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# Induced Voltage and Current of Electrical Power Line on Adjacent Buried Pipeline

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**Abstract**

An effective approach is introduced to apply Transmission Line Model (TLM) to calculate induced voltage and current on a buried pipeline due to electrical power line. The approach can be applied to the parallel or nonparallel pipelines. The method also extended for any complexity system with different conditions and locations of the pipeline. A two ports circuitry network model is achieved for a parallel pipeline. This two ports network is then modified for each small length, straight and ramped pipeline relative to the power line, which are used for circuitry modelling a complicated configuration of the pipeline. Two numerical services is proceeded to show the simplicity and effectiveness.

*Keywords:* induced voltage and current, longitudinal eclectic field, Carson impedance, propagation constant, characteristic impedance

## 1.Introduction

Induced voltage on a pipeline adjacent to a power line sometimes produces a major problem of shock hazard rather than damaging.[1, 2]. Point to point calculation of induced voltages can help to protect the non expert persons against the electric shock using the common mitigation methods. There are several methods based on the computer programming to find induced voltage on the nonparallel pipelines [3-8]. In this paper we introduced a simple but efficient and accurate approach which can be applied to all configurations of adjacent pipeline to calculate the induced voltage on the buried pipeline without complexity available in numerical methods.

According to view point of circuitry, coupling Between the electrical power line and pipeline can be done in three ways, conductive coupling, capacitive coupling, and inductive coupling [9, 10]. Conductive coupling through the soil, can be major problem when the three phase power line has more return current through earth wires and earth itself [11]. In this situation the adjacent soil of a buried pipeline will have high voltage and the pipeline remain low due to dielectric coating of pipeline. Capacitive coupling for buried pipeline can be neglected. Soil treats as a

Distributed conductor often with average resistivity equal to $100\Omega m$, then it is a relatively good shield to prevent of electric field diffusion under the ground, therefore capacitive coupling is weak. Inductive coupling is major due to magnetic permeability of earth which is approximately equal to the surrounding air.

This paper proposes a new simple and effective method to calculate the induced voltage of inductive coupling on the nonparallel compound configuration of buried pipeline.

First discussion is about how induction coupling generates a longitudinal electric field into the pipeline as a voltage source using Carson's mutual impedances. Later on TLM is discussed and a two

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ports circuitry network extracted for a simple parallel pipeline and then modified for each small length, straight and ramped pipeline, respectively. In the next section we will discuss around the series and parallel impedance of the pipeline and their calculations. Followed section involves combining the previous calculations and models to the nonparallel pipeline. Finally two numerical services are investigated.

## 2. Longitudinal Electric Field

Longitudinal Electric Field (ELF) due to magnetic interference of electrical power line on the adjacent conductive objects such as buried pipeline can be described by [12]:

$$E = I_A Z_A + I_B Z_B + I_C Z_C + I_{S1} Z_{S1} + I_{S2} Z_{S2} \; v/m \qquad (1)$$

where $E$ is longitudinal electric field, $Z_A, Z_B, Z_C, Z_{s1}, Z_{s2}$ are the mutual impedance between the pipeline and each conductor (wire) of the electrical transmission power line respectively. $I_A, I_B, I_C$ are the phase currents and $I_{s1}, I_{s2}$ ground wire currents. If the ground wire currents be equal to zero, equation (1) is reduced to:

$$E = I_A Z_A + I_B Z_B + I_C Z_C \quad volt\ /m \qquad (2)$$

Mutual impedance between each conductor and grounded pipeline is calculated using Carson's relation [12]:

$$Z = \frac{\omega\mu_0}{8} + \frac{j\omega\mu_0}{2\pi}\ln\frac{D_{ep}}{D_{lp}} + \Delta R + j\Delta X \;\; \Omega/m \qquad (3)$$

where $\omega$ is angle frequency and $\mu_0 = 4\pi \times 10^{-7}\, H/m$ is the magnetic permeability of vacuum. $D_{lp}$ is the distance between the conductor and pipeline and $D_{ep} \approx D_e$ can be found by $D_e = 660\sqrt{\rho / f}\;\; m$, where $\rho$ is the soil resistivity and $f$ is frequency in hertz.

When the pipeline is parallel to the transmission line, this mutual impedance for each conductor remains constant so the generated LEF will be invariant. $\Delta R, \Delta X$ are function of frequency and distance, and for $50Hz$ up to distance 100m can be neglected [13].

In fault conditions, LEF rises much more than the normal condition. In figures 1, 2, we see that how this quantity can be affected in fault conditions for a typical service. These plots have been simulated using numerical computer.

In this service phase (a) is the farthest and phase (c) is the nearest conductor to the pipeline. There is a ground wire and the tower is one level with separation 5m between the wires. Distance is measured between pipeline and phase (c).

In normal condition with balance currents, ELF is 3.5 V/Km at distance 1m. Therefore comparing values of ELF in fig.1 and 2 with the balance situation in normal condition, implies the fault conditions are incredible dangerous against to normal conditions. Faults to ground have more ELF than to the phase to phase faults.

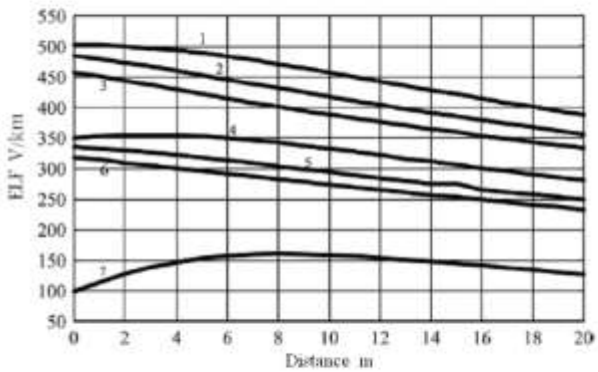


Fig.1 LEF as a function of distance in various faults to the ground, 1: phase c to ground, 2: phase b to ground, 3: phase a to ground, 4: phases a & c to ground, 5: phases a & b to ground, 6: phases b & c to ground, 7: phases a & b & c to ground.

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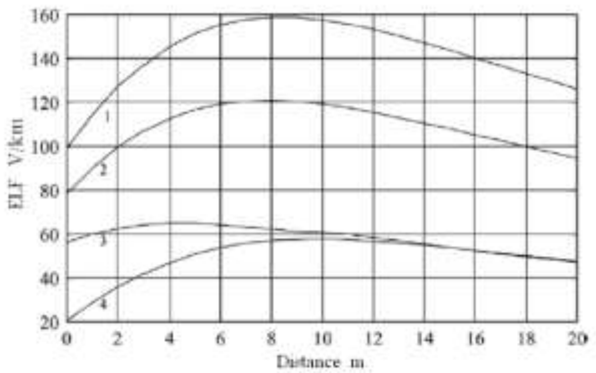

Fig.2 LEF as a function of distance in various phase to phase faults, 1: three phases together, 2: phases b & c, 3: phases a & c, 4: phases a & b.

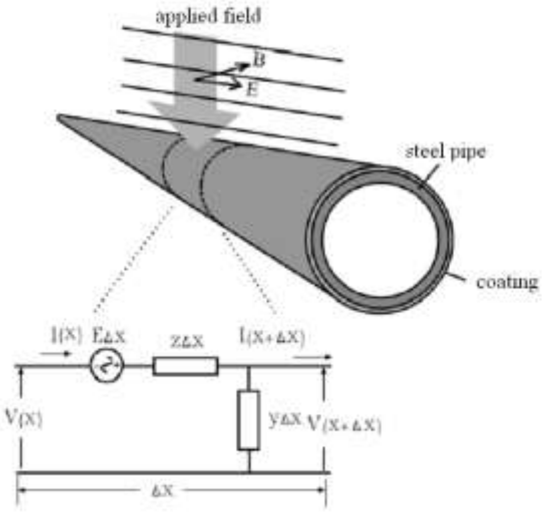

Fig.3 Transmission Line Model (TLM).

## 3.Transmission Line Model

Transmission Line Model (TLM) is a power full tool which has been used to modelling the electrical power transmission lines. It can be used to modelling the circuitry of a buried pipeline which is subjected by electrical transmission line due to magnetic induction [14, 15]. Fig.3 shows the pipe line and TLM model. Where E is the ELF, Z is series or longitudinal impedance, Y is parallel or latitudinal admittance and $\Delta x$ is the length element. Following differential equations are extracted from fig. 3,

$$\frac{dI(x)}{dx} = -yV(x) \qquad (4)$$
$$\frac{dV(x)}{dx} = -E - zI(x)$$

These equations are solved as a linear equation system, result in:

$$I(x) = \left(k_1 + p(x)\right)e^{-\gamma x} + \left(k_2 + q(x)\right)e^{\gamma x} \ A \qquad (5)$$

$$V(x) = Z_o\left(k_1 + p(x)\right)e^{-\gamma x} - Z_o\left(k_2 + q(x)\right)e^{\gamma x} \ V \qquad (6)$$

where $k_1, k_2$ are constant and can be found by boundary conditions, $\gamma$ and $Z_0$ are called propagation constant and characteristic impedance of the pipeline:

$$\gamma = \sqrt{zy} \quad m^{-1} \qquad (7)$$

$$Z_0 = \sqrt{\frac{z}{y}} \qquad (8)$$

$p(x)$ and $q(x)$ are functions which are calculated by,

$$p(x) = \frac{1}{2Z_o}\int_0^x e^{\gamma s}E(s)ds \qquad (9)$$

$$q(x) = \frac{1}{2Z_o}\int_x^L e^{-\gamma s}E(s)ds \qquad (10)$$

where L is the length of pipeline. For parallel pipeline where $E(s)=E_0$ is a constant, yields:

$$p(x)=\frac{E_0}{2\gamma Z_o}\left(e^{\gamma x}-1\right) \tag{11}$$

$$q(x)=\frac{E_0}{2\gamma Z_o}\left(e^{-\gamma x}-e^{-\gamma L}\right) \tag{12}$$

For the boundary condition $V(0),V(L)$ we can easily calculate $k_1,k_2$ as:

$$\begin{aligned} k_1 &= \frac{V(0)e^{\gamma L}-V(L)+Z_o\left(q(0)e^{\gamma L}+p(L)e^{-\gamma L}\right)}{Z_0(e^{\gamma L}-e^{-\gamma L})} \\ k_2 &= k_1-q(0)-\frac{V(0)}{Z_0} \end{aligned} \tag{13}$$

For a constant ELF,

$$k_1=\frac{V(0)e^{\gamma L}-V(L)}{2Z_0\sinh(\gamma L)}+\frac{E_0}{2\gamma Z_0} \tag{14}$$

**4.Two Ports Circuitry Network**

Two ports circuitry network or $\pi$ model will help us to connect the different sections of a pipeline with a different ELF together. Simpler form of $\pi$ model has been used frequently for modelling the electrical power lines themselves. By means a circuit is yielded which is equivalent circuitry model of all over the pipeline. Two ports $\pi$ model with the current sources is described by:

$$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}\begin{bmatrix} V(0) \\ V(x) \end{bmatrix}+\begin{bmatrix} I_{s1} \\ I_{s2} \end{bmatrix}=\begin{bmatrix} I(0) \\ I(x) \end{bmatrix} \tag{15}$$

where $I_{s1},I_{s2}$ are current sources.
Using relations (5) and (6),

$$I(0)=(k_1+p(0))+(k_2+q(0))$$

$$V(0)=Z_o(k_1+p(0))-Z_o(k_2+q(0))$$

result in:

$$k_1=\frac{I(0)}{2}+\frac{V(0)}{2Z_o}-p(0)$$

$$k_2=\frac{I(0)}{2}-\frac{V(0)}{2Z_o}-q(0)$$

Then we apply these two last relations in to the relations (5) and (6) to extract current I(0) and I(x):

$$\begin{bmatrix} Z_o^{-1}\coth(\gamma x) & -Z_o^{-1}\operatorname{csc}h(\gamma x) \\ Z_o^{-1}\operatorname{csc}h(\gamma x) & -Z_o^{-1}\coth(\gamma x) \end{bmatrix}\begin{bmatrix} V(0) \\ V(x) \end{bmatrix}+\begin{bmatrix} I_{s1} \\ I_{s2} \end{bmatrix}=\begin{bmatrix} I(0) \\ I(x) \end{bmatrix} \tag{16}$$

where,

$$\begin{aligned} I_{s1} &= \left[p(x)-q(x)+q(0)\right]\operatorname{csc}h(\gamma x) \\ I_{s2} &= \left[p(x)e^{-\gamma x}+\left(q(0)-q(x)\right)e^{\gamma x}\right]\operatorname{csc}h(\gamma x) \end{aligned} \tag{17}$$

For all length of the pipeline, in relations (16) and (17) we replace $x=L$. In this situation for a constant ELF, we can simply find that

$$I_{s1}=I_{s2}=\frac{E_0}{\gamma Z_0} \tag{18}$$

Fig. 4 shows a circuit which is extracted using relation (16),

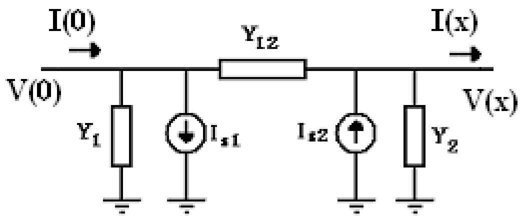


Fig. 4 Two ports $\pi$ model circuitry for the parallel pipeline

In fig. 4;

$$\begin{aligned} Y_{12} &= Z_o^{-1}\operatorname{csc}h(\gamma x) \\ Y_1=Y_2 &= Z_o^{-1}\left(\coth(\gamma x)-\operatorname{csc}h(\gamma x)\right) \end{aligned} \tag{19}$$

where we can replace $x=L$ for all length of the pipeline.
In this study the extracted model is used for parallel pipeline only for two reasons: first is that calculation of current sources in the model using (9) and (10) became very difficult for nonparallel pipeline and needs numerical methods to solve. Secondly after all we purpose to calculate the voltages and currents point to point along the pipeline, so we again encounter the problem of equations (9), (10) but this time harder because of parametric numerical solution. Therefore we consider following situations, For a very small length pipeline where,

$$|\gamma L| \le 0.01 \quad or \quad L \le \frac{0.01}{|\gamma|} \tag{20}$$

results in,

$$\sinh(\gamma L) \approx \gamma L \approx 0$$
$$\cosh(\gamma L) \approx 1$$

therefore

$$Z_{12} = Y_{12}^{-1} = Z_0 \sinh(\gamma L) \approx 0$$

Also admittances $Y_1, Y_2$ using Hopital theory in math get,

$$Y_1 = Y_2 = Z_o^{-1}\left(\coth(\gamma L) - \operatorname{csc}h(\gamma L)\right)$$
$$= Z_0^{-1}\frac{\cosh(\gamma L)-1}{\sinh(\gamma L)} \approx Z_0^{-1}\frac{\gamma \sinh(\gamma L)}{\gamma \cosh(\gamma L)} \approx 0$$

Current sources in model get parallel and are eliminated due to opposite directions. Therefore the $\pi$ model is reduced to just a wire as shown in fig. 5.

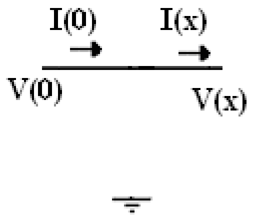


Fig. 5 Simplified model for very small length of pipeline.

Ramped pipeline relative to electrical power line is depicted in fig. 6. Parameter $\alpha$ is the angle between the pipeline and power line direction.

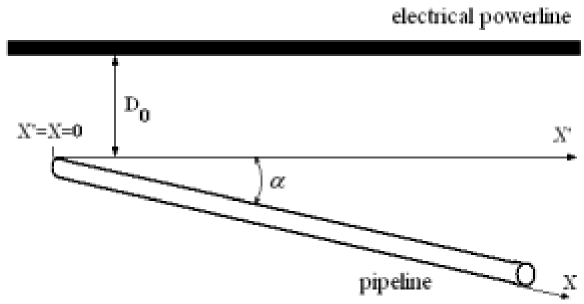


Fig. 6 Ramped pipeline relative to power line

Horizontal distance between the pipeline and power line can be described by,

$$D = D_0 + ax' \quad where \ a = \tan(\alpha)$$

Therefore the mutual impedance using relation (3) will be,

$$Z = \frac{\omega\mu_0}{8} + \frac{j\omega\mu_0}{2\pi}\ln\frac{D_e}{\sqrt{h^2+(D_0+ax')^2}}\,\Omega/m$$

where $h$ is the height of power line 's conductor. If we suppose that,

$$D_0 \gg ax' \quad or \quad ax' \approx 0.1D_0$$

and or

$$x' \approx \frac{0.1D_0}{a} \tag{21}$$

Then we can assume the mutual impedance and consequently ELF will remain constant in interval $0 \le x' \le x'_m$, where $x'_m$ is achieved by (21).
Therefore an effective and accurate method is extracted for a ramped pipeline using segmentation by length;

$$\Delta l = \frac{x'_m}{\cos\alpha} = \frac{0.1D}{\sin\alpha} \quad m \tag{22}$$

where D is the horizontal distance between the power line and beginning of the considered segment.
The mutual impedances are calculated by (3) respect to the middle of the considered segment.

ELF is calculated using (1) or (2) as a constant value for the segment, but direction of the calculated ELF is parallel to the direction of power line, therefore the component of ELF along the pipeline should be considered;

$$E_x = E_{x'} \cos\alpha \qquad (23)$$

Now we can construct a circuitry $\pi$ model for each segment, and connect them for all length of ramped pipeline.
When the pipeline has orthogonal straight to the electrical power transmission line, magnetic interaction between the pipeline and power line gets zero according to relation (23), so just the impedances of the discussed model will be remained. Fig. 7 shows this situation,

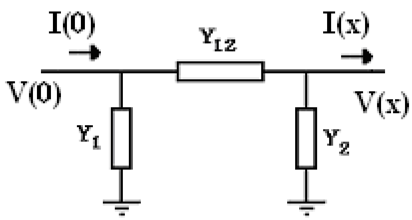


Fig. 7 Two ports $\pi$ model circuitry for the orthogonal pipeline

## 4.Pipeline Impedances

There are various relations for pipeline impedances which have been used so far. Nevertheless we describe a new simple and accurate method for some of them. Pipeline has a latitudinal or parallel admittance due to capacitive and conductive characteristics of the pipeline dielectric coating to the surrounding soil. Resistivity of the coating is thousands time greater than the surrounding soil, thus in this study we assumed the soil is conductor relative to the dielectric coating.
In fig. 8 the pipeline and its coating is depicted. Following Maxwell equation or consequently Gaussian surface theory is utilized to solve for the electric field in the coating between the surrounding soil and the steel pipe,

$$\nabla.\vec{D} = \rho_F \Rightarrow \oint_s \vec{D}.\vec{ds} = Q_F$$

where $\vec{D}$ is the electric field density, $Q_F$ free electric charge inside the Gaussian surface, and $s$ is the Gaussian area. Vectors $\vec{D}$ and $\vec{ds}$ on above and under areas of the Gaussian surface, are perpendicular to the surface, therefore Gaussian integral is reduced just on side surface,

$$\int_{s'} \vec{D}.\vec{ds} = Q_F \Rightarrow D \times 2\pi r l = Q_F$$

$$\vec{D} = \frac{Q_F}{2\pi r l}\hat{a}_r$$

$$\vec{E} = \frac{Q_F}{2\pi \varepsilon r l}\hat{a}_r$$

where $\vec{E}$ is electric field vector, and $\varepsilon$ is the electric permeability of dielectric.
Different potential across the inner and outside of the coating can be calculated as,

$$V_0 = -\int_{-}^{+} \vec{E}.\vec{dl} = -\int_b^a \frac{Q_F}{2\pi\varepsilon r l}\hat{a}_r.dr\hat{a}_r$$

$$= \frac{Q_F}{2\pi\varepsilon l}\ln\frac{b}{a}$$

By means the capacitor across the coating will be,

$$C = \frac{Q_F}{V_0} = \frac{2\pi\varepsilon l}{\ln\frac{b}{a}} \quad (Farad)$$

Or

$$C = \frac{2\pi\varepsilon}{\ln\frac{b}{a}} \quad (F/m) \qquad (24)$$

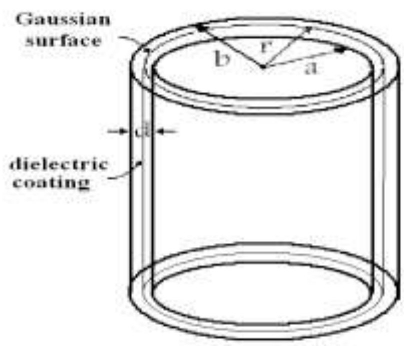


Fig. 8 Pipeline, Gaussian surface and dielectric coating.

Resistance of the coating is found by calculating the current flowing between the inner to outside areas using ohm law,

$$I = \int_s \sigma \vec{E}.\vec{ds} = \sigma E \int_s ds = \frac{\sigma Q_F}{2\pi\varepsilon a l} \times 2\pi a l$$
$$= \frac{\sigma Q_F}{\varepsilon}$$

where $\sigma$ is the conductivity of the coating. Therefore,

$$R = \frac{V_0}{I}$$
$$= \frac{\frac{Q_F}{2\pi\varepsilon l}\ln\frac{b}{a}}{\frac{\sigma Q_F}{\varepsilon}} = \frac{1}{2\pi\sigma l}\ln\frac{b}{a} = \frac{\rho}{2\pi l}\ln\frac{b}{a} \;\; \Omega$$

Or

$$R = \frac{\rho}{2\pi}\ln\frac{b}{a} \quad (\Omega m) \tag{25}$$

where $\rho$ is the resistivity of the coating. The capacitor and resistor are parallel with each other. Then the total admittance of the coating to the earth will be,

$$y = \frac{2\pi}{\rho \ln\frac{b}{a}} + j\frac{2\pi\varepsilon\omega}{\ln\frac{b}{a}} \quad (1/\Omega m) \tag{26}$$

Longitudinal or series impedance has two parts, one is resistance of the steel pipe itself, and other is the self inductance of the pipeline. Resistance of the pipeline should be calculated with considering the skin effect of the steel. Skin depth for steel is equal to $\delta = 2.4mm$ at 50Hz frequency. Thickness of the steel buried pipelines is often greater than the skin depth. When the thickness is greater than the skin depth, we can approximately assume that the total current is followed uniformly in the area with thickness equals skin depth $\delta$. Therefore the resistive or internal impedance of the pipeline will be,

$$R_p = \rho_p \frac{L}{S} = \rho_p \frac{L}{\pi\left(a^2 - (a-\delta)^2\right)}$$
$$= \rho_p \frac{L}{\pi\delta\left(2a-\delta\right)} \quad \Omega$$

Or

$$R_p = \rho_p \frac{1}{\pi\delta\left(2a-\delta\right)} \approx \frac{\rho_p}{2a\pi\delta} \quad (\Omega/m) \tag{27}$$

where $\rho_p$ is the resistivity of the pipeline material.

For calculating self inductance we must consider that the current follows through the pipeline, returns via the earth. Adjacent soil is not a perfect conductor and also is distributed in unlimited around space. Therefore for calculating this external impedance (not just inductance), Carson theory for circuitry modelling the soil is used [16],

$$z_{ext.} = \frac{\omega\mu_0}{8} + j\frac{\omega\mu_0}{2\pi}\ln\frac{1.85}{a'\sqrt{\gamma^2 + j\omega\mu_0\left(\frac{1}{\rho} + j\omega\varepsilon\right)}} (\Omega/m) \tag{28}$$
$$a' = \sqrt{a^2 + 4h^2}$$

where, $\gamma$ is the propagation constant of the pipeline, $\rho$ is the soil resistivity, $\varepsilon$ is the electric permeability of the soil and $h$ is the buried depth between the earth surface up to center of the pipe. So that total longitudinal impedance of the pipeline will be;

$$z = R_p + z_{ext.} \tag{29}$$

**5.Circuitry Model Of The Pipeline**

For a nonparallel complicated configuration pipeline, we segment the pipeline to the parts so that in each part the longitudinal electric field or ELF can be considered fixed value along the segmented pipeline. Then we construct a two ports $\pi$ equivalent circuit for each segment according to the discussions in section IV.

After all these, using the node voltage analysis method, voltage of nodes or the voltages on boundaries of each segment are calculated. With these boundary condition voltages, and using responses (5), (6) and (13), (14) for $k_1, k_2$ constants, the voltage and current functions for each segment and consequently all over the pipeline will be found.

In this method we can analyze the system even when external impedances such as mitigation impedances are connected to the pipeline. Easily the pipeline is segmented where the impedances are connected, and then these impedances are connected to the $\pi$ model at the location of them.

## 6.Numerical Services

To observe simplicity and efficiency of this method to find induced voltages and currents on a pipeline adjacent to an electrical power line, two complicated services are considered. Fig. 9 depicts one of these services. A three phase electrical power line with a transpose at point p is assumed. A buried pipeline has been located adjacent the power line as shown in the figure. The pipeline data has been given in table 1. The power line has one level three conductors without any ground wire. The conductor current is 500A/phase at frequency 50Hz. Separation between the wires and height are also 5m and 10m respectively. The pipeline has been buried in depth 1.75m relative to the pipe center.

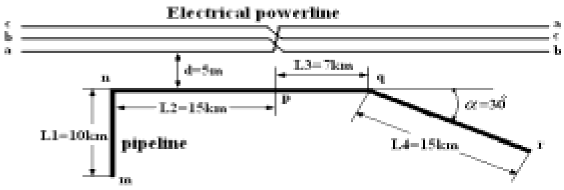


Fig. 9 Power line and adjacent pipeline.

Table 1
Pipeline and soil data

| | |
|---|---|
| Relative electrical permeability of soil | 3 |
| Conductivity of soil | 0.001 s/m |
| Buried depth | 1.75m |
| Pipe diameter | 1m |
| Coating thickness | 5cm |
| Resistivity of the coating | 353186 ohm-m |
| Soil resistivity | 1000 ohm-m |
| Pipe resistivity (steel) | 0.000000862 ohm-m |
| Relative magnetic permeability of pipe | 1452 |
| Relative electrical permeability of coating | 37 |

Coating admittance or latitudinal admittance using (26) yields,

$$y = 0.1866 + 0.00678j \ \frac{s}{km}$$

By (26), (25) and several times iteration,

$$z = 0.2056 + 0.6233j \quad \Omega/km$$

Therefore propagation constant and characteristic impedance of the pipeline will be

$$\gamma = 0.2733 + 0.2053j \quad km^{-1}$$

$$z_0 = 1.5763 + 1.0967j \quad \Omega$$

Between points m to n or segment $s_1$, longitudinal electric field or ELF along the pipeline is zero, thus just the impedances of $\pi$ model is calculated for this segment:

$$Y_{12} = -0.0598 - 0.0314j \quad \Omega^{-1}$$

$$Y_1 = Y_2 = 0.4872 - 0.2616j \quad \Omega^{-1}$$

Between points n to p or segment $s_2$, ELF along the pipeline is constant and can be calculated by (2). Of course we should find mutual impedances using (3) for each conductor,

$$D_e = 2951.6 \ m$$

$$Z_a = 0.0493 + 0.342j \ \Omega / km$$

$$Z_b = 0.0493 + 0.3301j \ \Omega / km$$

$$Z_c = 0.0493 + 0.3168j \ \Omega / km$$

Considering sequence ABC for three phase current,

$$E = 500\angle 0° Z_a + 500\angle -120° Z_b + 500\angle 120° Z_c$$

$$= 5.759 + 9.275j \ \ V / km$$

Using (18),

$$I_{s1} = I_{s2} = 16.168 - 3.905j \quad A$$

and (19),

$$Y_{12} = -0.0147 + 0.009j \quad \Omega^{-1}$$

$$Y_1 = Y_2 = 0.4425 - 0.3065j \quad \Omega^{-1}$$

Between points p to q or segment $s_3$, as segment $s_2$, we will have;

$$E = 10.912 - 6.3j \ \ V / km$$

$$I_{s1} = I_{s2} = -3.906 - 18.794j \quad A$$

$$Y_{12} = -0.0695 - 0.1336j \quad \Omega^{-1}$$

$$Y_1 = Y_2 = 0.476 - 0.1563j \quad \Omega^{-1}$$

For ramped part of the pipeline using relation (22),

$$\Delta l = \frac{0.1 \times 5}{\sin 30°} = 1 \quad m$$

It is too small for first segment. This small value has been found due to relative large value of angle $\alpha$. Therefore relation (20) is checked,

$$l \le \frac{0.01}{|\gamma|} = 29m$$

and relation (22) for this length,

$$\Delta l = \frac{0.1 \times D}{\sin 30^\circ} \le 29m \Rightarrow D \le 145m$$

These two last calculation shows that we can use simplified model of fig. 5, up to the pipeline distance from the power line gets about 145m. For distances greater than 100m we can neglect the magnetic coupling between power line and the pipeline. Therefore only the impedances of remaining part (or better total ramped length) of the pipeline get affected. So for the segment q up to r,

$$Y_{12} = -0.0147 + 0.009j \quad \Omega^{-1}$$

$$Y_1 = Y_2 = 0.4425 - 0.3065j \quad \Omega^{-1}$$

Now we draw the equivalent circuit for all pipeline length as fig. 10.

Using node voltage analysis method, voltages of nodes can be found,

$$V_m = 2.1\angle -96^\circ V \quad V_n = 16.1\angle -158.06^\circ V$$

$$V_p = 16.36\angle 89.47^\circ V \quad V_q = 20.45\angle -37.89^\circ V$$

$$V_r = 0.676\angle 145.43^\circ V$$

Now we can use these values as the boundary condition voltages for each segment, and by (5), (6) and (13), (14), able to find voltage and current relations for each segment. For example for segment 3,

$$k_1 = 4.2845 - 2.0195j$$

$$k_2 = -0.0761 + 0.5727j$$

$$I(x) = 5.07\angle -30.7^\circ \; e^{-\gamma x} + 1.48\angle 19.4^\circ \; e^{\gamma x} + 19.19\angle -101.7^\circ \quad A$$

$$V(x) = 9.74\angle 4.1^\circ \; e^{-\gamma x} - 2.72\angle 54.3^\circ \; e^{\gamma x} \quad V$$

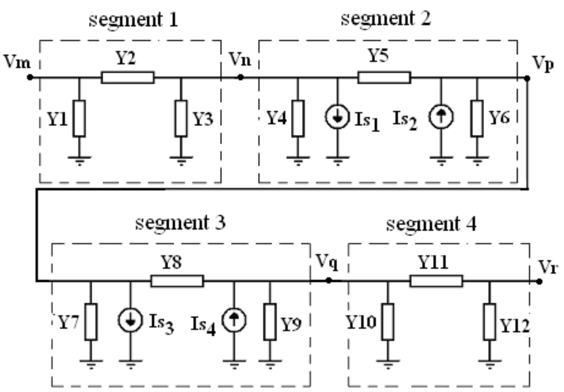


Fig. 10 Pipeline equivalent circuit.

In the second example assume a ramped pipeline in the previous system which has 5km length. Horizontal distance between the pipeline and power line is variable so that at the beginning is 5m and at the end 7.5m. Fig. 11 shows this service. Angle $\alpha$ will be,

$$\alpha = \sin^{-1}\frac{7.5-5}{5 \times 10^3} = 0.0286^\circ$$

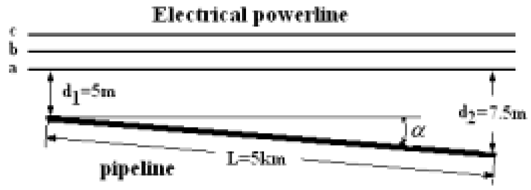


Fig. 11 ramped pipeline.

Using relation (22) for first segmentation,

$$\Delta l_1 = \frac{0.1 \times 5m}{\sin\alpha} \approx 1km$$

next,

$$\Delta l_2 = \frac{0.1 \times (5 + \Delta l_1 \sin\alpha)}{\sin\alpha} \approx 1.1km$$

and also,

$$\Delta l_3 = 1.2km$$

$$\Delta l_4 = 1.3km \to 1.7km$$

For remaining 400m length of the pipeline, we can define a new segment, but in this example with a little more approximation we added it to part four.

Other quantities and equivalent circuit parameters of the pipeline are extracted as the previous example, except that the ELF must be calculated using relation (23) to change its direction toward the pipeline. Fig.12 shows the equivalent circuit with values of elements.

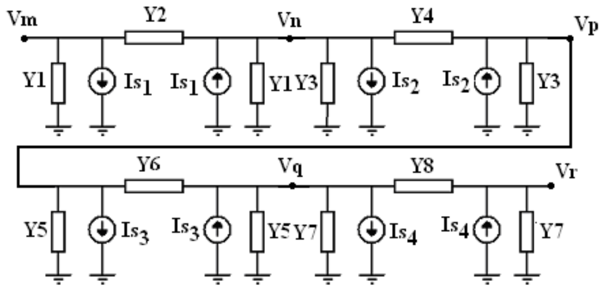


Fig. 12 Equivalent circuit of ramped pipeline

Y1=0.0887+2.4035j, Y2=0.448-1.447j, Is1=11.455+12.324j, Y3=0.0975+2.4532j, Y4=0.4014-

1.314j, Is2=11.367+12.225j, Y5=0.1063+2.447j, Y6=0.3623-1.2062j, Is3=11.336+12.076j, Y7=0.15+1.452j, Y8=0.231-0.851j, Is3=11.202+11.754j,

Finally using this equivalent circuit we can calculate voltages of each node consequently current and voltage functions for each segment using relations (5), (6) and (13), (14).

## 7.Conclusion

In this paper a straight forward method has been constructed from beginning to end of calculating the induced voltage from the electrical power line to adjacent nonparallel complicated configuration of buried pipeline. Longitudinal electric field simulation shows the induced voltages can be increased dangerously very much during fault conditions. A two ports circuitry network has been extracted for modelling the pipeline as the method used for electrical power line itself. This circuitry network has been modified for each small length pipeline and also orthogonal and ramped pipelines respect to the power line which have been utilized for complicated configuration of pipeline. The longitudinal impedance and latitudinal admittance of the pipeline have been discussed and a relation for latitudinal admittance has been extracted by assuming soil as a conductor relative to dielectric coating of the pipeline. Two numerical services in different situations were analyzed to show simplicity and effectiveness of the method for every type of services.

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