Power Systems in Close Proximity to Pipelines

JOHN P. NELSON, SENIOR MEMBER, IEEE

Abstract—In recent years, a trend has developed toward building energy corridors which better utilize land resources. Due to the adverse environmental impacts of building electrical power lines by utility companies and the installation of pipelines by the petrochemical industry, many governmental entities are requiring that electric power lines and underground pipelines use the same transmission (energy) corridor. The energy corridor, by design, is used to minimize the land requirements for transmitting energy—whether by electrical transmission lines or through pipelines. The energy corridor does not necessarily minimize the lengths of transmission lines but, conversely, may require longer lines to utilize the land resources better by paralleling transmission systems. The electric power companies have utilized this practice in the past with electrical corridors and are being pressured to make every effort to parallel electric lines in the future on these same corridors. The effect of paralleling electric circuits has been long understood by the electrical engineer. Induced currents and voltages occur between the electrical circuits and may cause relaying, communications, and safety problems. Proper engineering has led to solutions to most of these problems. A problem has developed with the addition of pipelines to the electrical corridors or, conversely, electrical lines to the pipeline corridors. The problem is that the pipeline has become part of the electrical circuit due to electrostatic and electromagnetic coupling. This coupling may cause induced currents and voltages to exist on the pipeline. The pipeline is addressed as an electrical circuit. Induced voltages on the pipeline are modeled so that both the electrical engineer and the pipeline engineer can understand the effects of power systems in close proximity to pipelines.

INTRODUCTION

ENERGY corridors have been and will continue to be built to transport large quantities of energy in the form of natural gas, petroleum products, and electricity. In the future, it appears that additional products, such as coal, sulfur, and nitrogen, will share these same corridors. High costs of land and environmental concerns will continue to force the energy industry into using these common corridors. As such, the trend of paralleling electrical lines and pipelines will continue.

Pipelines also run in close proximity to electrical substations. This has occurred where a pipeline has been installed near an existing substation, a substation has been built near an existing pipeline, and a substation has been built in conjunction with a pipeline for pumping or compression.The trend toward building pipelines and electrical substations in close proximity will continue.

The existence of a pipeline in close proximity to an electrical system presents a challenge primarily to the pipeline company whose employees may work on pipelines which are in close proximity to an electrical system. The problems associated with an employee coming into direct contact with an electrical conductor can be rather easily explained. However, things such as transferred or induced potentials are not so easily explained, much less understood.

PIPELINES AND ELECTRIC POWER LINES

When a pipeline crew is working close to an electrical line, they are more likely to be aware of it if they are near a line structure (Figs. 1 and 2). However, when they are working between structures, the crew may carelessly overlook the relative proximity of the electrical line to equipment, such as a crane. A danger exists when a piece of equipment is brought too close to an overhead line due to the fact that most overhead electrical lines are bare and rely on air as the electrical insulation.

Fig. 3 represents a conductor with a piece of heavy equipment in close proximity to it. Since the conductor is bare, a certain air space of radius r is required around that conductor for insulation (see Table I). Entry into that air space is similar to cutting the insulation on an electrical cable, and a failure or flashover could result. If a flashover were to occur, a person who is in contact with the heavy equipment and who presents a parallel path for the current to flow to ground could be injured seriously or even fatally. To minimize the chances of such an accident, several steps may be taken.

1) Place an observer near the heavy equipment to inform the operator when he is too close to the line. Train employees on precautions required when working near electrical lines.

2) Avoid unnecessary contact between the employees and the heavy equipment when in close proximity to a power line. Employees in contact with the equipment present a parallel path for current, which could cause a serious injury.

3) If a piece of equipment should come in contact with a live conductor, the operator should not try to jump from his position. Doing so may result in his going from a safe position to one which allows him to be a path for the current to flow.

4) Coordinate any work to be done under the power line with the company responsible for the electric line. Although most lines cannot be de-energized, some can. Also, other safety options may be available by the owner of the electric line.

While direct contact with an electric conductor presents the most obvious danger to the pipeline worker, two other safety hazards exist from an indirect contact.

1) Electrostatic charges can be developed on equipment and materials near the electric line. Such charges are caused by the capacitive coupling and can result in a shock to an employee or the ignition of fuel that is improperly handled.

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The author is with Nelson Engineering, Inc., P. O. Box 1265, Arvada, CO 80001.

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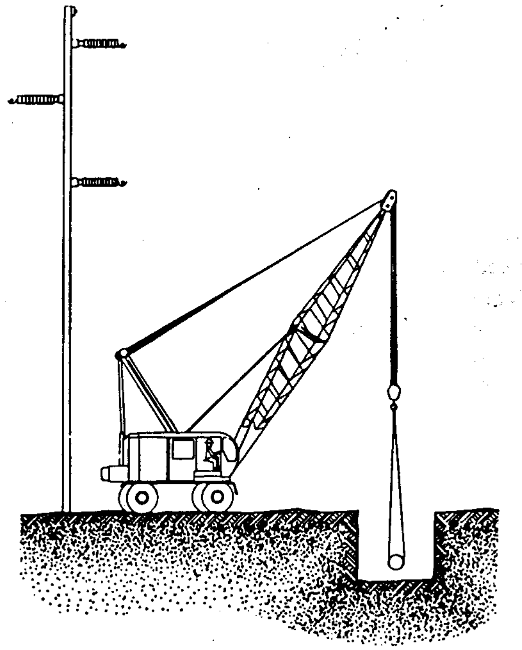

Fig. 1. Equipment near power line.

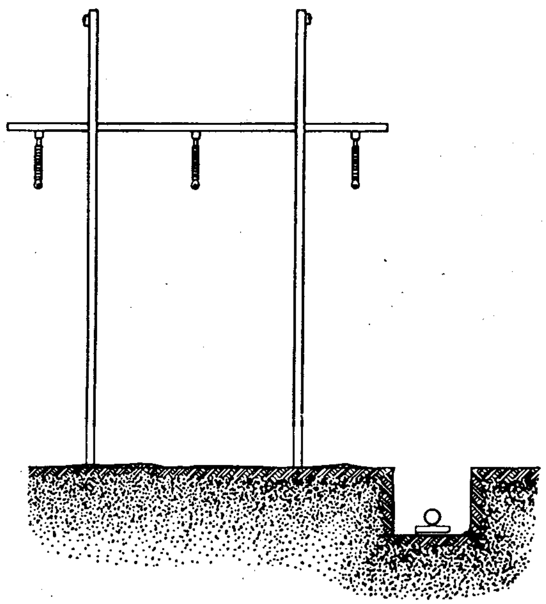

Fig. 2. New pipeline installation.

2) Induced voltages can be caused by the electromagnetic coupling between the electric line and the pipeline. This can result from normal load currents but is more dangerous during a fault condition on the electric line.

PIPELINES AND SUBSTATIONS

When a pipeline is in close proximity to a substation, there are several concerns that the pipeline company should have. The first, and perhaps most obvious, is whether or not the electric lines entering the substation are going to present any problems on the pipeline. The second, and less obvious, is whether or not the substation will have any adverse effects on the pipeline.

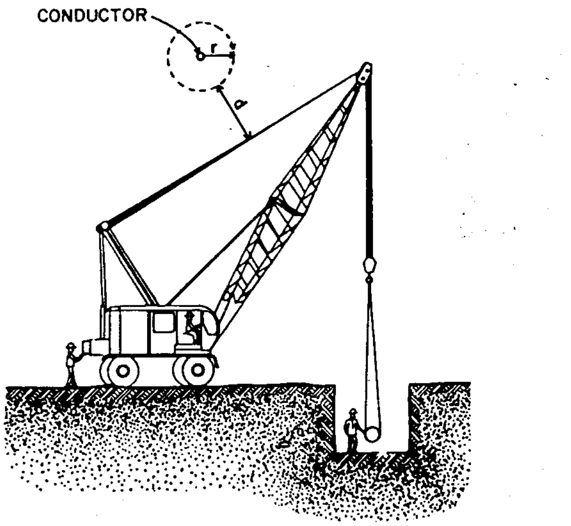

Fig. 3. Dangers associated with pipeline construction.

TABLE I
MINIMUM CLEARANCES

Nominal Voltage Between Phases (V)	Minimum radius (r) (cm)	Minimum radius (r) (in)
301-600	5	2
2400	8	3
7200	10	4
13 800	15	6
23 000	23	9
34 500	31	12
46 000	41	16
69 000	58	23
115 000	94	37
138 000	112	44
161 000	147	58
230 000	168	66

The first problem is caused by the fact that most substations have extensive copper ground grids. These ground grids are designed for the safety of personnel working within the substation and are made of corrosion-resistant copper materials. If this copper grounding system is in close proximity to a pipeline, it can adversely affect the cathodic protection on the pipeline and result in additional corrosion on the pipeline.

The second problem results from an electrical failure within the substation which causes a ground grid potential rise. Equation (1) shows that the ground grid potential rise is dependent on the product of the available line-to-ground fault current and the ground grid resistance:

$$V_{\text{grid}} = I_{\text{fault}} \cdot R_{\text{grid}}. \tag{1}$$

Even a relatively low value of resistance for a ground grid such as 0.5 Ω can create a relatively high ground potential rise if the ground fault current is sufficiently high. For example, using (1) with a 0.5-Ω ground grid resistance along with a 10 000-A ground fault current results in a ground grid potential rise of 5000 V. That voltage is sufficiently high to cause serious injury or death to an employee, or to destroy a cathodic protection rectifier. Furthermore, if a conducting path exists, a transfer potential could exist at long distances from the substation.

Induced Voltages on a Pipeline

When a pipeline runs parallel to an electric distribution or transmission line (Fig. 4), it can and does become part of the electrical circuit by electrostatic and electromagnetic coupling (Fig. 5). The magnitude of such coupling is dependent on such constraints as

1) voltage magnitude and angle on the various conductors,
2) current magnitude and angle on the various conductors,
3) conductor spacing in relationship to the pipeline,
4) conductor spacing in relationship to the other conductors,
5) relative unbalance of the currents and voltages.

Under steady-state conditions, transmission lines are usually considered well-balanced systems with the voltage and current on one phase conductor being close in magnitude to those on the other phases and the angle relationship among the various phases being 120° between each. However, the nonsymmetries of the system are such that even transmission lines that are thought to be balanced do have some unbalances. Depending on the application, these variances can be large enough so that they need to be taken into consideration on calculating induced fields on parallel circuits. However, on the other hand, these slight unbalances normally can be ignored. The circumstances in each case must be reviewed to determine whether or not the unbalances can be ignored.

In comparison, the typical distribution system may have some large unbalances due to phase-to-phase and single phase-to-ground loads. Therefore, current magnitudes and angles and, to a lesser extent, voltage magnitudes and angles will tend to vary on each phase. These unbalances under steady-state conditions can result in induced voltages on parallel circuits such as is the case on the pipeline. Again the magnitude of such induced voltages and currents may be tolerable under steady-state conditions.

The electromagnetic coupling between an electrical power line and a pipeline can be better understood by looking at the electrical circuit represented by (2). The circuit is composed of three phase conductors, two overhead ground wires (static wires), and the pipeline (Fig. 5). Assuming that each of the phase and ground wire conductors could have a current flowing in it, there would be an electromagnetic coupling to the parallel pipeline which is now part of the electrical circuit. The electromagnetic coupling will result in an induced voltage E on the pipeline as shown in (2):

$$E = I_A Z_{AP} + I_B Z_{BP} + I_C Z_{CP} + I_{g1} Z_{g1p} + I_{g2} Z_{g2p} \qquad (2)$$

where

E	induced voltage at some point p,
I_A, I_B, I_C	phase currents,
I_{g1}, I_{g2}	overhead ground wire currents,
Z_{ip}	mutual impedances for each respective conductor to a point of observation p.

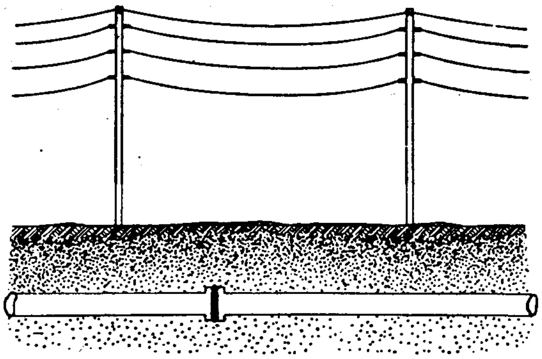

Fig. 4. Pipeline paralleling power lines.

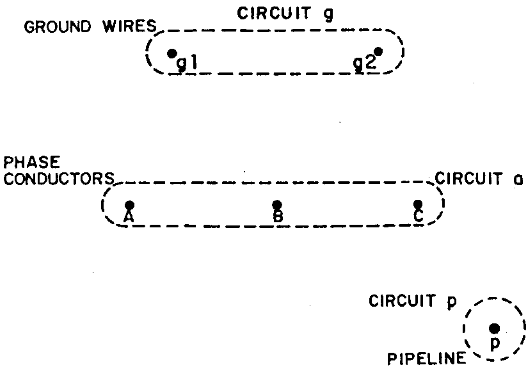

Fig. 5. Pipeline as electrical circuit.

To show some generalities, it will be assumed that the currents in the two overhead ground wires are negligible and, therefore, can be assumed to be equal to zero. Equation (2) will then reduce to

$$E = I_A Z_{AP} + I_B Z_{BP} + I_C Z_{CP}. \qquad (2a)$$

The circuit represented by (2a) is such that the induced voltage on the pipeline is caused by the phase currents from the three phase conductors. Although this is not totally true, some important observations can be made regarding the circuit which could be obscured by the more complex (2). To show this, (2a) can be expanded into a form that will show the symmetrical component currents. Equation (3) shows such an expansion:

$$\begin{aligned} E = {} & 1/3(I_A + I_B + I_C)(Z_{AP} + Z_{BP} + Z_{CP}) \\ & + 1/3(I_A + aI_B + a^2 I_C)(Z_{AP} + a^2 Z_{BP} + aZ_{CP}) \\ & + 1/3(I_A + a^2 I_B + aI_C)(Z_{AP} + aZ_{BP} + a^2 Z_{CP}) \qquad (3) \end{aligned}$$

where a is an operator similar to j, but equal to

$$\exp(j2\pi/3) \text{ or } 1\angle 120^\circ.$$

Although (3) appears to be complex, reference to the symmetrical component equations for positive, negative, and zero sequence currents will greatly simplify the appearance of this equation. Refer to (4), (5), and (6) for the representations of the positive, negative, and zero sequence currents, respectively:

$$I_1 = 1/3(I_A + aI_B + a^2 I_C) \tag{4}$$

$$I_2 = 1/3(I_A + a^2 I_B + aI_C) \tag{5}$$

$$I_0 = 1/3(I_A + I_B + I_C). \tag{6}$$

Substitution of (4)–(6) into (3) will result in the simplified (7):

$$E = I_0(Z_{AP} + Z_{BP} + Z_{CP}) + I_1(Z_{AP} + a^2 Z_{BP} + aZ_{CP}) + I_2(Z_{AP} + aZ_{BP} + a^2 Z_{CP}). \tag{7}$$

Equation (7) will now be used to show the effects of several types of conditions which may exist on a power system.

1) For a balanced system, the negative and zero sequence currents I_2 and I_0 will be equal to zero. The result will be (7a). The induced voltage will be proportional to the positive sequence current I_1 which may be nothing more than the normal load current. Also, the induced voltage is proportional to the vector sum of $(Z_{AP} + a^2 Z_{BP} + aZ_{CP})$. For points in close proximity to the electrical line, this equation shows the possibility of substantial coupling because of the relative distances between conductors. However, as the point becomes farther and farther away from the phase conductors, the values for Z_{AP}, Z_{BP}, and Z_{CP} become close to equal so that the equation would approach (7b) and the induced voltage approaches zero:

$$E = I_1(Z_{AP} + a^2 Z_{BP} + aZ_{CP}) \tag{7a}$$

$$E = I_1 Z_{AP}(1 + a^2 + a) = 0 \tag{7b}$$

where

$$(1 + a + a^2) = 0.$$

2) For an unbalanced system, (7) provides the complete solution for a transmission line without overhead ground wires and an approximation for a transmission line with overhead ground wires. Again, as with the balanced system, the calculation of induced voltages in close proximity to the phase conductors will require the use of the entire equation for a solution. However, at greater distances from the phase conductors, Z_{AP}, Z_{BP}, and Z_{CP} become approximately equal. Therefore, the impedances associated with the positive and negative sequence currents approach zero, resulting in (7c). The result of (7c) is to show that the zero sequence circuit remains the prominent factor on induced voltages on the pipeline:

$$E = I_0(Z_{AP} + Z_{BP} + Z_{CP}) \tag{7c}$$

because

$$Z_{AP} \approx Z_{BP} \approx Z_{CP}$$

and

$$(Z_{AP} + a^2 Z_{BP} + aZ_{CP}) \approx 0$$

along with

$$(Z_{AP} + aZ_{BP} + a^2 Z_{CP}) \approx 0.$$

Zero Sequence Induced Voltages on Pipelines

Although induced voltages can be created on pipelines under steady-state balanced conditions, the magnitude, in all probability, will be small in comparison with those under fault conditions. Also, certain fault conditions will present higher induced voltages in general than others.

With reference to (7c), it appears that the zero sequence current will normally cause the greatest induced voltage on the pipeline. This voltage is created under single phase-to-ground loading for steady-state conditions and faults involving ground for fault conditions. Three-phase and phase-to-phase faults not involving ground do not have zero sequence currents flowing and can be considered a special type of balanced system where the magnetic fluxes from the currents tend to cancel at distances far away from the phase conductors.

With the fact in mind that the zero sequence fault current will have the greatest effect on the induced voltages on the pipeline, a more rigorous solution of the zero sequence circuit will be developed which includes the overhead ground wires of the transmission line. This will be accomplished by assuming that three electrical circuits exist:

1) the first circuit will consist of the three phase conductors, circuit a;
2) the second circuit will consist of the overhead ground wires, circuit g;
3) the third circuit will consist of the pipeline, circuit p.

Please refer to Fig. 5 for this representative circuit.

Three zero sequence equations can be developed from the three circuits shown in Fig. 5. These are shown in (8), (9), and (10) which are for the phase conductor, the overhead ground wire, and the pipeline circuits, respectively. To determine the induced voltage on the pipeline, E_{P0}, caused by a current I_0 from the phase conductors in circuit a, the ratio of E_{P0}/I_0 is to be found using (8)–(10). The ratio (11) provides the zero sequence voltage in the pipeline caused by a zero sequence current in the phase conductors with all other circuits present. Once the value Z_{CF} (coupling factor) is determined, the induced voltage is calculated according to (12):

$$E_{a0} = I_0 Z_{0(a)} + I_g Z_{0(ag)} + I_p Z_{0(ap)} \tag{8}$$

$$E_{g0} = I_0 Z_{0(ag)} + I_g Z_{0(g)} + I_p Z_{0(gp)} \tag{9}$$

$$E_{p0} = I_0 Z_{0(ap)} + I_g Z_{0(gp)} + I_p Z_{0(p)} \tag{10}$$

where

E_{a0}	zero sequence voltage of circuit a,
E_{g0}	zero sequence voltage of circuit g,
E_{p0}	zero sequence voltage of circuit p,
I_0	zero sequence current of circuit a,
I_g	zero sequence current of circuit g,
I_p	zero sequence current of circuit p,
$Z_{0(x)}$	zero sequence self-impedance of circuit x,
$Z_{0(xy)}$	zero sequence mutual impedance between circuit x and y;

$$Z_{CF} = E_{p0}/I_0 \qquad \Omega/\text{km} \tag{11}$$

where Z_{CF} is the coupling factor in Ω/km or, better yet, V/A/km;

$$E_{p0} = 3I_0 \cdot Z_{CF} \cdot D \tag{12}$$

where

E_{p0} induced voltage in the pipeline (V),
$3I_0$ zero sequence current in the three phase conductors (A),
D distance in which the electric transmission line is in parallel with the pipeline (km).

Two assumptions may now be made regarding (8), (9), and (10). First, the overhead ground wires are normally grounded at each structure so the E_{g0} equals zero (13). Secondly, the pipeline normally has an insulating coating and insulated flanges for cathodic protection and, therefore, I_p may be assumed to equal zero (14). With these two assumptions, the solution for the coupling factor Z_{CF} becomes easier:

$$E_{g0} = 0 \tag{13}$$

$$I_p = 0. \tag{14}$$

To begin, substitution of (13) and (14) into (9) and rearranging the terms results in a solution for I_g as shown in (15). Now, (14) and (15) may be substituted into (10) with (16) being the result of the substitutions. Finally, a point is reached where the coupling factor can be determined by rearranging (16) into (16a):

$$I_g = -\frac{I_0 Z_{0(ag)}}{Z_{0(g)}} \tag{15}$$

$$E_{p0} = I_0 Z_{0(ap)} - I_0 \frac{Z_{0(ag)} \cdot Z_{0(gp)}}{Z_{0(g)}} \tag{16}$$

$$Z_{CF} = \frac{E_{p0}}{I_0} = Z_{0(ap)} - \frac{Z_{0(ag)} \cdot Z_{0(gp)}}{Z_{0(g)}}. \tag{16a}$$

Although (16a) is based on complex numbers, two conclusions may be drawn from it which may become intuitively obvious in retrospect.

1) The first term $Z_{0(ap)}$ is the zero sequence mutual impedance between the phase conductors and the pipeline. Without the overhead ground wires, the equation would reduce to this simple mutual impedance.

2) The second term is a correcting factor that tends to reduce the induced voltage on the pipeline because of the overhead ground wires.

CALCULATION OF THE COUPLING FACTOR Z_{CF}

The coupling factor Z_{CF} was found in (16a) and is composed of several complex impedances. To calculate Z_{CF}, the values for the complex impedances must be determined.

A common factor in each of the equations for the impedances is the term representing the spacing reactance X_d. The reactance of a conductor is based on the self-reactance X_a of a conductor at 0.30 m (1 ft) and the reactance based on the spacing factor X_d. X_d, based on the reactance of a set of conductors in one circuit, is represented by $X_{d(x)}$. Similarly, the mutual reactance between circuits x and y is given as $X_{d(xy)}$ in (17a).

$$X_{d(x)} = 0.0896 + 0.1736 \log_{10} D_{(x)} \quad \Omega/\text{km} \tag{17}$$

where $D_{(x)}$ is the self-geometric mean distance of the conductors in circuit x (m).

$$X_{d(xy)} = 0.0896 + 0.1736 \log_{10} D_{(xy)} \quad \Omega/\text{km} \tag{17a}$$

where $D_{(xy)}$ is the mutual geometric mean distance of the conductors in circuit x and circuit y. In (16a), the second term is the result of having one or more ground wires in the circuit. Without the ground wire circuit, the equation reduces to

$$Z_{CF} = Z_{0(ap)}. \tag{18}$$

However, for circuits with n overhead ground wires, where n is one or more conductors, the second term of (16a) must be calculated. The first impedance to be calculated is that of the self-zero sequence impedance of the ground wire(s) as shown in (19):

$$Z_{0(g)} = \frac{3_{ra}}{n} + r_e + j\left(x_e + \frac{3x_a}{n} - \frac{3(n-1)}{n} xd_{(g)}\right) \tag{19}$$

where

r_a resistance of the ground wire conductor (Ω/km),
x_a reactance of the ground wire conductor (Ω/km),
r_e, x_e earth resistance and reactance factor based on Carsons equation (Table II) (Ω/km),
$x_{d(g)}$ space reactance of the ground wire circuit (Ω/km),
n number of overhead ground wires, $n \geq 1$.

The zero sequence mutual reactances between the pipeline and the phase conductors, the ground wires and the phase conductors, and the ground wires and the pipeline are given in (20), (21), and (22), respectively.

$$Z_{0(ap)} = r_e + j(x_e - 3x_{d(ap)}) \tag{20}$$

$$Z_{0(ag)} = r_e + j(x_e - 3x_{d(ag)}) \tag{21}$$

$$Z_{0(gp)} = r_e + j(x_e - 3x_{d(gp)}). \tag{22}$$

SAMPLE CALCULATION OF Z_{CF}

Fig. 6 shows an example of a transmission line in parallel with a pipeline. Circuit a represents the phase conductors, circuit g represents the overhead ground wires and circuit p represents the pipeline. The following constants represent the system:

1) ground wire constants
   a) $r_a = 1.0427$ Ω/km;
   b) $x_a = 0.4331$ Ω/km;
2) soil resistivity $\rho = 100$ Ω·m;
3) $I_0 = 1000$ A;
4) $D = 2.0$ km.

Example:

$$X_{d(g)} = 0.0896 + 0.1736 \log_{10} D_{(g1,g2)}$$
$$= 0.1941 \quad \Omega/\text{km}$$

TABLE II
ZERO-SEQUENCE RESISTANCE AND INDUCTIVE REACTANCE FACTORS[a]

Factor	Soil Resistivity p ($\Omega \cdot$m)	Factor Value (Ω/km)
r_e	all	0.177
	1	1.274
	10	1.534
X_e	100	1.795
	1000	2.055
	10 000	2.316

[a] Based on $r_e = 0.002954 f$ Ω/km, $X_e = 0.004341 f \log_{10} 4.6656 \times 10^6 p/f$ Ω/km.

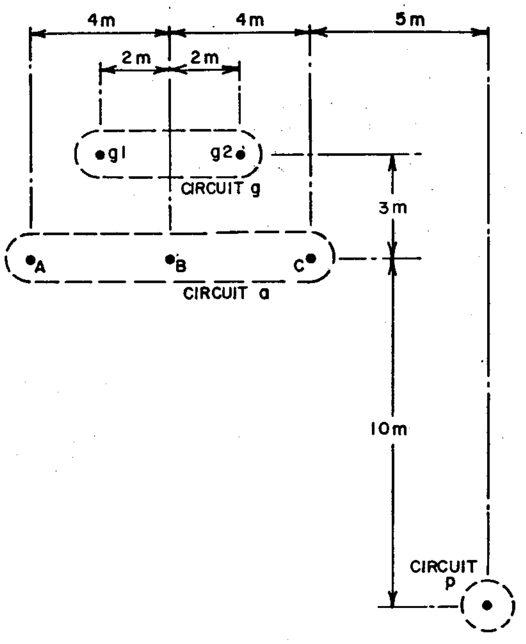

Fig. 6. Illustration of circuit distances.

where

$$D_{(g1,g2)} = 4 \quad \text{m}$$

$$X_{d(ap)} = 0.0896 + 0.1736 \log_{10} D_{(ap)} = 0.2858 \quad \Omega/\text{km}$$

where

$$D_{(ap)} = \sqrt[3]{d_{(AP)} \cdot d_{(BP)} \cdot d_{(CP)}} = 13.5 \quad \text{m}$$

and

$$d_{(AP)} = 16.4 \quad \text{m}$$

$$d_{(BP)} = 13.5 \quad \text{m}$$

$$d_{(CP)} = 11.2 \quad \text{m}$$

$$X_{d(ag)} = 0.0896 + 0.1736 \log_{10} D_{(ag)} = 0.2018 \quad \Omega/\text{km}$$

where

$$D_{(ag)} = \sqrt[6]{d_{(Ag1)} d_{(Bg1)} d_{(Cg1)} d_{(Ag2)} d_{(Bg2)} d_{(Cg2)}} = 4.43$$

and

$$d_{(Ag1)} = 3.6 \quad \text{m}$$

$$d_{(Bg1)} = 3.6 \quad \text{m}$$

$$d_{(Cg1)} = 6.7 \quad \text{m}$$

$$d_{(Ag2)} = 6.7 \quad \text{m}$$

$$d_{(Bg2)} = 3.6 \quad \text{m}$$

$$d_{(Cg2)} = 3.6 \quad \text{m}$$

$$X_{d(gp)} = 0.0896 + 0.1736 \log_{10} D_{(gp)} = 0.2980 \quad \Omega/\text{km}$$

where

$$D_{(gp)} = \sqrt{d_{(g1p)} d_{(g2p)}} = 15.86 \quad \text{m}$$

$$d_{(g1p)} = 17.0 \quad \text{m}$$

$$d_{(g2p)} = 14.8 \quad \text{m}$$

$$Z_{0(g)} = 1.7411 + j2.1535 \quad \Omega/\text{km}$$

$$Z_{0(ap)} = 0.177 + j0.9376 \quad \Omega/\text{km}$$

$$Z_{0(ag)} = 0.177 + j1.1896 \quad \Omega/\text{km}$$

$$Z_{0(gp)} = 0.177 + j0.9010 \quad \Omega/\text{km}$$

$$Z_{\text{CF}} = Z_{0(ap)} - \frac{Z_{0(ag)} Z_{0(gp)}}{Z_{0(g)}} = 0.6411 \angle 61^\circ \quad \Omega/\text{km}.$$

The induced voltage on the pipeline E_p is found to be

$$E_p = 3I_0 \cdot Z_{\text{CF}} \cdot D = 3847 \quad \text{V (see (12)).}$$

CONCLUSION

With the present trend to combine the electrical and pipeline right-of-ways into the same corridor, the pipeline engineer should review all of the safety aspects for the design, construction, and operation of the pipeline near any power systems. In addition, he should consider the pipeline as an extension of the electrical system as the pipeline may become energized by induced or transfer potentials.

In particular, several conclusions can be drawn on the effects of a power system in close proximity to a pipeline.

1) Cathodic protection problems may occur on the pipeline due to copper ground grids on the power system.
2) High transfer potentials may occur under line-to-ground fault conditions.

3) Safety hazards can exist during the installation of a pipeline where the equipment can contact an air-insulated conductor.
4) The coupling between an electrical line and pipeline is substantially affected by zero sequence currents.
5) High induced potentials can exist on a pipeline during a line-to-ground fault on the power system.
6) Ground wires on power lines tend to reduce the induced voltages on the pipeline.

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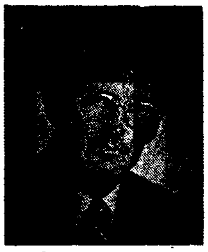

John P. Nelson (S'73-M'76-SM'82) received the B.S. degree in electrical engineering from the University of Illinois, Champaign-Urbana, in 1970, and the M.S. degree from the University of Colorado, Boulder, in 1975. He also performed postgraduate work in business administration at the University of Colorado during 1976-1979.

He began his career with the Public Service Company of Colorado as an Engineer-in-Training in June 1969. After completing the one-year training program, he spent five months on active duty with the United States Army. Upon returning from active duty, he was assigned as an Engineer in the Electrical Engineering Department. In 1974, he was promoted to the position of Senior Engineer, and in 1977 he was transferred to the Engineering Services Department. In late 1977 he was transferred to the Fuel Supply Development Department. He joined the staff of Power Line Models in 1979 as a Project Manager and was involved with the design of electrical substations, transmission lines, and distribution lines. In 1980, he was promoted to the position of Vice President in charge of electric power engineering. In 1984, he set up Nelson Engineering, Inc., to provide technical services in the electric power industry. He is presently involved with power system planning, energy management, power system design, and power system optimization. He has also provided expert testimony on behalf of numerous utilities.