IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 3 May/June 1979

PREDICTION METHOD FOR BURIED PIPELINE VOLTAGES DUE TO 60 Hz AC INDUCTIVE COUPLING

PART I - ANALYSIS

Allen Taflove, Member, IEEE

John Dabkowski, Non-Member

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

Abstract - The voltages induced on gas transmission pipelines by 60 Hz ac power transmission lines sharing a joint right-of-way are predicted using electrical transmission line theory. Thevenin equivalent circuits for pipeline sections are developed which allow the decomposition of complex pipeline-power line geometries. Programmable hand calculator techniques are used to determine inducing fields, pipeline characteristics, and Thevenin circuits.

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 presents the prediction method developed by IITRI for the induced voltages on buried pipe lines. The approach utilizes electrical transmission line theory to locate and quantize pipeline voltage peaks using a programmable hand calculator. Complex ac power line features such as multiple circuits, shield wires, and phase transpositions can be modeled in a systematic way. The approach developed has proven to be more accurate than existing methods in field tests, and is applicable to realistic pipeline-ac power line corridors. The methodology and results of these field tests are discussed in Part II of this paper.

This paper first reviews available analytical methods for the prediction of inductive coupling to buried pipelines. Next, the basic elements of the new approach are presented. Equations and equivalent circuits are derived to estimate inductive coupling for the following cases of pipeline construction near an ac power transmission line:

1) parallel construction;
2) non-parallel construction;
3) combinations of parallel and non-parallel constructions and power line discontinuities.

The required numerical inputs to the equations and equivalent circuits are obtained using hand calculator programs developed by IITRI. The capabilities of these tools are briefly summarized in the last section of this paper.

F 78 698-3. A paper recommended and approved by the IEEE Insulated Conductors Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Summer Meeting, Los Angeles, CA, July 16-21, 1978. Manuscript submitted February 1, 1978; made available for printing May 3, 1978.

REVIEW OF AVAILABLE ANALYTICAL TECHNIQUES

For many years, concern was directed to coupling between overhead high voltage ac power lines and adjacent above-ground communication circuits. Equations presented originally by Westinghouse[1] have been used to predict the induced voltage per mile on an above-ground conductor due to single phase and three phase ac power lines. An equivalent approach[2] used Carson's series[3] to compute the mutual impedances between the power line conductors and the affected communications line. The International Telegraph and Telephone Consultative Committee (CCITT) has summarized available prediction and mitigation methods for induced voltages on above-ground conductors.[4]

One body of literature has attempted to apply the above-ground coupling equations directly to the case of the buried pipeline. Representative papers[5-10] determined the induced pipeline voltage in the following general way:

$$V_{max} = f(I,d)\cdot L \qquad (1)$$

where V_{max} is the maximum expected voltage; f is some function of power line current, I, and distance, d, from the pipeline; and L is the length of the pipeline. Uniformly, the values of pipeline voltage calculated using these methods are too high by a factor of about 10, as acknowledged by several of the workers.[5,10]

The application of the above-ground equations fails for the buried pipeline case simply because a buried pipeline differs electrically from an overhead conductor. A buried pipeline, either bare or wrapped in an electrically insulating coating, has a finite resistance to earth distributed over its entire length, whereas an overhead line has, at most, point grounds at large intervals. To describe the distributed interaction between a buried pipeline and its surrounding earth, factors such as pipeline diameter, coating conductivity, earth resistivity, depth of burial, and pipe longitudinal resistance and inductance must be taken into account.

A second body of literature has attempted to construct such a realistic model of inductive coupling to a buried pipeline. The analytical approach used in these references considers a buried pipeline as a lossy electrical transmission line with a distributed voltage source function due to electromagnetic coupling. However, available published work in this area[11-15] has evidently failed to achieve accurate methods simplified enough for widespread usage by the pipeline and power line communities.

THE DISTRIBUTED SOURCE ANALYSIS APPROACH

The analysis of this paper treats inductive coupling to arbitrary buried pipelines using a theory called the distributed source analysis.[15,16] Here, a pipeline and its surrounding earth form a lossy electrical transmission line characterized by the propagation constant, γ, and the characteristic impedance, Z_o. The inductive coupling effect of a nearby ac power line is included by defining a distributed voltage source function, $E_x(s)$, along the pipeline, where $E_x(s)$ is the longitudinal driving electric field parallel to the path of the pipeline.

As shown in Fig. 1, specific coupling problems are treated as special cases of the general distributed source theory. The general theory is first specialized with respect to the orientation of the pipeline section relative to the adjacent ac power line:

1) parallel case (pipeline section parallel to the ac power line);
2) non-parallel case (pipeline section at an angle to the ac power line).

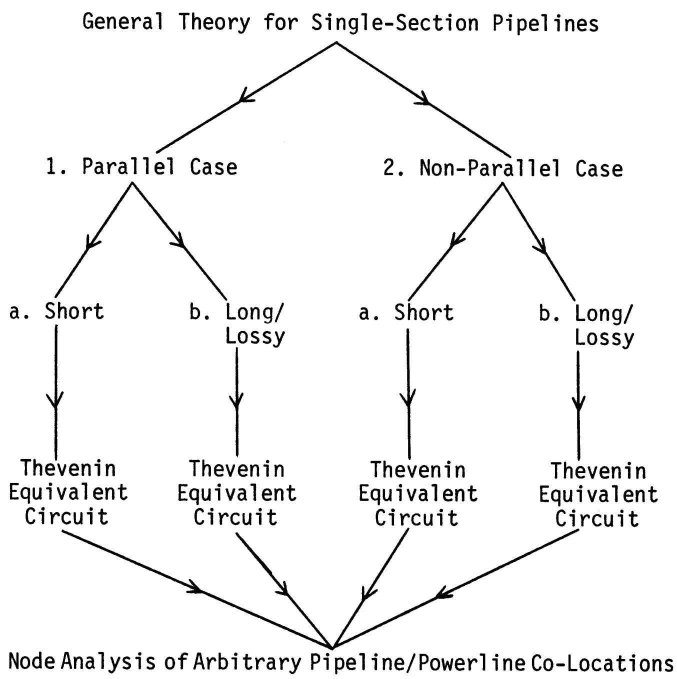


Fig. 1. Application of the Distributed Source Analysis

The theory is further specialized by grouping pipeline sections according to electrical length:

1a, 2a) Electrically short case

$$L < \frac{0.1}{|\gamma|} \simeq 300 \text{ m}$$

where L is the length of the pipeline section

1b, 2b) Electrically long-lossy case

$$L > \frac{2}{\text{Real }(\gamma)} \simeq 10 \text{ km}.$$

As shown later in this paper, the terminal behavior of pipeline sections of Classes 1a, 1b, 2a, and 2b can be described by simple Thevenin equivalent circuits. These circuits can be connected together to allow prediction of the inductive coupling to pipelines of arbitrary geometry and composed of several connected dissimilar sections

General Analysis

In this analysis, each pipeline length increment, dx, is assumed to have a source voltage increment, $E_x dx$, as shown in Fig. 2. E_x has the dimensions of electric field strength (volts/meter) and is called the longitudinal driving electric field. (E_x should not be confused with the transverse, or electrostatic field, due to ac power lines.) Except for the voltage source, Fig. 2 is identical to the elemental circuit for the usual electrical transmission line, with the same definitions of impedance per unit length, $Z = R + j\omega L$, and admittance per unit length, $Y = G + j\omega C$.

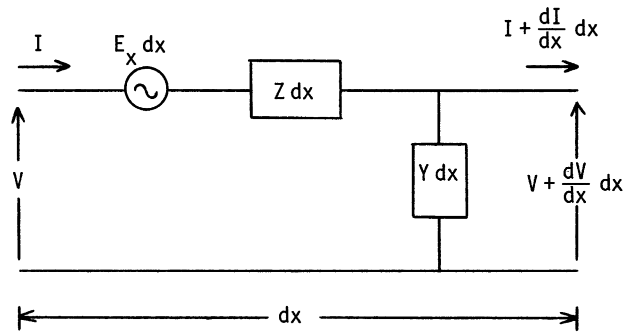


Fig. 2. Equivalent Elemental Pipeline Circuit

For harmonically varying signals ($e^{j\omega t}$), the differential equations for the voltage and current along the pipeline element of Fig. 2 are:

$$\frac{dV}{dx} = E_x - IZ \tag{2a}$$

$$\frac{dI}{dx} = -VY. \tag{2b}$$

Differentiation and substitution results in the following second-order differential equations:

$$\frac{d^2V}{dx^2} - \gamma^2 V = \frac{dE_x}{dx} \tag{3a}$$

$$\frac{d^2I}{dx^2} - \gamma^2 I = -YE_x \tag{3b}$$

where

γ = pipeline propagation constant

= $\sqrt{ZY}$ meters^{-1}.

Except for the terms containing E_x, Equations 2 and 3 are identical to those for the classical electrical transmission line. Assuming the terminating impedances Z_1 at $x = x_1$ and Z_2 at $x = x_2$ (for $x_2 > x_1$), the solutions to Equations 3a and 3b are

$$I(x) = \left[K_1 + P(x)\right]e^{-\gamma x} + \left[K_2 + Q(x)\right]e^{\gamma x} \text{ amps} \tag{4a}$$

$$V(x) = Z_o\left\{\left[K_1 + P(x)\right]e^{-\gamma x} - \left[K_2 + Q(x)\right]e^{\gamma x}\right\} \text{ volts} \tag{4b}$$

where

Z_o = pipeline characteristic impedance

= $\sqrt{Z/Y}$ ohms

$$P(x) = \frac{1}{2Z_o}\int_{x_1}^{x} e^{\gamma s}\, E_x(s)\, ds \qquad (5a)$$

$$Q(x) = \frac{1}{2Z_o}\int_{x}^{x_2} e^{-\gamma s}\, E_x(s)\, ds \qquad (5b)$$

$$K_1 = \rho_1 e^{\gamma x_1}\,\frac{\rho_2 P(x_2)e^{-\gamma x_2} - Q(x_1)e^{\gamma x_2}}{e^{\gamma(x_2-x_1)} - \rho_1\rho_2 e^{-\gamma(x_2-x_1)}} \qquad (6a)$$

$$K_2 = \rho_2 e^{-\gamma x_2}\,\frac{\rho_1 Q(x_1)e^{\gamma x_1} - P(x_2)e^{-\gamma x_1}}{e^{\gamma(x_2-x_1)} - \rho_1\rho_2 e^{-\gamma(x_2-x_1)}} \qquad (6b)$$

and ρ_1, ρ_2 are reflection coefficients given by:

$$\rho_1 = \frac{Z_1 - Z_o}{Z_1 + Z_o}; \qquad \rho_2 = \frac{Z_2 - Z_o}{Z_2 + Z_o} \qquad (7)$$

Using Equations 4-7, the analysis presented permits general treatment of inductive coupling to a buried pipeline having an arbitrary, but constant, γ and Z_0; arbitrary terminations Z_1 and Z_2; and arbitrary driving field $E_x(s)$. The analyses to follow will treat special cases of the general analysis. In doing so, certain special characteristics of inductive coupling to buried pipelines will become apparent. Further, the treatment of pipes having discontinuities of either γ, Z_0, or $E_x(s)$ will be discussed. Methods for computing γ, Z_o, and $E_x(s)$ are deferred to the end of this paper.

Application to the Parallel Pipeline With Arbitrary Terminations

In the following analysis, the driving field, $E_x(s)$, is assumed to equal E_0, a constant. This assumption is valid for buried pipelines parallel to electric power lines which continue beyond the region of parallelism. The pipeline is assumed to extend from x = 0 to x = L meters, as shown in Figure 3. At the end points, the pipeline is assumed to be connected to remote earth through the impedances, Z_1 and Z_2. These terminations may be realized by installed grounding systems, connected non-parallel pipeline sections, or insulating joints. The analysis is sufficiently general to cover all possible Z_1, Z_2, and L for single section buried, parallel pipelines

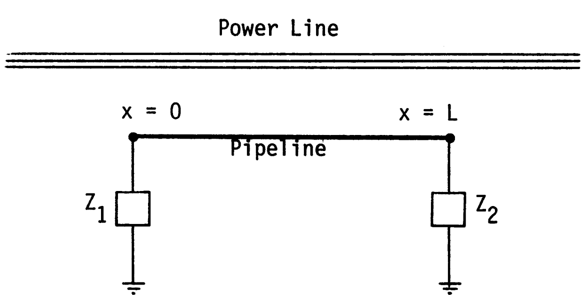


Fig. 3. Geometry of a Single-Section Buried Pipeline Parallel to Power Line

Substituting $E_x(s) = E_o$ into Equations 5a and 5b results in

$$P(x) = \frac{1}{2Z_o}\int_{0}^{x} e^{\gamma s}\, E_o ds = \frac{E_o}{2\gamma Z_o}\,(e^{\gamma x} - 1) \qquad (8a)$$

$$Q(x) = \frac{1}{2Z_o}\int_{x}^{L} e^{-\gamma s}\, E_o ds = \frac{E_o}{2\gamma Z_o}\,(e^{-\gamma x} - e^{-\gamma L}). \qquad (8b)$$

Using the results of Equation 8 in Equation 6 yields:

$$K_1 = \frac{\rho_1 E_o}{2\gamma Z_o}\left[\frac{\rho_2(1-e^{-\gamma L}) + 1 - e^{\gamma L}}{e^{\gamma L} - \rho_1\rho_2 e^{-\gamma L}}\right] \qquad (9a)$$

$$K_2 = \frac{\rho_2 E_o e^{-\gamma L}}{2\gamma Z_o}\left[\frac{\rho_1(1-e^{-\gamma L}) + 1 - e^{\gamma L}}{e^{\gamma L} - \rho_1\rho_2\, e^{-\gamma L}}\right] \qquad (9b)$$

Substituting K_1, K_2, P(x), and Q(x) into Equation 4b, the general solution for V(x) in terms of the terminating impedances, Z_1 and Z_2, is obtained:

$$V(x) = \frac{E_o \cdot \left\{\begin{array}{l}\left[Z_2(Z_1-Z_o) - Z_1(Z_2+Z_o)e^{\gamma L}\right]e^{-\gamma x} - \\ \left[Z_1(Z_2-Z_o) - Z_2(Z_1+Z_o)e^{\gamma L}\right]e^{\gamma(x-L)}\end{array}\right\}}{\gamma\left[(Z_1+Z_o)(Z_2+Z_o)e^{\gamma L} - (Z_1-Z_o)(Z_2-Z_o)e^{-\gamma L}\right]} \qquad (10)$$

At x = 0 or at x = L, it can be shown that the dependence of V(0) and V(L) upon the terminating impedances, Z_1 and Z_2, respectively, can be modeled by Thevenin equivalent circuits. For example, at x = 0,

$$V(0) = V_\theta \cdot \frac{Z_1}{Z_1 + Z_\theta} \qquad (11a)$$

where V_θ is the Thevenin equivalent voltage source given by

$$V_\theta = V(0)\Big|_{Z_1 = \infty}$$

$$= \frac{E_o}{\gamma}\cdot\frac{2Z_2 - (Z_2+Z_o)e^{\gamma L} - (Z_2-Z_o)e^{-\gamma L}}{(Z_2+Z_o)e^{\gamma L} - (Z_2-Z_o)e^{-\gamma L}} \qquad (11b)$$

and Z_θ is the Thevenin source impedance* given by

$$Z_\theta = Z_o \cdot \left[\frac{(Z_2+Z_o)e^{\gamma L} + (Z_2-Z_o)e^{-\gamma L}}{(Z_2+Z_o)e^{\gamma L} - (Z_2-Z_o)e^{-\gamma L}}\right]. \qquad (11c)$$

Recognition of the ability to employ Thevenin decomposition procedures is of prime importance since, in this way, the effect of the load impedance can be separated from that of the distributed voltage sources along

*Note that Z_θ is exactly the input impedance of a transmission line of characteristic impedance, Z_0, propagation constant, γ, and length, L, terminated by Z_2.

the pipe. Thus, the analysis of a multi-section pipeline or a pipeline subject to sharp variations of inducing field because of geometrical or electrical discontinuities can be treated by applying Thevenin procedures at the junctions or field discontinuities, as discussed later in this paper.

Equations 10 and 11 will now be simplified for the two most important pipeline cases: the electrically short pipeline; and the electrically long/lossy pipeline.

The Electrically Short Pipeline For this analysis, the length, L, of an electrically short pipeline satisfies the inequality

$$L < \frac{0.1}{|\gamma|} \simeq 300 \text{ m} \tag{12}$$

The limit of L for electrical shortness can be obtained by computing representative values of $|\gamma|$ using the calculator programs described later.

Subject to the inequality of Equation 12, the first-order-correct approximations

$$e^{\pm\Delta} \simeq 1 \pm \Delta \text{ for } \Delta = \begin{Bmatrix} \gamma L \\ \gamma x \\ \gamma(x-L) \end{Bmatrix} \tag{13}$$

can be used with the assurance that the error introduced is of the order of only 10 percent. Substituting the approximations of Equation 13 into the general solution of Equation 10 results in the following expression for the induced potential on a parallel, electrically short pipeline:

$$V(x) \simeq E_o \left(x - \frac{L\ Z_1}{Z_1+Z_2} \right) \tag{14}$$

The potential is seen to vary linearly with distance from termination Z_1, as shown in Figure 4a. The terminal values of V(x) are given by

$$V(0) \simeq -E_o L \cdot \frac{Z_1}{Z_1+Z_2} \tag{15a}$$

$$V(L) \simeq E_o L \cdot \frac{Z_2}{Z_1+Z_2} \tag{15b}$$

The dependence of V(0) and V(L) upon the values of Z_1 and Z_2 is modeled by the Thevenin equivalent circuit of Fig. 4b. In the figure, the Thevenin source impedance, Z_θ, is shown to Equal Z_r, the terminating impedance remote from the observation point. The magnitude of the Thevenin voltage source, V_θ, is proportional to the length of the pipeline section. V_θ assumes the "-" sign if $\vec{E}_o$ points toward the remote termination, and the "+" sign if $\vec{E}_o$ points toward the Thevenin observation point.

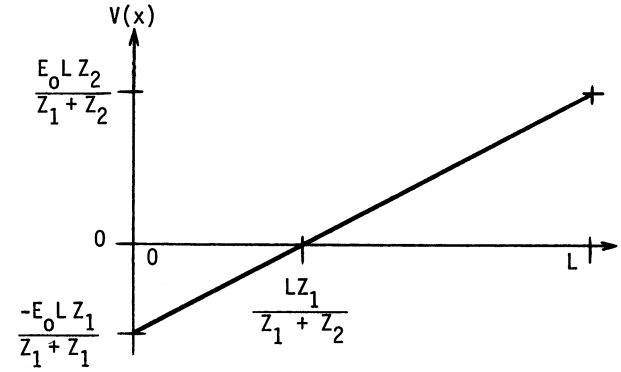
The Electrically Long/Lossy Pipeline The criterion for an electrically long/lossy pipeline is defined as

$$L > 2/\text{Real } (\gamma) \simeq 10 \text{ km.} \tag{16}$$

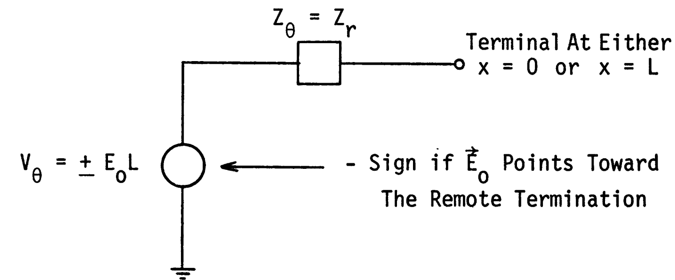
Subject to this condition, it can be stated that

$$|e^{-\gamma L}| \simeq 0.1 \ll 1. \tag{17}$$

The limit of L for large electrical length/loss is obtainable by computing representative values of $\mathrm{Re}(\gamma)$ using the calculator programs discussed later.



(a) Potential Distribution



(b) Thevenin Equivalent Circuit for the Terminal Behavior

Fig. 4. Electromagnetic Coupling to an Electrically Short Parallel Pipeline

Using the inequality of Equation 17, the general solution of Equation 10 can be reduced to obtain the following simple result for the induced potential on a parallel, electrically long/lossy pipeline:

$$V(x) \simeq \frac{E_o}{\gamma} \left[-\frac{Z_1}{Z_1+Z_o} \cdot e^{-\gamma x} + \frac{Z_2}{Z_2+Z_o} \cdot e^{\gamma(x-L)} \right] \tag{18}$$

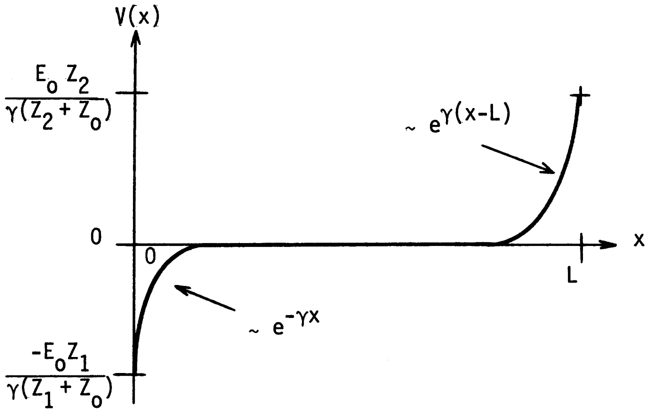
The potential is seen to vary exponentially with distance from each termination, as shown in Fig. 5a. The terminal values of V(x) are given by

$$V(0) \simeq \frac{-E_o}{\gamma} \cdot \frac{Z_1}{Z_1+Z_o} \tag{19a}$$

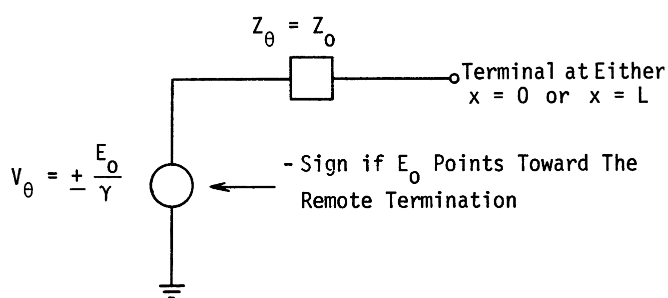
$$V(L) \simeq \frac{E_o}{\gamma} \cdot \frac{Z_2}{Z_2+Z_o} \tag{19b}$$

From Fig. 5a, V(0) and V(L) are seen to be the maximum induced pipeline voltages. These voltages are independent of pipeline length, assuming that the long/lossy criterion is met. Further, the magnitude of each terminal voltage is fixed by the local terminating impedance and is independent of the nature of the remote terminating impedance.

The dependence of V(0) and V(L) upon the values of Z_1 and Z_2 is modeled by the Thevenin equivalent circuit of Figure 5b. In the figure, the Thevenin source impedance, Z_θ, is shown to equal Z_o, the characteristic impedance of the pipeline. The magnitude of the Thevenin voltage source, V_θ, is independent of pipeline length. V_θ assumes the "-" sign if $\vec{E}_o$ points toward the remote termination.



(a) Potential Distribution



(b) Thevenin Equivalent Circuit for the Terminal Behavior

Fig. 5. Electromagnetic Coupling To a Long/Lossy Parallel Pipeline

Effect of a Non-Constant Driving Electric Field

The driving electric field, $E_x(s)$, can depend upon position along a pipeline which does not parallel a power line or is adjacent to a power line electrical discontinuity To explore the effects of a non-constant driving field, we postulate the existence of an electric field having a linear dependence upon position, s, along the pipe:

$$E_x(s) = Bs + C; \qquad 0 \le s \le L \tag{20}$$

Similar to the parallel pipeline (constant driving field) case, the analysis of the non-constant field case begins by substituting $E_x(s)$ of Equation 20 into Equations 5a and 5b to obtain $P(x)$ and $Q(x)$. These results are then used to derive K_1 and K_2 of Equation 6. The solution for $V(x)$ is as follows:

$$V(x) = Z_o \cdot \left\{ \frac{-B}{\gamma^2 Z_o} + \left[K_1 - \frac{1}{2\gamma Z_o}\left(\frac{-B}{\gamma} + C\right)\right]e^{-\gamma x} - \left[K_2 - \frac{e^{-\gamma L}}{2\gamma Z_o}\left(BL + \frac{B}{\gamma} + C\right)\right]e^{\gamma x} \right\} \tag{21a}$$

where

$$K_1 = \frac{\dfrac{\rho_1}{2\gamma Z_o} \cdot \left\{ \rho_2\left[BL + \left(-\frac{B}{\gamma} + C\right)\cdot\left(1-e^{-\gamma L}\right)\right] + \left[BL + \left(\frac{B}{\gamma} + C\right)\cdot\left(1-e^{\gamma L}\right)\right] \right\}}{e^{\gamma L} - \rho_1\rho_2 e^{-\gamma L}} \tag{21b}$$

$$K_2 = \frac{\dfrac{\rho_2 e^{-\gamma L}}{2\gamma Z_o} \left\{ \rho_1\left[-BL\ e^{-\gamma L} + \left(\frac{B}{\gamma} + C\right)\cdot\left(1-e^{-\gamma L}\right)\right] + \left[-BL\ e^{\gamma L} + \left(-\frac{B}{\gamma} + C\right)\cdot\left(1-e^{\gamma L}\right)\right] \right\}}{e^{\gamma L} - \rho_1\rho_2 e^{-\gamma L}} \tag{21c}$$

Equation 21 will now be simplified for the electrically short pipeline case and for the electrically long/lossy pipeline case.

The Electrically Short Pipeline For $L < 0.1/|\gamma|$, we substitute the approximations

$$e^{\pm\Delta} \simeq 1 \pm \Delta + \frac{\Delta^2}{2} \text{ for } \Delta = \begin{Bmatrix} \gamma L \\ \gamma x \\ \gamma(x-L) \end{Bmatrix} \tag{22}$$

into the general solution of Equation 21. After expanding, we keep only the first-order terms (γL, γx, $\gamma(x-L)$) to obtain

$$V(x) \simeq \left(\frac{Bx^2}{2} + Cx\right) - \left(\frac{BL^2}{2} + CL\right) \cdot \frac{Z_1}{Z_1+Z_2} \tag{23}$$

The terminal values of $V(x)$ are given by

$$V(0) \simeq -\left(\frac{BL^2}{2} + CL\right) \cdot \frac{Z_1}{Z_1+Z_2} \tag{24a}$$

$$V(L) \simeq \left(\frac{BL^2}{2} + CL\right) \cdot \frac{Z_2}{Z_1+Z_2} \tag{24b}$$

The dependence of $V(0)$ and $V(L)$ upon the values of Z_1 and Z_2 is modeled by a Thevenin equivalent circuit with $V_\theta = \mp (BL^2/2 + CL)$ and $Z_\theta = Z_r$, where the sign of V_θ is given as in Figs. 4 and 5, and Z_r is the terminating impedance remote from the observation point. The magnitude of V_θ is seen to equal the integral of $E_x(s)ds$ along the length of the pipe.

The Electrically Long/Lossy Pipeline For $L > 2/\mathrm{Real}(\gamma)$, we have $|e^{-\gamma L}| \simeq 0.1$, and are able to reduce Equation 21 to obtain

$$V(x) \simeq \frac{1}{2\gamma} \cdot \left\{ \frac{-2B}{\gamma} - \left[\rho_1\left(\frac{B}{\gamma} + C\right) + \left(-\frac{B}{\gamma} + C\right)\right]e^{-\gamma x} + \left[\rho_2\left(BL - \frac{B}{\gamma} + C\right) + \left(BL + \frac{B}{\gamma} + C\right)\right]e^{\gamma(x-L)} \right\} \tag{25}$$

The terminal values of $V(x)$ are given by

$$V(0) \simeq -\left(\frac{B}{\gamma^2} + \frac{C}{\gamma}\right) \cdot \frac{Z_1}{Z_1+Z_o} \tag{26a}$$

$$V(L) \simeq \left(\frac{BL}{\gamma} - \frac{B}{\gamma^2} + \frac{C}{\gamma}\right) \cdot \frac{Z_2}{Z_2+Z_o} \tag{26b}$$

At x = 0, the Thevenin equivalent circuit has $Z_\theta = Z_o$ and $V_\theta = -(\frac{B}{\gamma^2} + \frac{C}{\gamma})$. At x = L, the Thevenin equivalent circuit has $Z_\theta = Z_o$ and $V_\theta = (\frac{BL}{\gamma} - \frac{B}{\gamma^2} + \frac{C}{\gamma})$.

Equations 21 to 26 are seen to reduce to the respective parallel pipeline expressions if coefficient B is set equal to zero, giving $E_x(s) = C$, a constant. The distribution specified by Equation 25 has exponential components ($e^{-\gamma x}$, $e^{\gamma(x-L)}$) similar to those derived in the parallel pipeline cases. These components lead to voltage peaks at the ends of a non-parallel section. However, Equation 25 also has a constant term ($-2B/\gamma$) not present in the parallel pipeline cases. For $B \neq 0$, this term dominates near the middle of a long/lossy pipeline section. Thus, a pipeline exposed to a non-constant $E_x(s)$ can have a significant voltage at points far from its ends, even if the pipeline is terminated by ideal grounds $Z_1 = Z_2 = 0$ at each end.

The Long/Lossy Pipeline Approach Section Upon entering or leaving a right-of-way jointly shared with a power line, a pipeline is subject to a driving electric field which is virtually zero at its remote termination and maximum at the joint corridor. This behavior of the driving field permits simplification of Equations 4-7, resulting in a convenient integral expression for the terminal characteristics of a long/lossy pipeline approach section at its entry to the corridor.

For a long/lossy pipeline approach section of length, L, terminated by an arbitrary Z_1 at x = 0 far from the joint corridor, the effective remote termination sensed at x = L (the entry to the corridor) is simply the pipeline characteristic impedance, Z_0. This is because the driving field falls to zero somewhere between x = 0 and x = L along the pipeline, allowing the portion of the pipeline subjected to zero field to act as a characteristic impedance load for the portion being driven. Thus, ρ_1 of Equation 7 and K_1 of Equation 6a are equal to zero.

Now, the Thevenin equivalent voltage source for the pipeline approach section, as observed at x = L, the corridor entry point, is simply the open circuit pipe voltage at L:

$$V_\theta = V(L)\Big|_{Z_2 = \infty} \tag{27a}$$

With $Z_2 = \infty$, ρ_2 of Equation 7 is equal to 1. After computing K_2, P(L), and Q(L) for this case, V_θ is found to be

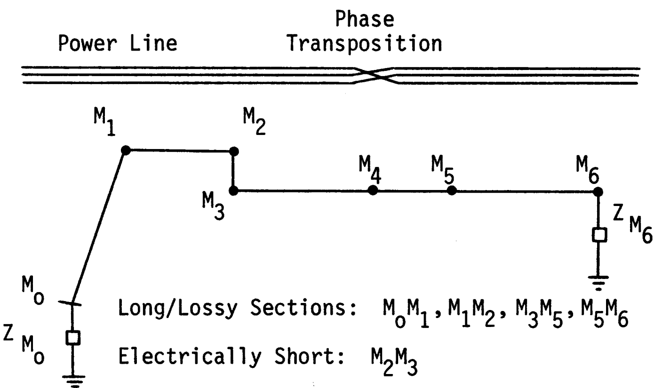
$$V_\theta = e^{-\gamma L} \int_0^L E_x(s)\, e^{\gamma s}\, ds \tag{27b}$$

This expression for V_θ is directly useful in its integral form for practical problems, as is shown in Part II of this paper. It is understood that Z_θ is equal to Z_0, the pipe characteristic impedance, because of the long/lossy nature assumed for the approach section.

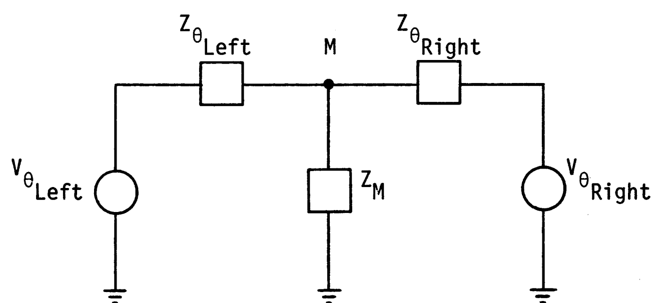
NODE ANALYSIS OF ARBITRARY PIPELINE/POWER LINE CO-LOCATIONS

This section presents a computation method for the peak induced voltages on a buried pipeline having multiple sections with differing orientations with respect to an adjacent power line, or subject to pronounced variations of the driving field due to power line discontinuities. The method is based upon the Thevenin decomposition procedures discussed earlier, leading to a node voltage analysis at pipeline or inducing field discontinuities.

Figure 6a illustrates the connection of several arbitrary pipeline sections adjacent to a power line with an electrical discontinuity (phase transposition). The peak induced voltages are computed by introducing a Thevenin observation plane at each junction, M, between dissimilar pipeline sections or at discontinuities of the driving field, as illustrated in Fig. 6b. This placement of the Thevenin plane is based upon the previous analyses which showed the generation of exponential pipeline voltage peaks at all non-zero impedance terminations of a long/lossy pipe section.



(a) Locations of Thevenin Observation Planes



(b) Connected Thevenin Circuits for the Induced Voltage Peak at Observation Plane M

Fig. 6. Peak-Voltage Analysis of a General Multi-Section Pipeline

In Fig. 6b, $V_{\theta_{left}}$ and $Z_{\theta_{left}}$ denotes the Thevenin source voltage and impedance, respectively, for the pipeline seen to the left of the observation point. Similarly, $V_{\theta_{right}}$ and $Z_{\theta_{right}}$ denote the Thevenin equivalent circuit of the pipeline to the right of the observation point. Z_M denotes the mitigating grounding impedance (if any) at M. The voltage peak, V(M), is given by

$$V(M) = \frac{\dfrac{V_{\theta_{left}}}{Z_{\theta_{left}}} + \dfrac{V_{\theta_{right}}}{Z_{\theta_{right}}}}{\dfrac{1}{Z_{\theta_{left}}} + \dfrac{1}{Z_M} + \dfrac{1}{Z_{\theta_{right}}}} \tag{28}$$

where V_θ and Z_θ can be obtained from the Thevenin equivalent circuits discussed previously.

From Equation 28, $|V(M)|$ can equal zero if either

1) $Z_M = 0$, or (29a)

2) $V_{\theta_{left}} Z_{\theta_{right}} = -V_{\theta_{right}} Z_{\theta_{left}}$. (29b)

For arbitrary connected buried pipeline sections, Equation 29b is virtually the same as specifying an assembled pipeline with constant physical and electrical characteristics, spatial orientation, and driving field distribution. In other words, an induced voltage peak is expected on a buried pipeline where one of these properties changes abruptly, including the following points:

1) Junction between a long/lossy parallel section and a long/lossy non-parallel section (point M_1);

2) Junction between two long/lossy parallel sections having different separations from the power line (points M_2 and M_3);

3) Adjacent to a power line phase transposition or a substation where phasing is altered in some way (point M_4);

4) Junction between two long/lossy sections of differing electrical characteristics, for example, at a high resistivity soil - low resistivity soil transition (point M_5);

5) Impedance termination (insulator or ground bed) of a long/lossy section (point M_6).

Points M_1, M_2, M_3, and M_6 are illustrative of pipeline orientation or termination discontinuities; point M_4 is illustrative of a discontinuity of the driving field; and point M_5 is illustrative of a discontinuity of the pipeline electrical characteristics. The magnitude of the voltage peak at any of these points is computed simply by applying Equation 28 at the discontinuity to the Thevenin equivalent circuits for the pipeline sections on either side. In this way, the use of a single node equation, along with a collection of Thevenin equivalent pipeline circuits, is sufficient to estimate the voltage peaks on an arbitrary multi-section, buried pipeline.

COMPUTATION AIDS

IITRI has developed four major programs for the Texas Instruments Model TI-59 programmable hand calculator which permit rapid computation of the driving electric field, pipeline characteristics, and Thevenin circuits needed to implement the prediction method of this paper. This section briefly summarizes the capabilities of each program. Precise details, including program listings and usage instructions, are available from EPRI and AGA in the handbook to be published, or directly from IITRI.

Driving Electric Field

Unknown Currents Program This program is used when the currents coupled to multiple earth return conductors near a power line are strong enough to affect the driving field of the pipeline of interest. The conductors may be either power line shield wires, long fence wires, telephone wires, railroad tracks, or other buried pipelines. Since the unknown currents influence each other through mutual coupling, the solution for the currents is obtained by solving a set of complex-valued simultaneous equations describing the interactions. The solution algorithm, the Gauss-Seidel iterative method, allows the TI-59 to process a system as complex as five unknown earth return conductors adjacent to 25 power line phase conductors, yielding both the magnitude and phase of each unknown current.

Mutual Impedance Program This program computes the mutual impedance between adjacent, parallel, earth return conductors using Carson's infinite series. The program computes and sums as many terms of the Carson series as is required to achieve 0.1% accuracy, using the recursive algorithm of Dommel,[3] regardless of earth resistivity conditions, conductor configuration (either aerial or buried), and conductor separation.

Pipeline Characteristics Program

This program computes the propagation constant, γ, and characteristic impedance, Z_0, of a buried pipeline having arbitrary characteristics. The program can take into account the burial depth, pipe diameter, pipe wall thickness, pipe steel relative permeability, pipe steel resistivity, pipe coating resistivity, and earth resistivity. The computation method employed for γ is a Newton's method solution of the Sunde complex-valued transcendental equation; Z_0 is then computed using the result for γ.[15]

Thevenin Circuit Program

This program computes the complex-valued Thevenin source voltage, V_θ, and source impedance, Z_θ for the terminal behavior of an arbitrary earth return conductor subject to a constant driving electric field. The nature of the conductor is specified for the program simply by feeding in the conductor's propagation constant, γ, and characteristic impedance, Z_0. The computation method involves the solution of Equations 11b and 11c of this paper.

CONCLUSIONS

This paper has presented a prediction approach for the voltages induced on gas transmission pipelines by 60 Hz ac power lines sharing a joint right-of-way. This prediction approach is based upon electrical transmission line theory and allows the characterization of complex features such as pipeline path changes and terminations and power line electrical discontinuities. Multiple phase conductors, shield wires, and adjacent grounded conductors such as railroad tracks and other pipelines can be accounted for. Advantageous use is made of a powerful new programmable hand calculator.

The new approach is more accurate than the oversimplified methods now in general use, and yet is still usable by technicians in the field because of the simple Thevenin formulation of voltage peaks and the use of magnetic card calculator programs. Field tests, to be discussed in Part II of this paper, verify the accuracy of the approach when applied to actual joint-use corridors.

REFERENCES

[1] Electrical Transmission and Distribution Reference Book, Fourth Edition. Westinghouse Electric Corp., 1964.

[2] "Electromagnetic Effects of Overhead Transmission Lines - Practical Problems, Safeguards, and Methods of Calculation," by IEEE Working Group on E/M and E/S Effects of Transmission Lines, IEEE Trans. Power App. Systems, Vol. PAS-94, pp. 892-899, May/June 1974.

[3] H. W. Dommel et al, Discussion, IEEE Trans. Power App. Systems, Vol. PAS-94, pp. 900-904.

[4] Directives Concerning the Protection of Telecommunication Lines Against Harmful Effects from Electricity Lines. International Telegraph and Telephone Consultative Committee (CCITT), International Telecommunications Union, 1962 (supplemented 1965).

[5] A. W. Peabody and A. L. Verhiel, "The Effects of High Voltage Alternating Current (HVAC) Transmission Lines on Buried Pipelines," Paper No. PCI-70-32 presented at IEEE/IGA Petroleum and Chemical Industry Conference, Tulsa, Oklahoma, 15 September 1970.

[6] C. G. Siegfried, "AC Induced Interference on Pipelines," presented at Interpipe 73 Conference, Houston, Texas, 31 October 1973.

[7] C. A. Royce, "Alternating Current Problems of Pipelines," presented at A.G.A. Operating Section Transmission Conference, Houston, Texas, 18 May 1971.

[8] E. C. Paver, Sr., "The Effects of Induced Current on a Pipeline," Paper No. 54 presented at NACE 26th Annual Conference, Philadelphia, Pa., 2-6 March 1970.

[9] M. A. Puschel, "Power Lines and Pipelines in Close Proximity During Construction and Operation," Materials Performance, Vol. 12, pp. 28-32, December 1973.

[10] Technical Compatibility Factors for Joint-Use Rights-of-Way (for Bureau of Land Management, Contract 08550-CT5-5). Aerospace Corp., 1 February 1975.

[11] J. Pohl, "Influence of High-Voltage Overhead Lines on Covered Pipelines," Paper No. 326 presented at CIGRE, Paris, France, June 1966.

[12] B. Favez and J. C. Gougeuil, "Contribution to Studies on Problems Resulting from the Proximity of Overhead Lines with Underground Metal Pipe Lines," Paper No. 336 presented at CIGRE, Paris, France, June 1966.

[13] D. N. Gideon et al., Final Report on Project Sanguine. Parametric Study of Costs for Interference Mitigation in Pipelines (to IIT Research Institute). Battelle Columbus Laboratories, Columbus, Ohio, 30 September 1971.

[14] J. R. Sherbundy, The Effects of High Voltage Overhead Transmission Lines on Underground Pipelines. M.S. Thesis, Department of Electrical Engineering, Ohio State University, 1975.

[15] E. D. Sunde, Earth Conduction Effects in Transmission Systems, New York: Dover Publications, 1968, pp. 14-16 and pp. 146-149.

[16] E. F. Vance, DNA Handbook Revision, Chapter 11, Coupling to Cables (for Dept. of the Army, Contract DAAG39-74-C-0086). Stanford Research Institute, Menlo Park, CA., December 1974

For Combined Discussion, see page 791

IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, No. 3 May/June 1979

PREDICTION METHOD FOR BURIED PIPELINE VOLTAGES DUE TO 60 Hz AC INDUCTIVE COUPLING

PART II -- FIELD TEST VERIFICATION

John Dabkowski

Allen Taflove, Member, IEEE

IIT Research Institute
10 West 35th Street
Chicago, Illinois 60616

Abstract - The results of field tests on a buried, 34-inch diameter gas pipeline adjacent to a 525 kV ac power transmission line for 54 miles are discussed. Comparison is made between measured inductive coupling data and predictions obtained using the theory developed in part I of this paper. An excellent agreement of the predicted and measured results is shown for the location and magnitude of all induced voltage peaks on the pipeline.

INTRODUCTION

In order to examine the accuracy and usefulness of the inductive coupling prediction method discussed in Part I of this paper, IITRI recently conducted field tests on an existing buried pipeline/ac power line corridor. Specifically, during April, 1977, tests were conducted in the Mojave Desert on 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 525 kV power transmission line for 54 miles and is subject to considerable electromagnetic induction. Two objectives of the tests were:

1. Measurement of the longitudinal electric field to determine the accuracy of the electric field prediction method employing Carson's infinite series; and
2. Measurement of the pipeline voltage distribution to determine the accuracy of the inductive coupling prediction method in locating and quantizing pipeline voltage peaks.

The experiments indicated an excellent agreement of the predicted and measured distributions of electric field and pipeline voltage. The experiments also showed the utility of the hand calculator programs for computing key data inputs under field conditions. This paper summarizes important results of these field tests.

TEST SITE

The electric power transmission line meets the gas pipeline at pipeline milepost 47.9 (47.9 miles west of Needles, California) and leaves it at milepost 101.7, as shown in Figure 1. The power line is in a horizontal configuration with a transposition at milepost 69 and with single-point grounded shield wires. No other conductors or pipelines share the right-of-way.

Average earth resistivity in the test site was measured at 40 kΩ-cm. An average value of 700 kΩ-ft^2 was assumed for the pipeline coating resistivity, based upon furnished data.

Power line currents were obtained at the time of the field tests by a two-way radio link with the appropriate Edison substation. An average loading of 700 amperes was reported during the duration of the tests. Hence, all experimental and calculated data discussed in this paper are normalized to, or based upon, an assumed 700-amperes balanced current loading.

A clockwise-phase-sense transposition is used on the power line. West of the transposition, the phase currents are I_A, I_C, and I_B in a south-to-north direction, respectively. East of the transposition, the corresponding phase currents are I_B, I_A, and I_C. All measured and predicted electric fields and voltages in this paper are phase-referenced to I_A, which is assigned a phase of 0°.

LONGITUDINAL ELECTRIC FIELD STUDIES

Prediction Method

In order to apply the results of Part I of this paper, the longitudinal driving electric field, $E_x(s)$, at the pipeline must be known along the entire route. Since the only contributors to E_x were the known power line phase currents, I_A, I_B, and I_C (the shield wire) currents were zero due to their single-point grounding), the driving field was computed simply as

$$E_x(s) = I_A Z_A(s) + I_B Z_B(s) + I_C Z_C(s) \tag{1}$$

where $Z_A(s)$, $Z_B(s)$, and $Z_C(s)$ represent the Carson mutual impedances between the respective phase lines and the pipeline at location, s, along the pipeline. Z_A, Z_B, and Z_C were computed using the Carson's infinite series program, developed for the programmable calculator, reviewed in Part I.

Had the shield wires been multiply-grounded, or had other long earth return conductors been present in the joint right-of-way, the programmable calculator unknown currents program discussed in Part I would have been used to determine the magnitude and phase of the current in each conductor in the presence of the pipeline. Then, the driving field would have been computed as

$$E_x(s) = I_A Z_A(s) + I_B Z_B(s) + I_C Z_C(s) + \sum_{j=1}^{m} I_j Z_j(s) \tag{2}$$

where I_j is the current in the jth earth-return conductor in the ROW, and $Z_j(s)$ is the Carson mutual impedance between the jth earth-return conductor and the pipeline at location, s, along the pipeline. If additional electric circuits had been present on the ROW, then the effects of each extra phase conductor current would have to be taken into account in both the unknown currents program and the final summation for $E_x(s)$.

F 78 699-1. A paper recommended and approved by the IEEE Insulated Conductors Committee of the IEEE Power Engineering Society for presentation at the IEEE PES Summer Meeting, Los Angeles, CA, July 16-21, 1978. Manuscript submitted February 1, 1978; made available for printing April 26, 1978.

0018-9510/79/0500-788$00.75

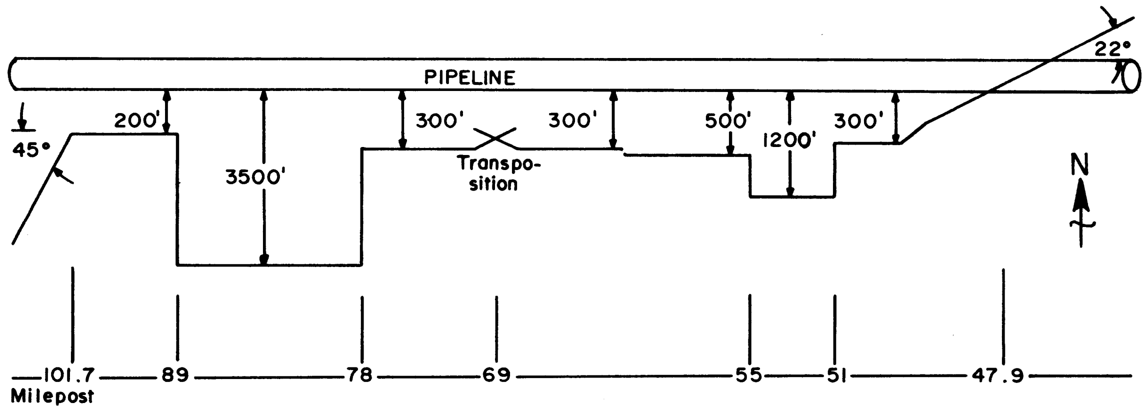


Fig. I MOJAVE DESERT PIPELINE-POWER LINE GEOMETRY

Field Test Procedures

Readings for the magnitude and relative phase of $E_x(s)$ were obtained using instrumentation developed by IITRI. The key elements of the instrumentation are separate reference-point and test-point grounded probe wires, used with a Hewlett-Packard Model HP 3575 gain-phase meter. The probe wires and the meter are shielded in a manner so as to eliminate measurement error due to spurious pickup of the power line's transverse (electrostatic) field and stray radio frequency fields. Further, to avoid error due to coupling by the induced pipeline current, free electric field measurements were made at a location of large separation between the pipeline and the power line (i.e., west of milepost 101.7).

Results

Table I lists the predicted and measured results for $|E_x|$ at varying distances from the power line. All computations and data are normalized to the case of 700 ampere balanced current loading of the power line.

Table I

Longitudinal Electric Field Results

Distance from Power Line (feet)	Predicted Field (volts/km)	Measured Field (volts/km)
0	10.2	10.4
20	18.3	14.3
40	27.3	24.5
60	29.0	27.0
80	27.2	22.2
100	24.2	22.2
200	14.0	14.0
300	9.5	8.5
600	4.8	4.0
1000	2.9	1.6
5000	0.4	
10,000	0.1	

For the balanced current case, $|E_x|$ was found to be the same for equal distances both north and south of the power line and also on both sides of the power line transposition.

Table II lists the predicted phase of E_x at distances between 60 feet and 2000 feet from the power line. The phase tended to remain relatively constant at the tabulated values except for rapid variations directly under the power line. Again, I_A serves as the phase reference ($\phi = 0^{\circ}$).

It was not possible to measure the absolute values of the electric field phase relative to the reference phase current, I_A. However, phase measurements relative to two ground locations were possible, and hence differences of the absolute values listed in Table II were measurable. For example, confirmation of the phase reversal occurring on opposite sides of the power line was readily obtained

Table II

Electric Field Phase

	West of Transposition	East of Transposition
North of power line	-120° $+60^{\circ}$	0° 180°

PIPELINE VOLTAGE STUDIES

Prediction Method

The node analysis discussed in Part I of this paper predicts the appearance of separably-calculable pipeline voltage peaks at all discontinuities of a pipeline-power line geometry spaced by more than 2/Real (γ) meters along the pipeline. Using the pipeline characteristics program reviewed in Part I, a value of $\gamma = (0.115 + j\,0.096)\ \text{km}^{-1} = 0.15\,\underline{/40^{\circ}}\ \text{km}^{-1}$ was computed for the Mojave pipeline. Thus, all geometry discontinuities spaced by more than (2/0.115) km = 17.4 km $\simeq$ 10 miles were assumed to be locations of separable induced voltage peaks. These discontinuities include:

1. Milepost 101.7 (near end of pipeline approach section);
2. Milepost 89 (abrupt separation change);
3. Milepost 78 (abrupt separation change);
4. Milepost 69 (power line phase transposition);
5. Milepost 55 (abrupt separation change);
6. Milepost 47.9 (pipeline intersecting the power line).

The voltages at these mileposts were predicted by applying Equation 28 of Part I to the Thevenin equivalent pipeline circuits observed at each point. Assuming that the pipeline characteristics γ and Z_0 were constant with position along the pipeline, $Z_{\theta left}$ and $Z_{\theta right}$ observed at each Thevenin plane were set constant at the value Z_0 (due to the long/lossy nature of the adjacent pipe sections). Further, Z_M was assumed to equal infinity at each Thevenin plane because no ac mitigation grounds were connected at the time to the pipeline. Equation 28 was thus simplified to

$$V(M) = \frac{V_{\theta left} + V_{\theta right}}{2} \tag{3a}$$

For the important special case where the driving electric field had a step discontinuity at M, that is, $E_x(M+) = E_{left}$ and $E_x(M-) = E_{right}$, Equation 3a can be further simplified to

$$V(M) = \frac{1}{2}\left[\left(\frac{E_{left}}{\gamma}\right) + \left(\frac{-E_{right}}{\gamma}\right)\right], \tag{3b}$$

giving

$$|V(M)| = \frac{|E_{left} - E_{right}|}{2|\gamma|} = \frac{|\Delta E(M)|}{2|\gamma|} \tag{3c}$$

In Equations 3a - 3c, the definition and sign of $V_{\theta left}$ and $V_{\theta right}$ were taken from Figure 5b of Part I. After substituting the computed value of $|\gamma| = 0.15\ km^{-1}$, the final form of the peak voltage prediction equation was

$$|V(M)| = \frac{|\Delta E(M)|}{0.3} = 3.33|\Delta E(M)|. \tag{3d}$$

To illustrate this computational approach, the predicted voltage peaks are calculated using Equation 3d, starting at the west end of the shared right-of-way.

<u>Milepost 101.7</u>: The first discontinuity occurs here because the power line approaches the pipeline to a distance of 200 feet. The angle of approach is 45° and, in general, it will be found that for angles greater than 15° to 20° that the drop-off in electric field strength with increasing distance from the power line is sufficiently fast so that the contribution to the observation point voltage from the approaching leg is small, as may be verified by performing a trapezoidal integration of Equation 27b of Part I. Hence, $E_{left} \simeq 0$ and $E_{right} \simeq E_x|200' = 14.0\ \underline{/-120^o}$ Volts/km (from Tables I and II), giving

$$|V(101.7)| \simeq 3.33 \cdot |14.0\ \underline{/-120^o}) - 0| \simeq 46.6 \text{ volts} \tag{4}$$

<u>Milepost 89</u>: The next discontinuity is a result of the pipeline-power line separation increasing to about 3500 feet in the 78 to 89 mile region. From Tables I and II, $E_{left} \simeq E_x|200' \simeq 14.0\ \underline{/-120^o}$ volts/km and $E_{right} \simeq E_x|3500' \simeq 0.6\ \underline{/-120^o}$ volts/km, giving

$$|V(89)| \simeq 3.33 \cdot |(14.0\ \underline{/-120^o}) - (0.6\ \underline{/-120^o})| \simeq 44.6 \text{ volts} \tag{5}$$

<u>Milepost 78:</u> At this point, the pipeline-power line separation decreases to about 300 feet. From Tables I and II, $E_{left} \simeq E_x|3500' \simeq 0.6\ \underline{/-120^o}$ volts/km and $E_{right} \simeq E_x|300' \simeq 9.5\ \underline{/-120^o}$ volts/km, giving

$$|V(78)| \simeq 3.33 \cdot |(0.6\ \underline{/-120^o}) - (9.5\ \underline{/-120^o})| \simeq 29.6 \text{ volts} \tag{6}$$

<u>Milepost 69</u>: At this point, a transposition of the power line occurs at a fixed pipeline-power line separation of 300 feet. From Tables I and II, $E_{left} \simeq 9.5\ \underline{/-120^o}$ volts/km and $E_{right} \simeq 9.5\ \underline{/0^o}$ volts/km, giving

$$|V(69)| \simeq 3.33 \cdot |(9.5\ \underline{/-120^o}) - (9.5\ \underline{/0^o})| \simeq 54.8 \text{ volts} \tag{7}$$

<u>Milepost 55</u>: By a few miles west of milepost 55, the lateral separation has gradually increased to approximately 500 feet. At Milepost 55 there is an abrupt discontinuity where the lateral separation becomes about 1200 feet. From Tables I and II,

$$E_{left} \simeq E_x|500' \simeq 5.8\ \underline{/0^o} \text{ volts/km, and}$$

$$E_{right} \simeq E_x|1200' \simeq 2.4\ \underline{/0^o} \text{ volts/km, giving}$$

$$|V(55)| \simeq 3.33 \cdot |(5.8\ \underline{/0^o}) - (2.4\ \underline{/0^o})| \simeq 11.3 \text{ volts} \tag{8}$$

<u>Milepost 47.9</u>: The power line and pipeline approach this point from the west at a separation of approximately 300 feet. At mile 47.9, the power line crosses the pipeline at an angle of about 22°, and continues onward. Similar to the case at Milepost 101.7, the drop-off in electric field strength with increasing distance from the power line is sufficiently fast so that the contribution to the observation point voltage from the departing leg is small. Hence, $E_{right} \simeq 0$ and $E_{left} \simeq E_x|300' = 9.5\ \underline{/0^o}$volts/km (from Tables I and II, giving

$$|V(47.9)| \simeq 3.33 \cdot |(9.5\ \underline{/0^o}) - 0| \simeq 31.6 \text{ volts} \tag{9}$$

<u>Field Test Results</u>

Figure 2 plots both the measured ac voltage profile of the Mojave pipeline and the computed voltage peaks. The solid curve represents voltages measured by IITRI; the dashed curve is a set of data (normalized to 700 amperes power line current) obtained by a Southern California Gas Company survey in December 1976.

From Figure 2, it is apparent that the prediction method of this paper succeeded in locating and quantizing each of the pipeline voltage peaks with an error of less than ± 20%. Considering the effects of finely-detailed ground resistivity non-uniformities and coupling between adjacent discontinuities (not accounted for when using the Thevenin node analysis of long/lossy sections), this level of accuracy is sufficient for many engineering purposes and greatly exceeds that of previous available approaches.

CONCLUSIONS

Experimental verification has been obtained for the peak-inductive-coupling prediction method of Part I of this paper. Locations of induced voltage peaks on buried pipelines are readily identifiable and their magnitudes calculable with an accuracy not obtainable previously.

As shown, the peak-voltage calculations for the Mojave pipeline are quite simple. This is due to the fact that successive pipeline/power line discontinuities were spaced far enough apart to minimize their interaction. In a dense urban environment, this would not be the case. Here, the calculations would become more complex, but voltage prediction in this situation would still be within the scope of the distributed source theory and programmable calculator programs developed in Part I of this paper.

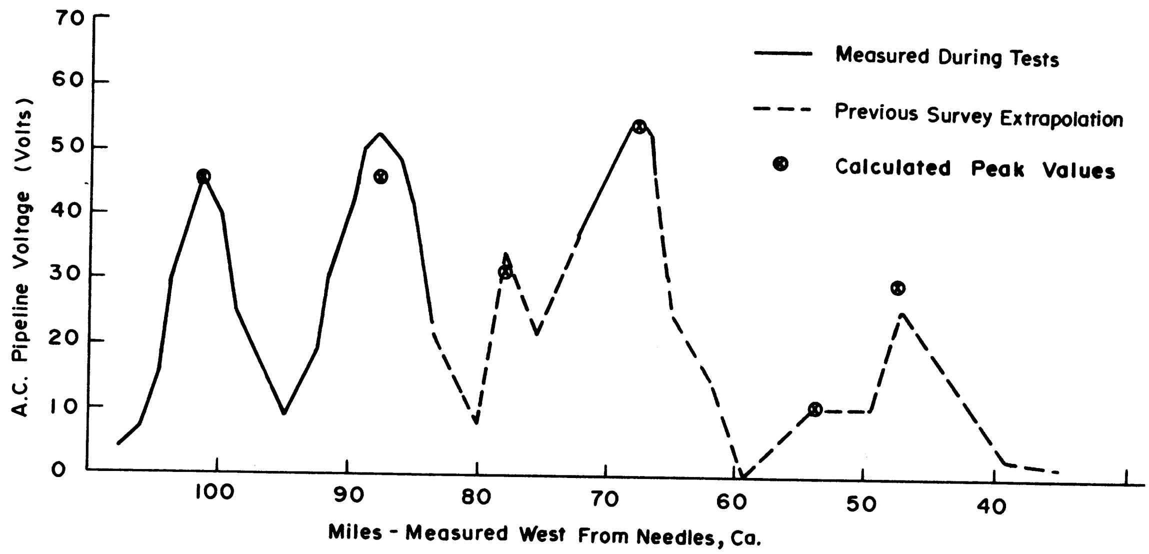


Fig. 2 MOJAVE DESERT PIPELINE VOLTAGE PROFILE

REFERENCE

[1] Work reported in Parts I and II of this paper was done under EPRI Contract No. RP742-1 and PRC/AGA Contract No. PR132-80.

John Dabkowski was born in Chicago, IL, on February 15, 1933. He received the B.S., M.S., and Ph.D degrees in electrical engineering from Illinois Institute of Technology, in 1955, 1960, and 1969, respectively.

He is a Senior Engineer with IIT Research Institute, Chicago, IL, and presently is the project engineer for a program concerned with the evaluation and mitigation of the effects of induced ac voltages on natural gas transmission pipelines.

Dr. Dabkowski is a member of Sigma Xi.

Allen Taflove (M'75) was born in Chicago, Il, on June 14, 1949. He received the B.S., M.S., and Ph.D. degrees from Northwestern University, Evanston, Il, in 1971, 1972, and 1975, respectively all in electrical engineering.

In 1975 he joined the IIT Research Institute, Chicago, IL. His work has been in the area of the interaction of electromagnetic fields with complex scatterers or Systems. Currently he is a Research Engineer and is responsible for microwave interaction studies and innovative fuel recovery techniques. He has applied for two U. S. patents and has authored five published papers.

Dr. Taflove is a member of the IEEE Antennas and Propagation and Microwave Theory and Techniques Societies, Eta Kappa Nu, Tau Beta Pi, Sigma Xi, and AAAS.

Combined Discussion[1, 2]

H. W. Dommel (University of British Columbia, Vancouver, Canada) and **J. E. Drakos, P. S. Wong, R. M. Shier,** and **J. H. Sawada** (British Columbia Hydro and Power Authority, Vancouver, Canada): We are particularly interested in these two papers, because, as one part of a study which we are just completing for the Canadian Electrical Association (Research Project 75-02), we have also developed methods for predicting induced voltages and currents in pipelines paralleling ac transmission lines. Our methods are similar in principle with the authors' method, but differ somewhat in detail because our goal was not the development of simple hand calculator techniques, for which the authors are to be congratulated.

Our first approach was based on work done by Boecker and Oeding [1]. This is an excellent, though not well known reference, which discusses the influence of earth resistivity and coating conductivity (which can vary greatly) and shows good agreement between calculated and measured pipeline voltages and currents. Instead of deriving Thevenin equivalent circuits which depend on the two terminating impedances Z_1 and Z_2, we derived a termination-independent equivalent π-circuit. The impedances of this π-circuit are identical with those of the equivalent π-circuit for long overhead lines familiar to power engineers. The only difference is a current source $+I$ across one terminal and another current source $-I$ across the other terminal, which are a function of the longitudinal driving electric field E_o. A general multi-section pipeline, as in Fig. 6(a) of the authors' paper, is then modelled as a cascade connection of such active π-circuits. While not as simple as the authors' method, it does not require a knowledge of the terminating impedances Z_1 and Z_2.

In our second approach we used multi-conductor π-circuits, which are the generalization of the well-known single-phase π-circuit. A three-phase power line with two shield wires and two parallel pipelines is simply modelled as a 7-conductor system with a 7×7 series impedance matrix per unit length and a 7×7 shunt admittance matrix per unit length. The equivalent multiconductor π-circuit is found from these per unit length matrices either through eigenvalue/eigenvector analysis or through a cascade connection of short "nominal" π-circuits [2]. To complete the model, three-phase Thevenin equivalent circuits must be added to both ends of the power line which will produce correct power flow and short-circuit currents (similar to Thevenin equivalent circuits used in switching surge studies). The network solution will then produce voltages and currents on the pipelines as well as in the power line and shield wires. This approach is unnecessarily complicated for routine

[1] A. Taflove and J. Dabkowski, Prediction Method For Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling, Pt. I: Analysis, this issue, pp. 780.

[2] J. Dabkowski and A. Taflove, Prediction Method For Buried Pipeline Voltages Due to 60 Hz AC Inductive Coupling, Pt. II: Field Test Verification, this issue, pp. 788.

studies, but it is well suited for analyzing transient conditions. Preliminary studies have shown that fairly high voltages may be induced in the pipeline during power line switching (e.g., during normal energization). Since frequencies up to a few kHz are involved in switching surges, the equivalent π-circuit must be replaced by cascade connections of short nominal multiconductor π-circuits in this case, with the section length typically in the order of 0.08 km. Approximate modelling of the frequency dependence of line parameters did not change the switching-surge-induced overvoltages significantly.

Would it be easy for the authors to calculate currents in the pipeline as well? Currents in the pipe may be of concern if a single-line-to-ground fault occurs on the power line, where 30% or more of the fault current may return through the pipe. Do the authors foresee any convergence difficulties in the "Unknown Currents Program" if the number of unknown currents gets close to the upper limit of 5? Gauss elimination would be direct, of course, but may no longer fit into programmable hand calculators.

One of the key parameters affecting pipeline induced voltages is the pipeline shunt conductance per unit length, which has two series components—the coating conductance per unit length and the earth conductance per unit length. The authors refer to a "coating resistivity" of 700 k$\Omega \cdot$ ft^2. Does this mean that the resistance through one square foot of coating is 700kΩ, or is this actually the resistivity value of the coating but with units of k$\Omega \cdot$ ft?. If the former applies, the coating conductance per unit length of pipeline turns out to be about 0.04 mS/m. Could the authors give more details on the test procedure used to determine the value of 700 k$\Omega \cdot$ ft^2, and also give a description of the coating?

Inserting the value of earth resistivity of 400 $\Omega \cdot$ m and the dc component of the author's value of γ into Sunde's expression for the earth conductance per unit length yields a value of about 0.8 mS/m. The relative magnitudes of coating and earth conductances per unit length indicate a well coated pipeline. However, in some cases the coating conductance per unit length may be large with respect to the earth conductance per unit length, e.g. where the coating is poor or the earth resistivity is high. In these cases only a portion of the total ac voltage from pipeline to remote earth appears across the coating. The expected voltage from pipeline to near earth should then be obtained by taking the total calculated voltage and apportioning it across the coating and earth conductances. Have the authors made field tests where this modification was required?

REFERENCES

[1] H. Boecker and D. Oeding, "Induced voltages in pipelines on the right-of-way of high voltage lines (in German), "Elektrizitatswirtschaft", vol. 65, pp. 157-170, 1966.

[2] User's manual for program "Line Constants of Overhead Lines", Bonneville Power Administration, June 1972.

Manuscript received August 15, 1978.

Luke Yu (The Ralph M. Parsons Company, Pasadena, CA): The authors are to be commended for presenting two fine articles regarding the induced voltage in buried pipeline from a nearby A.C. power transmission line. This phenomena became more significant at the advent of EHV or UHV power transmissions. Upon having gone with great interest through the papers, I would like to express my viewpoints and raise some queries:

1. In order to determine the interference between an overhead A.C. power line and an adjacent above-ground communication circuit, a rigorous method should take into account the distributed inductive and capacitive couplings as well as the line terminations of both systems. I found that a hugh discrepancy exists between the computed results based on a rigorous approach and on a simple method which takes into consideration the mutual inductive coupling only for a sample study.

2. Ex(s), the driving field appears to be the governing factor in determining the induced pipeline voltage. However, as shown in Equation (1) of Part II, Ex(s) is simply computed from the products of line currents and mutual impedances. It appears to me a more precise approach should be adopted in determining Ex(s). In fact, the line currents vary along the lines especially for long EHV or UHV power transmission lines.

3. As shown in Table I of Part II, the predicted field values and the measured field data appear in general to be pretty close. However, there are certain degrees of discrepancy between them with respect to different distances. In my opinion the study of induced pipeline voltage should take the pipeline as a part of the whole electrical system in the analysis as well as A.C. power lines because they are electrically interlinked and form a complete system. All the unknowns should be solved simultaneously. The authors' comments are appreciated.

Manuscript received August 14, 1978.

Donald C. Anderson (Southern California Gas Company, Los Angeles, CA): Figure 1 showing the Mohave Desert pipeline-power line geometry is a simplified depiction of the actual spatial relationships between the facilities. At Milepost 89 the power line actually recedes from the pipeline at an angle of approximately 4°. This is not the same as the abrupt separation change depicted in Figure 1 and treated as such mathematically in equation (5), i.e., $E_{right} \cong E_x|3500' \cong 0.6 \angle -120°$ volts/km (from Table 1). Recognition of the shallow angle at which the power line recedes from the pipeline beginning at Milepost 89 would appear to result in a lower predicted voltage at Milepost 89 but a significantly higher voltage easterly of Milepost 89. This seems to be consistent with the voltage pattern measured during the tests, as shown in Figure 2. Assistance in how to treat less than abrupt separation changes in the context of the prediction method would be appreciated.

At Milepost 78, E_{left} is shown as approximately equal to $E_x|3500' \cong 0.6 \angle -120°$ volts/km. Since the approach angle at the point of observation is 90° (Figure 1) and a lesser but still significant angle in the field, I wonder why E_{left} is not shown as equal to zero. This would result in a slightly higher predicted voltage at Milepost 78, which again appears to be consistent with the voltages measured during the tests. Further, for Milepost 101. 7 and Milepost 47.9, E_{left} and E_{right} respectively are shown as zero because "the drop-off in electrical field strength with increasing distance from the power line is sufficiently fast so that the contribution to the observation point voltage from the approaching/departing leg is small". A reason for the different treatment of essentially similar approach angles would be appreciated.

Manuscript received August 14, 1978.

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

Perhaps the derivation of Equation 11c would be clearer if it was noted that Equations 10 and 11b are substituted into Equation 11a to get Equation 11c. This derivation also leads to the determination of the load current through the terminating impedance:

$$I(0) = V(0)/Z_1 = E_0/\gamma\,[2Z_2 - (Z_2 + Z_0)e^{\gamma L} - (Z_2 - Z_0)e^{-\gamma L}]/$$
$$[(Z_1 + Z_o)(Z_2 + Z_o)e^{\gamma L} - (Z_1 - Z_o)(Z_2 - Z_0)e^{-\gamma L}].$$

A transposition in a power line adjacent to a pipeline is an interesting case where the transposition could induce a peak voltage onto the pipeline. This paper indicates that even a mere phase shift in the driving electric field, due to the transposition, induces a peak voltage where one might expect a nullifying effect.

The Southern California Edison Company is applying this distributed source analysis approach to various transmission line projects. Edison's proposed 240 mile long Devers-Palo Verde 525kV Transmission Line is expected to parallel approximately 100 miles of several sections of buried pipeline. The analysis presently indicates that a peak voltage of up to 300 volts could be induced at the insulated terminals of some of these sections.

Manuscript received August 1, 1978.

Adrian L. Verhiel (Trans Mountain Pipe Line Company Ltd., Vancouver, B.C.): I commend the authors for this interesting and significant research on the methods developed to predict the potentials that may result from 60 Hz—A.C. induction coupling in buried pipelines. For over 10 years, we have carried out tests and measurements on these problems with very marginal results due to inadequate basic research.

The induced potential, being a function of the pipeline propagation constant γ and the characteristic impedance Zo are both dependent on pipeline resistance. The methods of induced potential calculations apply to gas pipelines, normally of constant wall thickness. What would be the effect if applied to liquid pipelines with large varying wall thicknesses in relative short distances?

In remote areas where commercial electric power is not economically available, cathodic protection for the pipelines may be supplied by sacrificial anode systems. The latter may be of the distributed anode type or of the concentrated anode bed variety. What would be the effect of the various point grounds on the induced potential?

In determining the pipeline characteristics, it appears that only single pipeline cases have been considered. What would be the effect on multiple pipelines in the same right-of-way? The electrical constants of the pipeline characteristics could vary considerably due to the pipelines' mutual impedance and it is wondered if future consideration will be given to this part of the problem. Table I under "Results" may require some clarification as to the distance from the powerline.

The authors have laid a very important foundation for calculating induced potential effects on buried pipelines and it is hoped that further research will be carried out to enable the pipeline industry to calculate the effects mentioned above and to develop the necessary mitigation methods.

It is now up to the industry to apply the suggested methods and report the findings for varification.

Manuscript received June 26, 1978.

Allen Taflove and **John Dabkowski:** The authors thank the discussors for their comments and interest in the companion papers. The questions for each of the prepared discussions will be addressed in turn.

In reply to the question from Mr. A. L. Verhiel, the following comments are offered.

1) If the wall-thickness variations of liquid-carrying pipelines occur in short distances relative to 2/Real (γ), the effect of the variations upon the induced pipeline potential is greatly smoothed. In effect, for this case, choosing an average value of pipe thickness is sufficiently accurate. If, however, variations in wall thickness occurs at much longer intervals [comparable to or greater than 2/Real (γ)], the node analysis should be applied using the particular value of wall thickness to determine the induced voltage peak at that point. The analysis is valid for both liquid and natural gas transmission and distribution pipelines.

2) Point grounds located at large intervals [comparable to 2/Real (γ)] can be accounted for by applying the node analysis at the location of each point ground, using as a value of Z_M of Figure 6 and Equation 28 the value of the ac grounding impedance of the ground bed. In general, if Z_M is small compared to Z_o of the pipeline, mitigation of induced pipeline voltages will be achieved within an interval of 2/Real (γ) of the ground bed. Now, if a distributed anode system is installed, i.e., if point grounds are connected at very small intervals relative to 2/Real (γ), the principal effect of the grounds is to increase the effective average admittance of the pipeline coating and thus increase the magnitude of γ. Here, the relative increase in pipeline mitigation, obtained for the entire length of the distributed anode system, can be determined by computing the magnitude of γ before and after the installation, and forming the ratio of the computed magnitudes.

3) Although this paper deals only with the single pipeline case (for simplicity), multiple pipelines in the same right-of-way can be accommodated by the analysis. For most cases of pipeline coating quality, earth resistivity, and separation between adjacent pipelines, it can be shown that the mutual impedance between pipelines is dominated by the inductive component, calculable by Carson's series, rather than the resistive component, due to the direct interchange of pipe currents through the earth. Thus, the Unknown Currents Program, discussed under the heading Computation Aids, can be used with accuracy to compute the mutual effects between as many as five pipelines in the same right-of-way. A more detailed description of this case is contained in the reference book to be published.

4) In Table I of Part II, the distance from the power line is measured from the center phase conductor.

The following comments are provided to the discussion of Mr. R. E. Aker.

1) Equations 11a, 11b, and 11c of Part I are in fact a direct decomposition of Equation 10 for the case x = 0. The purpose of performing this decomposition is to prove that the terminal behavior of a pipeline can be represented by a Thevenin equivalent circuit where the effects of inducing field, pipeline characteristics, and load impedances can be conveniently separated.

2) As noted, a key consequence of the theory is the importance of the phase of the inducing field. In particular, rapid shifts of the phase with distance along the pipeline lead to pronounced induced pipeline voltge peaks.

The following comments are provided to the discussion of Messrs. Dommel, Drakos, Wong, Shier, and Sawada.

1) Unless one is at a large distance (> 2/Reγ) from an end, it is not clear how the discussors can dispense with knowledge of the pipeline terminating impedances, Z_1 and Z_2, in determining induced pipeline voltages using the approach of Boecker and Oeding. Z_1 and Z_2 can range from very high values (for insulator terminations) to very low values (for ground-bed terminations) and are shown by the distributed source analysis approach to definitely affect the position and magnitude of pipeline voltage peaks.

2) Currents in a pipeline are computed using Equation 4a of Part I. The simplification of this equation was not pursued in the paper because the emphasis was on induced pipeline voltages. The authors acknowledge that pipeline currents may be of concern during fault conditions. An approximate value of the maximum induced pipeline current can be obtained by applying the Unknown Currents Program, discussed in the section Computation Aids.

3) The authors foresee no convergence difficulties in the Unknown Currents Program if the number of unknown currents gets close to the upper limit of 5. The upper limit here is determined solely by the memory limits of the calculator used. The basic Gauss-Seidel solution algorithm is well known and has been used successfully to solve much larger systems of equations.

4) The pipeline coating resistivity means the resistance observed through one square foot of coating. The coating resistance was not directly measured by the authors. The value given is estimated from a value measured at the time of pipe installation which was adjusted to take into account subsequent deterioration. This latter factor was estimated on the basis of the increase in time of the impressed cathodic protection current required to maintain a constant pipe-to-soil potential. Details of the coating composition are unknown to the authors.

5) For a good coating, as in this case, the total ac voltage from the pipeline to remote earth appears essentially across the coating. Situations have been encountered on other pipelines where current leakage from the pipe was significant and care had to be taken in obtaining a true remote earth termination for the measurement voltmeter.

The following comments are provided to the discussion of Mr. D.C. Anderson.

1) The authors have found that a pipeline section receding from an ac power line at virtually any angle greater than 0° develops only a small value of Thevenin source voltage, $V\theta$, observed at the point of closest approach to the power line. A good rule of thumb is that $V\theta$ can be set to zero for pipe sections having recession angles exceeding Real (γ) $\times$ 10°, where γ is the pipeline propagation constant taken in units of km^{-1}. Essentially, at angles larger than this, only an electrically short section of the receding pipeline is subject to an appreciable driving electric field, resulting in a relatively small voltage contribution of the entire receding section. Thus, in the paper, all angled pipeline sections were considered to essentially develop a zero voltage contribution since all had recession angles exceeding Real (γ) $\times$ 10° = 0.115 $\times$ 10° = 1°.

2) Use of this assumption is relatively obvious for the calculations made at Mileposts 101.7 and 47.9. At both locations the pipeline completely receded from the power line. At Mileposts 89 and 78, the pipeline receded from the power line a large but still finite distance. Hence, a small but larger than zero contribution to the induced voltage could be expected from the receding sections. An approximate method to take this into account, as used in the paper, thus yielded non-zero values for E_{right} at Milepost 89 and E_{left} at Milepost 78, respectively. A more detailed and rigorous discussion of the treatment of the Thevenin characterization of pipeline departure and approach sections is contained in the reference book to be published. The main attempt of the material presented in this paper was to establish the concept that a voltage peak on the pipeline can be expected at a location of an electric field discontinuity.

The following comments are provided to the discussion of Mr. L. Yu.

1) The paper dealt only with inductive coupling to buried pipelines, and not to above-ground communications circuits. Capacitive coupling to buried pipelines is negligible.

2) Part II of the paper dealt only with a single verification case involving a simple right-of-way containing one ac power line and one pipeline. Here, E_x (s) can be taken simply as a summation of the products of line currents and mutual impedances. However, as explained in Part I, the analysis is sufficiently general to take into account the presence of multiple conductors in the right-of-way, such as pipelines, shield wires, and railroad tracks. The Unknown Currents Program, summarized in the section Computation Aids, can account for the

mutual interaction between up to five long earth-return conductors in the right-of-way. This program has been used successfully in a number of other case history tests involving much more complicated rights-of-way than that discussed in Part II. Full description of these case histories and the usage of all of the computation aids is contained in the reference book to be published.

3) Under the non-fault conditions discussed in the paper, the authors have found that the induced current in pipelines buried near ac power lines has a limit of about 5% of the typical phase conductor current. The reaction of this pipeline current back to the phase conductor currents is typically small enough so that, for all practical purposes, the phase currents can be treated as being unaffected by the pipe current. Another way of looking at this situation is that the phase currents are provided by a voltage source with a very low source impedance relative to the Carson mutual impedance between the phase conductors and the pipeline. The authors believe that solving for the phase currents simultaneously with the pipe current introduces needless complication in this situation, given the added work involved and the marginal increase in accuray. However, this is not the case during power line fault conditions when 30% or more of the fault current may return through the pipe due to earth current effects as well as Carson-type coupling. Here, accuracy demands a simultaneous solution of all currents.

Manuscript received October 16, 1978.