta}\right)^2\right] \tag{9b}$$

$$+ j\frac{\omega\mu}{8\pi} \quad \text{ohms/meter}$$

where a is the wire radius, and δ = wire skin depth = $(\pi\sigma f\mu)^{-1/2}$.

*The design procedures for the different types of mitigation wires considered here were developed from field tests made in December 1977 on the Southern California Gas Company Line 235 extending from Needles to Newberry, California.

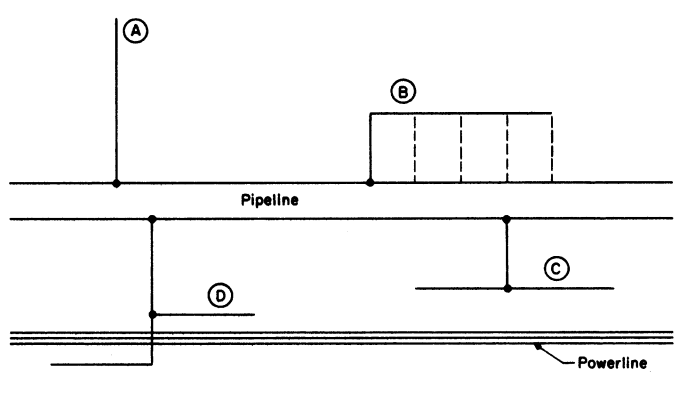
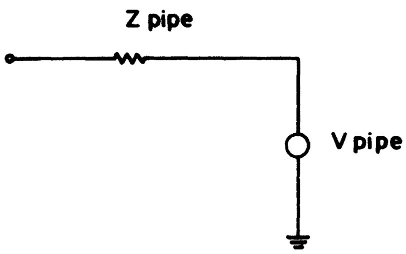
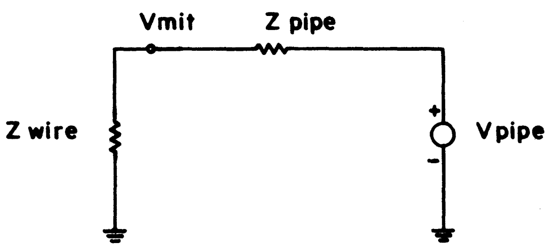


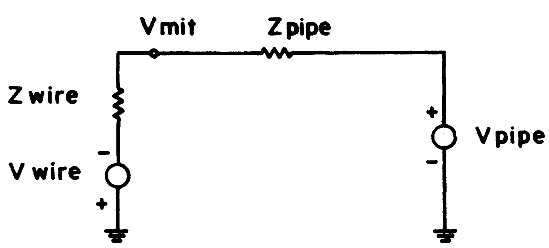
Figure 3 TYPES OF HORIZONTAL GROUND CONDUCTOR INSTALLATIONS



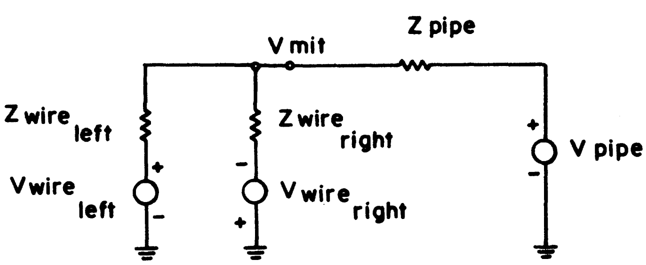
(a) Pipeline alone at observation point



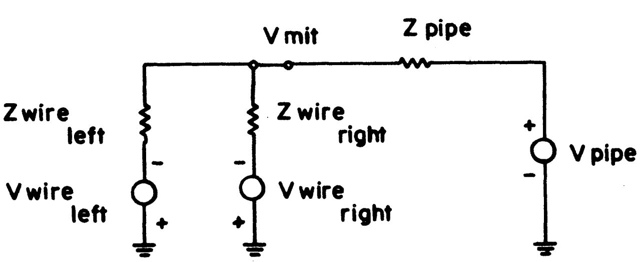
(b) With Mitigation wire "A"



(c) With Mitigation wire "B"



(d) With Mitigation wire "C"



(e) With Mitigation wire "D"

Figure 4 HORIZONTAL GROUND WIRE EQUIVALENT CIRCUITS

2. Determine the wire's ac grounding impedance, Z_{wire}. This may be done by applying the calculator program "THEVENIN", which is documented in Reference 2, to the data obtained in Step 1. This program is suitable for wires of arbitrary length and having arbitrary far-end impedance loads. The program achieves this degree of generality by solving the impedance-transformation equation of an electrical transmission line (Equation 11c of Reference 1).

3. Determine the unknown node voltage, V_{mit}, of Figure 4b. This may be done by applying the calculator program "NODE", which is documented in Reference 2, to the data Z_{wire}, V_{pipe}, and Z_{pipe}. This program allows computation of the common-node voltage and loop currents for up to three Thevenin equivalent circuits connected at a common node. V_{mit} is the value of the pipeline voltage after connection of the horizontal ground wire.

Figure 5 illustrates the importance of accounting for the transmission line properties of a ground wire when determining its mitigation effectiveness. Here, the straight line plots the dc resistance of an experimental wire installed at the Mojave test site, as computed using the most common grounding formula,

$$R = \frac{\rho}{\pi \ell}\left(\ln \frac{2\ell}{a} - 1\right) \text{ ohms} \tag{10}$$

where ρ = ground resistivity; ℓ = length of wire; and a = radius of wire. The curve plots the values of Z_{wire}, obtained using the calculator programs "WIRE" and "THEVENIN" discussed above. Finally the solid squares represent values of grounding impedance actually measured during the field test. It is seen that the experimental results agree extremely well with the results of the transmission line approach of the calculator programs, which predicts a leveling off of the grounding impedance at $Z_{o,wire}$ as the wire length exceeds $1/\text{Real}(\gamma_{wire})$. Hence, for a given grounding installation, there is an optimum length (in the vicinity of the knee of the curve) where the mitigation efficiency/cost ratio is greatest. Thus, indiscriminately lengthening a perpendicular ground wire may not necessarily be cost effective. This is in sharp contrast to

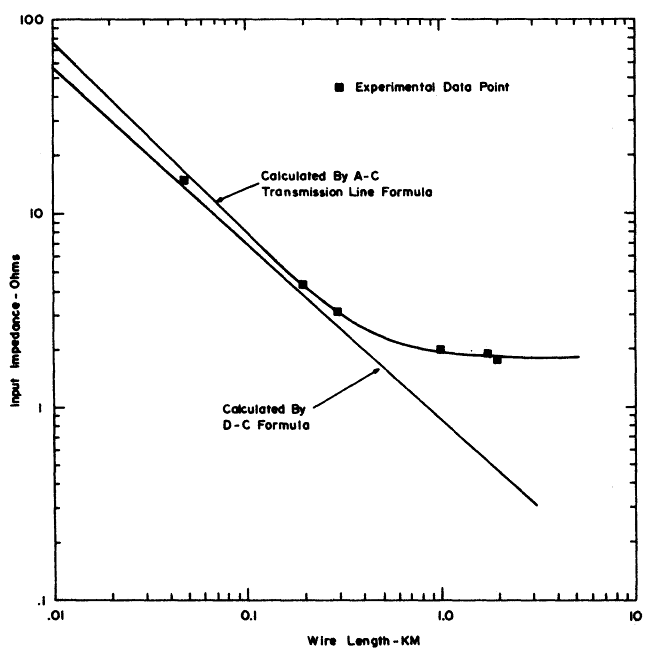


Figure 5 GROUNDING IMPEDANCE OF HORIZONTAL WIRE

results implied by the dc grounding resistance formula, which is evidently useful only for small-to-moderate conductor lengths.

End-Connected Parallel Ground Wire. This ground wire configuration, denoted as B in Figure 3, requires additional analysis steps to account for the effects of voltage build-up on the ground wire due to its parallelism with the power line and mutual coupling between the pipeline and the ground wire. In this configuration, the wire acts as both the grounding impedance, Z_{wire}, and the voltage source, V_{wire}, as shown in Figure 4c. The overall mitigation effect is computed in six steps:

1. Determine the Carson mutual impedances between the power line phase conductors and each passive multiple-grounded conductor sharing the right-of-way, including the pipeline to be mitigated and the ground wire. Repeat the procedure to determine the mutual impedances between all passive, multiple-grounded conductors on the right-of-way. This may be done by applying the calculator program "CARSON" which is documented in Reference 2. This program applies the Dommel algorithm[7] to obtain Carson mutual impedances to better than 0.1% accuracy, regardless of earth resistivity, conductor configuration (either aerial or buried, and conductor separation.

2. Determine the maximum currents within the pipeline to be mitigated and other passive conductors of the right-of-way under the influence of the power line, the ground wire, and each other. This may be done by applying the calculator program "CURRENTS" which is documented in Reference 2. This program solves the set of complex-valued simultaneous equations describing the interactions between each long, multiply-grounded conductor of the right-of-way.

3. Determine the longitudinal driving electric field at the ground wire location. This may be done by multiplying the ground wire current, determined in Step 2, by the ground-wire series self-impedance, Z_i, of Equation 9b.

4. Determine the propagation constant and characteristic impedance of the ground wire by applying the calculator program "WIRE".

5. Determine the Thevenin equivalent circuit, V_{wire} and Z_{wire}, of the ground wire by applying the calculator program "THEVENIN" to the data obtained in Steps 3 and 4.

6. Determine the final mitigated voltage, V_{mit} of Figure 4c, by applying the calculator program "NODE" to the data V_{wire}, Z_{wire}, V_{pipe}, and Z_{pipe}.

For best results with this ground wire configuration, the phase of V_{wire} should equal that of V_{pipe} + 180° in order to achieve a voltage cancellation effect at V_{mit}. This is illustrated in Figure 4c by the choice of signs of the V_{wire} and V_{pipe} voltage sources. In the ideal case, $V_{wire}/Z_{wire} = -V_{pipe}/Z_{pipe}$, so that $V_{mit} = 0$. The wire impedance and voltage properties can be adjusted by choosing the wire length and separation from the power line. However, this usually does not give enough adjustment range to attain the ideal case. Additional adjustment can be realized by either a continuous or lumped inductive loading of the ground wire to alter its transmission line characteristics. Program "WIRE" is structured to permit data input of the average added inductive reactance per kilometer due to inductive loading to allow rapid calculation of the new wire propagation constant and characteristic impedance. Then, program "THEVENIN" can be used to compute the new V_{wire}/Z_{wire} ratio. The chief effect of connecting a long, parallel ground wire and an adjacent pipeline with multiple ties (indicated by the dashed lines of the "B" configuration of Figure 3) is the reduction of the effective V_{wire} and Z_{wire}, in a manner discussed below. This can be useful under conditions where voltage cancellation at V_{mit} is not deemed important. If such ties are used, they should be spaced no closer than 1/Real (γ_{wire}) for maximum effect at minimum cost.

Center-Connected Parallel Ground Wire. This ground wire configuration, denoted as C in Figure 3, is aimed at achieving minimum values of V_{wire} and Z_{wire} for any given length of wire. Its performance is most easily understood by examining the equivalent mitigation circuit shown in Figure 4d. From this figure, it is seen that the center connection causes the effective V_{wire} to equal zero because of the bucking effect of $V_{wire,left}$ and $V_{wire,right}$. Further, the effective Z_{wire} is seen to equal the parallel combination of $Z_{wire,left}$, and $Z_{wire,right}$. This value is always less than the grounding impedance for the wire when used in an end-connected manner for mitigation because of the leveling off of the impedance curve with length. (In effect, two short wires give a lower grounding impedance than one long wire having the combined length of the short wires).

The mitigation effect of this ground wire configuration can be computed simply by applying program "WIRE" to determine γ_{wire} and $Z_{o,wire}$; then applying "THEVENIN" to determine $Z_{wire,left}$ and $Z_{wire,right}$; and finally applying "NODE". In applying "NODE", the voltage sources $V_{wire,left}$ and $V_{wire,right}$ need not be known specifically because of their self-cancelling effect, so that a value of zero volts can be assumed for both. Thus, in many respects, calculation of the mitigation effectiveness of a center -connected parallel ground wire is the same as for the perpendicular ground wire.

Back-to-Back Parallel Ground Wire.* This ground wire configuration, denoted as D in Figure 3, is aimed at achieving simultaneously a maximum value of V_{wire} and a minimum value of Z_{wire} for a given length of wire. This is made possible by moving one ground wire leg to the opposite side of a horizontal configuration power line, so that the fields driving the two legs are equal in magnitude but 180° out of phase. Thus, as shown in Figure 4e, $V_{wire,left}$ and $V_{wire,right}$ reinforce each other instead of bucking, allowing a maximum cancellation effect at V_{mit}. Similar to the center-connected parallel ground wire, the effective Z_{wire} is seen to equal the parallel combination of $Z_{wire,left}$ and $Z_{wire,right}$.

The mitigation effect of this ground wire configuration can be computed by treating the left and right halves of the ground wire as two distinct end-connected parallel ground wires, and combining the results for $V_{wire,left}$, $Z_{wire,left}$, and $V_{wire,right}$ using program "NODE".

Complete Pipeline Mitigation

The previous discussions were directed toward considering each mitigation wire individually, and, hence, mitigation at a single point on the pipeline. In general, due to multiple physical or electrical discon-

*Best applicability for mitigation of the effects of power lines having a combination of configurations and phase sequences which yield an electric field phase difference of approximately 180° from one side of the line to the other.

tinuities along the right-of-way, a pipeline will develop a number of induced voltage peaks. Installation of a single mitigation wire may reduce the local pipeline voltages but leave the other peaks unaffected. In fact, slight increases of the pipeline voltage may be caused a few miles from the grounding point due to the discontinuity of the corridor geometry introduced by the ground wire itself. However, as discussed below, experimental results show that complete pipeline mitigation is possible by mitigating successive voltage peaks individually.

An assessment of the possibility of complete pipeline mitigation, obtained by direct measurements at the Mojave test site, is summarized in Figure 6. Figure 6a shows the mitigation obtained by installing a 2.25 km (7400 ft) total length, back-to-back parallel ground wire at Milepost 101.7. The wire was stranded aluminum, 9.4 mm (0.37 in.) diameter, and buried at a depth of 30 cm (1 ft) along two paths parallel to the power line and 18.3 m (60 ft) to either side of the power line center phase. From the figure, it is seen that the original voltage peak at Milepost 101.7 of nearly 50 volts was reduced by about 90% by installing this ground wire, representing a virtually complete mitigation. In fact, some mitigation was recorded at Milepost 89. However, although not necessarily serious, an increase in the induced voltage was measured in the region between the two peaks. This is reminiscent of the balloon effect -- i.e., "squeeze" the pipeline voltage at one point and it enlarges somewhat at other points.

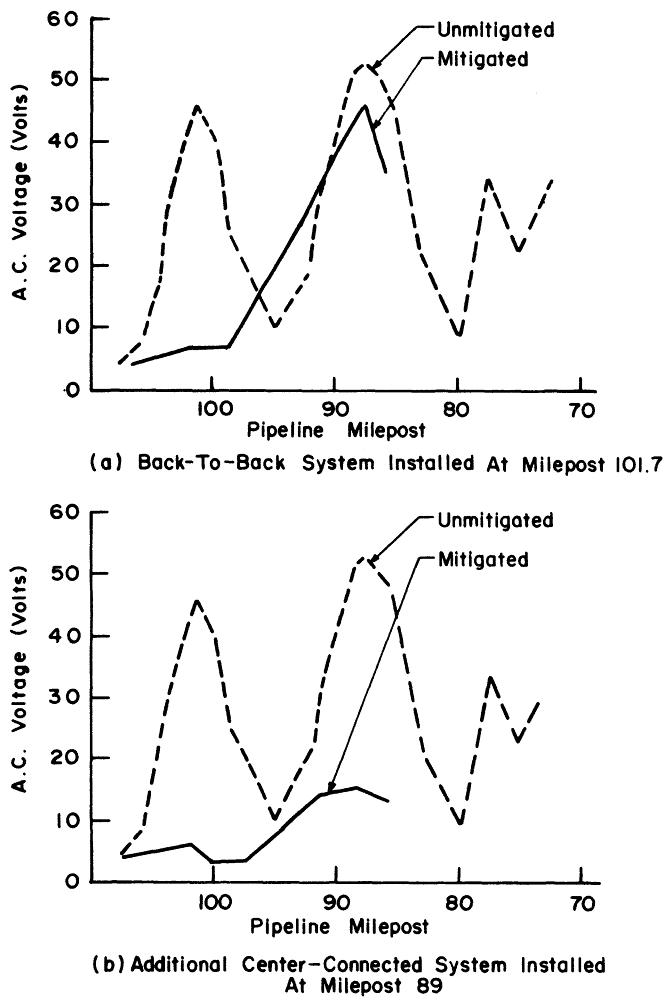


Figure 6 EXPERIMENTAL MITIGATION OF THE MOJAVE PIPELINE

Figure 6b shows the extra mitigation obtained by installing an additional 0.8 km (2600 ft) total length, center-connected parallel ground wire at Milepost 89. This wire was solid aluminum, 3.0 mm (0.12 in.) diameter, and buried at a depth of 5 cm (2 in.) along a path parallel to the power line and 30 m (100 ft) from the center phase. From the figure, it is seen that the combined mitigation system at Mileposts 101.7 and 89 succeeded in pipeline voltage reduction not only at the peaks, but at intermediate locations as well. Hence, it has been demonstrated that installation of properly-designed grounding systems at points of corridor discontinuities can mitigate long lengths of pipeline.

Additional Grounding Methods

Bonding to Tower Footings. At times, it may seem convenient to achieve the grounding of a pipeline by connecting it to nearby ac power line tower grounding systems. However, this procedure is not recommended because of personnel and pipeline hazards which may result during fault conditions of the power line.

Connection of an above-ground or buried pipeline to a power line ground can result in the elevation of the pipeline potential to dangerous levels during power line fault conditions. The flow of fault current to ground through the affected power line towers results in the tower footings being placed at a high potential with respect to remote earth, and the application of this potential to any metal structure that is connected to the tower footings. This potential can range above 1000 volts for representative values of earth resistivity and fault current magnitude. This high voltage can be applied to the entirety of an above-ground pipeline connected to a tower footing, endangering pipeline workers or other personnel contacting the pipe metal during the fault. The resulting hazards can be mitigated only by providing ground mats, as discussed in the following subsection, at each location of possible human contact with the pipeline.

Connection of buried pipeline sections to a power line ground can also result in puncture of either the pipeline coating or steel during power line fault conditions. The flow of fault current to remote earth is channeled through the buried pipeline, which acts as a virtual counterpoise for the powerline because of its bonding to the tower footings. At points somewhat removed from the affected towers, the fault current carried by the pipeline can jump off to the surrounding low potential earth. Fault current jump-off points are marked by pipeline coating punctures and possibly even pipeline steel punctures (if the current densities are high enough). Mitigation of this hazard is possible only by avoiding any direct connections between the buried pipeline and the power line grounds.

Ground Mats. Mitigation of earth current and inductive coupling to a pipeline under construction can be realized easily and effectively by installing ground mats at all worker locations. These mats, bonded to the pipe, serve to reduce touch and step voltages in areas where persons can come in contact with the pipe. These mats can be portable steel mesh grids laid on the ground at welding positions, and connected with a cable to the pipe. At permanent exposed pipeline appurtenances, such as valves, metallic vents, and corrosion control test points, ground mats can be constructed of strip galvanic anode material buried in a spiral pattern just below the surface and connected to the pipeline electrically. (By using galvanic anode material, such mats reinforce any cathodic protection systems on the pipeline rather than contribute to the pipeline corrosion problem, as would be the case if copper grounding were used.)

With mats so installed and connected, the earth contacted by the mat is at virtually the same potential as the pipe. In this way, a worker touching the pipe is assured that the potential appearing between his hands and feet is only that which is developed across the metal of the mat, regardless of the mode of ac interference affecting the pipe. This effective shunting of the worker by a metal conductor provides protection for very severe cases of coupling, such as occur during lightning strikes and faults. It is especially useful for pipes subject to simultaneous interference by electrostatic, electromagnetic, and earth-current coupling.

Ground mats should be designed large enough to cover the entire area on which persons can stand while either touching the pipe or contacting it with metal tools or equipment. Each mat should be bonded to the pipe at more than one point to provide protection against mechanical or electrical failure of one bond. Step potentials at the edges of each mat can be mitigated by providing a layer of clean, well-drained gravel beneath the mat and extending the gravel beyond the perimeter of the mat. This serves to reduce the conductivity of the material beneath the mat, and to provide a buffer zone between the earth and the ground mat.

ADDITIONAL PIPELINE MITIGATION METHODS

Use of Insulating Devices

Risers and Vent Pipes. Insulating materials may be used in place of steel in some cases where the danger of high ac pipeline potentials is known to be a factor. As an example, vent pipes accessible to the public may be constructed of plastic to eliminate the possibility of electric shock should a high potential exist on the casing pipe. Riser conduit may be plastic; junction boxes may be plastic or plastic coated; terminal blocks may be "dead front", requiring the insertion of contact making plugs in order to connect leads to the carrier pipe.

Joints. Insulating joints are used on pipelines to electrically separate sections of the line from terminal facilities and pumping systems. They are also used to divide the line into sections so that the development of contacts with other structures or the failure of cathodic protection facilities are confined to a single section. These sections can be as long as several miles.

In the past, insulating joints have been used to attempt mitigation of ac coupling effects on pipelines by reduction of the electrical length of the pipelines exposed to the coupling source. Indeed, the use of insulating joints exclusively to systematically bound pipeline voltages has been investigated.[8] However, a given pipeline situation must be analyzed carefully because the introduction of insulating joints may worsen, rather than mitigate, the interference problem, i.e., buried pipeline sections longer than $2/\text{Real}(\gamma)\text{pipe}$ should develop exponential voltage peaks at the locations of the insulators. Thus, while a long pipeline might have only two voltage peaks (at its ends) the insertion of an insulator at the midpoint of the pipeline could cause a third voltage peak to appear at the location of the new insulator.

To avoid the generation of induced voltage peaks at pipeline insulators, a low-impedance polarization cell should be connected across each insulator. In this way, direct current required for cathodic protection could be confined to the desired pipeline section, but no pipeline discontinuities would be presented to the 60 Hz electromagnetic field and, thus, no spurious induced voltage peaks would be generated. Installation of polarization cells at each insulator would have the additional advantage of providing protection from insulator flashover during fault conditions of the power line. Additional insulator protection can be provided by installing lightning arrestors with a threshold of no more than 150 volts across each insulator-polarization cell parallel combination.

Pipeline Extensions

The appearance of exponential induced voltage peaks at the ends of a parallel, buried pipeline (as discussed in References 9 and 10) suggests that the pipeline potential distribution can be altered for mitigation purposes by simply extending the pipe. In this way, the locations of the voltage peaks might be shifted from an accessible, or functional, section to an inaccessible, or non-functional section. The induced potentials at the original endpoints of the pipe section could be reduced by as much as 63% for each extension of the pipe by $1/\text{Real}(\gamma_{pipe})$ beyond the original end points. While there are obvious limitations to this technique in practice, it is conceivable that it could be preferred in some cases where mitigation is required on a large, in-service line.

CONCLUSIONS

This paper has presented a mitigation approach for the voltages induced on gas transmission pipelines by 60 Hz ac power lines sharing a joint right-of-way. This mitigation approach involves the optimum deployment of pipeline grounding systems, and is based upon the distributed-source analysis of References 1 and 2. It is most usefully applied after installation of all of the utilities of a joint-use corridor when the exact positions and magnitudes of the pipeline voltage peaks can be measured.

The paper treats as part of this approach vertical anodes and horizontal conductors of several types. Experimental results are summarized which indicate that complete pipeline mitigation is possible using this approach. Additional pipeline mitigation measures such as the uses of insulating devices and pipeline extensions are reviewed.

ACKNOWLEDGEMENT

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Combined Discussion[1, 2]

Adrian L. Verhiel (Trans Mountain Pipe Line Co., Ltd., Vancouver, B.C.): Both papers are excellent contributions to assist pipeline as well as electrical transmission line design and operating personnel to mitigate the ever more serious becoming pipe line induced potential problems.

It is recommended, to eliminate the use of transmission line phase transpositions, in order to avoid high points along the pipeline in induced potentials.

In operating electrical transmission line systems, it is very difficult and extremely costly to eliminate existing in-line transpositions. In new systems, the optimized phase sequencing resulting in minimum pipeline induced potentials can be achieved by proper transmission line terminal design. In existing terminals, re-arrangement of the station bus work to achieve the proper phase roll may be possible. The resultant induced potential peak is inherent due to the transmission line termination facility. It has been assumed, of course, that in-line transpositions are not required for inductive coordination purposes with communication facilities and that phase-to-phase impedances are balanced. No mention is made under optimized phase sequencing of the level of unbalance in the phase currents that can be tolerated and still maintain a reasonable reduction in induced potential. Some guidelines on this would be helpful.

In the practical application of horizontal back-to-back parallel grounding, great care must be exercised in order that sufficiently large enough electrical clearances are being maintained between the grounding facility of the pipeline and the grounding facilities including tower foundations of the electrical transmission line. The required clearance being dictated by maximum possible gradient potentials and available short-circuit currents. This is extremely important for those facilities equipped with a counterpoise which can be laid inadvertently close to the pipeline and its grounding network.

The use of ground mats is mentioned as a safety precaution during construction or operation of a pipeline, while working on the pipeline near an electrical transmission line. A ground mat, by definition, must have a resistance to ground, of less than 1 ohm. This is not the intent here. The potential difference between the pipeline, its appurtenances, working equipment and surrounding ground, etc., has to be minimized, thus, gradient control mats are required and reference should be made to that, not ground mats.

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J. E. Drakoş and **A. Akhtar** (British Columbia Hydro and Power Authority, Vancouver, B.C.): Referring to the section "Bonding to Tower Footings", we agree with the authors in not recommending direct connections between the pipeline and power line tower. However, simply avoiding any such direct connections may not be enough to prevent energization of the pipeline or damage to the pipeline coating or the pipeline steel itself. B. C. Hydro has recently completed a research project entitled "Study of Problems Associated with Pipelines Occupying Joint-Use Corridors with AC Transmission Lines" under contract with the Canadian Electrical Association. One part of this study involved field tests in which fault current was injected into the ground near test sections of pipe. The field tests indicated that substantial current could flow from a tower footing to a nearby pipeline because of partial or total electrical breakdown of the soil. In some cases this current flow resulted in damage to the pipeline coating and to the pipeline steel. We concluded that the damage to the coating was inconsequential as the area of damage was small and would require an insignificant amount of additional cathodic protection current. However, the damage to the steel consisted of small craters surrounded by a heat affected zone. The nature of this damage is such that cracks can form and in some cases were observed in the heat affected zone. The cracks can propagate only under very extreme conditions of high fault current, small separation distance between pipeline and tower and a pipeline of steel of low fracture toughness. Low fracture toughness usually occurs only at very low temperatures. Burn-through of the pipe can occur if the fault current is sufficiently high and separation distance between the tower and the pipeline is small. There are recorded cases of burn through.

[1] A. Taflove, M. Genge, and J. Dabkowski, Mitigation of Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling, Pt. I: Design of Joint Rights-of-Way, this issue pp. 1806-1813,

[2] J. Dabkowski and A. Taflove, Mitigation of Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling, Pt. II: Pipeline Grounding Methods, this issue, pp. 1814-1823.

Reference

[1] Final report on Research Project 75-02, "Study of Problems Associated with Pipelines Occupying Joint-Use Corridors with AC Transmission Lines," January, 1979, Volume I, Canadian Electrical Association.

Manuscript received March 1, 1979.

Luke Yu (The R. M. Parsons Co., Pasadena, CA): The authors are to be commended for their valuable contribution presented in their papers.

The following points are listed for the authors' consideration:

1. Should Eq. (1b) be read as
   $\%\ \text{reduction} = 100 \left| \frac{Z\theta}{Zm+Z\theta} \right|$ instead?
   (Because $Z\theta$ and Zm may not be in phase.)
2. In Eq. (2) of Part II, it appears that $Z\theta/Zm$ has a significant effect on the value of shock current produced as Zw is assumed to be 500 ohms minimum theoretically. (Ref. 3 of Part I). Would the authors explain the reason of suggesting $Zm \approx 2$ ohms?
3. How should the auxiliary grounded shield wire as described in Part I, be physically grounded with respect to the grounding set-up of the nearby electrical power transmission line?
4. Would the authors elaborate on the electrical induction of pipelines due to various fault conditions of a nearby power transmission line?

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R. E. Aker (Southern California Edison Co., Rosemead, CA): The authors are commended for their contributions to the distributed source analysis approach to the mitigation of induced voltages on buried pipelines.

Two specific horizontal ground wire configurations are described on Page 6, Part II, where an assessment of a complete pipeline mitigation is summarized for two pipeline-power line geometries. Various procedures could be used to size these wires and align them along the joint-use corridor.

One such procedure which could be used to select an efficient and economical wire size for a particular mitigation configuration would be as follows:

1. Determine the propagation constant, γ_{wire}, and characteristic impedance, Zo_{wire}, for various practical ground wire diameters.
2. Determine the wire's length from the formula $\ell = 1/\mathrm{Re}(\gamma_{wire})$ for each wire diameter case. This length insures that each wire leg of the mitigation configuration has the minimum grounding impedance, Z_{wire}, equal to that leg's characteristic impedance.
3. Determine the Thevenin equivalent circuit, V_{wire} and Z_{wire}, of each ground wire leg.
4. Determine the final mitigated voltage, V_{mit}, with all of the wire legs of the mitigation configuration connected to the pipeline, for each wire diameter case.
5. Select the optimum wire diameter and length which produces a minimum mitigated voltage.
6. Select the wire separation distance from the power line centerline to an alignment along which the magnetic field is a maximum, thereby inducing the largest ground wire voltage.
7. Select a burial depth for each wire leg deep enough to shield it from the power line's electrostatic field as well as protect it from ground surface disturbances.

With this procedure, the selection of an efficient and economical wire size for any mitigation configuration requires the successive calculation of the mitigated voltages and wire lengths as functions of the ground wire diameter. Then, the optimum wire diameter and length would be selected to produce a minimum mitigated voltage.

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Allen Taflove and John Dabkowski: The authors wish to express their appreciation to the discussors for their attentive review and suggestions. The following remarks are directed toward specific comments of the discussors.

Discussion of R. E. Aker. The discussor has suggested a possible procedure for selecting an efficient and economical wire size for a particular mitigation configuration. Step No. 2 of his procedure is somewhat misleading, however. The choice of a ground wire length, ℓ, equal to $1/\mathrm{Re}(\gamma_{wire})$, does *not* insure that the minimum grounding impedance has been realized. As shown in Fig. 5 of Part II of the paper, the minimum grounding impedance is realized only for wire lengths in excess of $1/\mathrm{Re}(\gamma_{wire})$, where the grounding impedance curve levels off at $Z_{o_{wire}}$. All that can be said is that a choice of $\ell = 1/\mathrm{Re}(\gamma_{wire})$ represents an optimum length for the best mitigation efficiency/cost ratio for ground wires perpendicular to the ac power line. However, greater lengths may possibly be of use for ground wires parallel to the ac transmission line. Here, the increased voltage pickup due to greater length of the ground wire can be used to buck out some of the pipeline voltage at the desired connection point. The wire placement for maximum voltage pickup will be at a location where the longitudinal electric field is a maximum.

It should be emphasized that a number of ground wire parameters (that can be selected by the user) interact in varying degrees to determine overall mitigation effectiveness. These parameters include ground wire length, diameter, conductivity, permeability, orientation and distance from the power line, and burial depth. Thus, it is strongly advised to perform multiple iterations of the Thevenin analysis discussed in this paper to arrive at the most cost-effective ground wire configuration for a particular pipeline.

Discussion of L. Yu. Comments Nos. 1 and 2 by the discussor indicate that some clarification of Equations 1a and 1b of Part II is needed. First, the authors do *not* suggest that $Z_m \simeq 2$ ohms is sufficient for mitigation of the shock current, I_w, through a pipeline worker. Indeed, it is clearly stated in the sentence after Equation 2 that: "Mitigation of I_w requires values of Z_m significantly *less* than Z_θ." This statement is the intent of Equation 1a, which, in addition, specifies the usual range of Z_θ, the pipeline Thevenin source impedance, as in the order of 2 ohms.

Equation 1b is valid for this desirable grounding condition, namely, $|Z_m| < |Z_\theta|$, and based on the definition

$$\% \text{ Reduction} = 100\,(1 - |V_m/V|).$$

The authors believe this to be an appropriate definition since *voltage magnitude ratios only* are of concern here. The expression given by the discussor is equivalent to the definition

$$\% \text{ Reduction} = 100\,|1 - (V_m/V)|$$

which is not equivalent to the above definition. The discussor's definition can lead to a computed mitigation where in fact, there is none, or vice versa.

In Part I, the auxiliary grounded shield wire is an integral part of the ac power line in that it is strung between the transmission towers and grounded to them. It is simply an addition to the set of shield wires which may already exist to protect the ac power line. However, the position of the auxiliary grounded wire is chosen to minimize the induced longitudinal electric field (and not to deter lightning strokes). Thus, it may be optimally placed below the phase conductors as well as above them, depending upon the circumstances.

Mitigation of ground fault phenomena is not within the scope of this paper, which is limited to the mitigation of the effects of steady-state 60 Hz ac inductive coupling. Additional effects to be accounted for during transient ground faults include: 1) direct earth current flow from the affected power line towers to the adjacent pipeline; 2) severe power line unbalance causing heightened zero-phase 60 Hz ac inductive coupling; and 3) high-frequency inductive coupling due to spike-like power line current waveforms.

Discussion of J. E. Drakos and A. Akhtar. The additional information provided by the discussors is important. It indicates that direct earth current flow from power line towers to an adjacent pipeline can be substantial during fault conditions even if there is no direct connection between the two structures. Two mitigation approaches seem possible. First, increase the distance between the pipeline and the power line to the maximum allowed, given the constraints of the joint right-of-way. Second, provide an excellent counterpoise ground for the ac power line so that most of the fault current is channeled through the counterpoise rather than the adjacent pipeline. Prediction of the severity of direct earth current coupling seems difficult due to the presence of partial or total electrical breakdown of the soil, which would depend upon a number of variables including the fault magnitude and the soil moisture at the time of the fault.

Discussion of A. L. Verhiel. In optimally phasing an ac transmission line for minimum inductive coupling, it is assumed that up to a 5% unbalance of the phase currents can be tolerated and still maintain a useful reduction in pipeline voltages.

The authors agree that substantial clearance should be provided between any horizontal-wire pipeline grounding facility and the grounding facilities of the ac power line. As pointed out by the previous discussors (J. E. Drakos and A. Akhtar), substantial earth current can flow between such facilities under fault conditions due to earth electrical breakdown effects. As stated previously, a second mitigation approach is to increase the quality of the power line counterpoise ground system so as to shunt most of the fault current away from any adjacent metal structures.

A semantics problem seems to have arisen in the paper's usage of the term "ground mat" as opposed to the discussor's preferred term "gradient control mat." The authors' definition of ground mat *conforms* to that of NACE (National Association of Corrosion Engineers) Standard RP-01-77, "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems." The authors have not been aware of the particular distinction made by the discussor.

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