PIPELINE GROUNDING CONDITION: A CONTROL OF PIPE-TO-SOIL POTENTIAL FOR AC INTERFERENCE INDUCED CORROSION REDUCTION

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Abstract: The interference effect from high voltage overhead lines on nearby metallic pipelines is a major challenge for utility owners due to the induced AC potentials on metallic pipelines. Nevertheless, numerous mitigation techniques have been proposed in the past to curtail the effect of AC potentials on pipelines. One of these techniques is the use of grounding conditions for the metallic pipelines. In this paper, we present through modelling, the computation and comparison of the various approaches for grounding metallic pipe installed near high voltage overhead lines for AC mitigation purposes. A Rand Water pipeline installed near an Eskom 275 kV transmission line at Strydpan, South Africa was used as a case study. The model simulation results of the studied network show that the pipe grounding condition in which the pipeline isolated at both ends of the parallel region with an insulating flange gives better performance in terms of AC potential reduction. This, in conjunction with other AC mitigation techniques can reduce the level of AC potential to the barest minimum or below a threshold in which AC corrosion possibilities are lower.

Key words: AC interference, pipeline, grounding, mutual impedance, pipe-to-soil potential.

1. INTRODUCTION

The problem of AC interference from high voltage power lines on metallic pipelines has captured all-round recognition in the past years. This is due to the tendency to locate metallic pipelines in the same utility corridor with transmission lines. In addition, due to the land use regulation and environmental issues, pipelines and power lines are now frequently being installed to follow the same route. The currents flowing through the transmission line conductors produce a time varying electromagnetic field which couples to metallic pipelines (buried or aerial) placed in parallel with the line. Unfortunately, the ground does not provide shielding to magnetic field and therefore makes underground metallic pipeline in proximity to overhead high voltage transmission lines (HVTLs) to be prone to inductive coupling from the lines. Consequently, voltage is induced in the pipelines. The induced voltage is known to accelerate the corrosion process of pipelines [1, 2]. More so, its effect on the operational condition of the pipeline cathodic protection system has also been reported [3-5].

Several standards and safety guides dealing with this problem are available in the published literature. These standards are meant to protect the pipeline from corrosion [6] as well as for operational personnel safety [7]. According to [7], the induced potential on pipes should be mitigated if the value exceeds 15 V_{rms}, for personnel safety. More so, in order to reduce the corrosion probability, the potential on the pipe at any point along the parallel route of the transmission lines should not exceed;

(i) 10 V when the surrounding soil resistivity is greater than 25 Ωm; and
(ii) 4 V when the soil resistivity is less than 25 Ωm [6].

For pipeline in perfect parallelism with the transmission lines, the magnetic line of flux cuts across the metallic pipe at maximum strength and as a result, the effect of the inductive coupling is mostly felt. Moreover, with the increasing human population, there are more tendencies of installing pipelines in the same utility corridor with an existing HVTL. Therefore, the threat posed by AC on metallic pipelines increases. This makes it an important research area over the last years.

AC assisted corrosion has been a major challenge to pipeline owners around the world. While it has gained widespread recognition, the past years have seen a surge of research activities in this area. Research activities in this area, to mention but a few, include; the influence of magnetic field distribution on metallic pipelines [8-11], induced voltage analysis on buried and aerial pipelines [12-15], the influence of soil topologies on the induced potential on metallic structure from nearby faulted power line [16-18], the influence of energy demand on the corrosion rate of pipelines [19]. In [19], the authors revealed that pipelines installed in urban cities where the energy demand is high has the greatest possibility of accelerated corrosion. Conversely, for pipes installed in rural areas, AC corrosion possibility is minimal due to the reduced energy demand. It follows, therefore, that in any of the cases, whether rural or urban cities, pipelines are public asset and must be prevented from damage through AC corrosion. In the past, several AC mitigation techniques were reported to include the use of Faraday cage, insulation joints, AC decoupling devices and pipe grounding [20-24] to mention but a few. Even with the use of these techniques, several cases of AC assisted corrosion are still being reported [22, 24]. Pipeline grounding is an equivalent of a reduction in the coating resistance of a pipe and has been reported to be an effective means of reducing the AC induced potentials [23].

In this paper, the different pipe grounding conditions to arrest AC potential is examined through modelling. A Rand water pipeline installed in the energy utility corridor of high voltage transmission line at Strydpan, South Africa is used as a case study. The rest of the paper is organised accordingly. Section 2 presents the methodology used featuring the model description and formulations. In Section 3, the simulation results of the model were presented while Section 4 concludes the paper.

2. NETWORK MODEL

2.1 Network of the HVTL and Pipeline Description.

The studied network consists of a single circuit transmission line in horizontal configuration (one of the Eskom transmission line at Strydpan, South Africa) and a buried pipeline of depth h_p as illustrated in Figure 1.

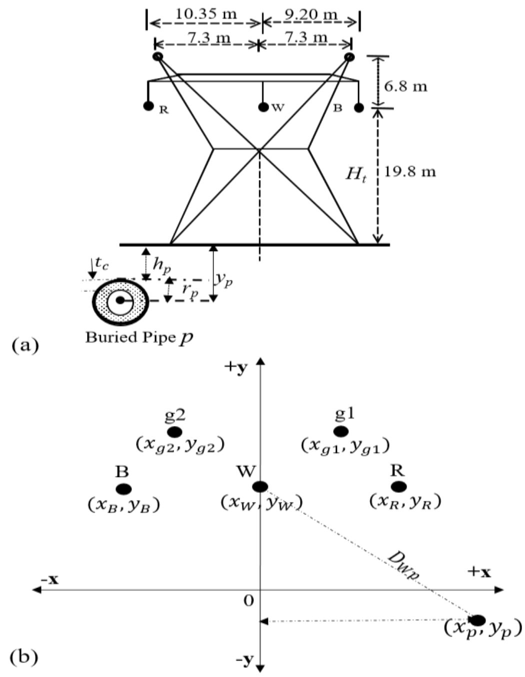

Figure 1: Schematics of the study network (a) transmission line-pipeline right of way (ROW) (b) coordinates of the pipeline-transmission lines.

Considering the Figure 1, the pipeline with a radius r_p is coated with fusion bonded epoxy with a coating thickness of t_c, runs parallel to the HVTLs for a distance L. The dimension of the transmission line tower obtained from the Eskom power utility is also illustrated in Figure 1.

Considering the single-circuit overhead line with i^{th} earth wire, each current in the phase conductors induces a voltage on the pipeline through the appropriate mutual impedance between the pipeline and the conductor. The longitudinal emf induced on the pipeline due to the three-phase currents I_R, I_W, I_B and the earth wire current can be expressed as

$$E_p = I_R Z_{Rp} + I_W Z_{Bp} + I_B Z_{Bp} - \sum_{i=1}^{n} I_{g_i} Z_{g_i p} \qquad (1)$$

where, I_R, I_W, I_B and I_{gi} are the steady state currents in the phase conductors and the i^{th} earth wires, and Z_{Rp}, Z_{Wp}, Z_{Bp} , Z_{gip} are the mutual impedances (Ω/m) between the phase conductors, the i^{th} earth wire and the pipeline, n represents the number of earth wires on the tower. The potential drop across the i^{th} earth wire due to the effect of the phase conductors can be expressed as

$$V_{g_i} = I_R Z_{Rg_i} + I_W Z_{Wg_i} + I_B Z_{Bg_i} \qquad (2)$$

Therefore, the currents in the earth wires I_{gi} is given as

$$I_{g_i} = \frac{V_{g_i}}{Z_{gg_i}} = \frac{1}{Z_{gg_i}}\left(I_R Z_{Rg_i} + I_W Z_{Wg_i} + I_B Z_{Bg_i}\right) \qquad (3)$$

where, Z_{ggi} denotes the self-impedance of the i^{th} earth wire. By substituting (3) into (1), the emf induced on the pipeline is expressed as

$$E_p = I_R\left(Z_{Rp} - \sum_{i=1}^{n}\frac{Z_{Rg_i} Z_{g_i p}}{Z_{gg_i}}\right) + I_W\left(Z_{Wp} - \sum_{i=1}^{n}\frac{Z_{Wg_i} Z_{g_i p}}{Z_{gg_i}}\right) + I_B\left(Z_{Bp} - \sum_{i=1}^{n}\frac{Z_{Bg_i} Z_{g_i p}}{Z_{gg_i}}\right) \qquad (4)$$

The mutual impedance between a k^{th} conductor and the buried pipeline is given by equation [25, 26]

$$Z_{k-p} = \frac{\mu_0 \omega}{8} + j\left(\frac{\mu_0 \omega}{2\pi}\log_e\left(\frac{\delta_e}{D_{k-p}}\right)\right) \quad \forall k \in (\mathrm{R,W,B,g}_i) \qquad (5)$$

In (5), μ_0 represents the permeability of free space, ω is the angular frequency of the line, $D_{k\text{-}p}$ represents the geometric mean distance (GMD) linking the R,W,B or g_i conductors and the pipeline. The earth's skin depth (depth of penetration) δ_e, with the earth relative permittivity μ_r, is expressed as [12, 27]

$$\delta_e = \sqrt{\frac{\rho}{\mu_0 \mu_r \pi f}} \qquad (6)$$

From (5), the GMDs linking each of the R-W-B or g_i conductors and the pipeline or between the R-W-B phase conductors and the i^{th} earth wire can be derived using Figure 1 (b) from (7)

$$D_{k-p} = \left(\left(x_p - x_k\right)^2 + \left(y_k - y_p\right)^2\right)^{1/2} \quad \forall k \in (\mathrm{R,W,B,g}_i) \qquad (7)$$

where x_p represents the horizontal position of the pipeline across the transmission line ROW, $y_p=h_p+r_p+t_c$ represents the pipe depth from the ground to the centre of the pipe. Also, $y_k \, \forall k \in (\mathrm{R,W,B,g}_i)$ are the various heights of the phase conductors or the earth wire from the ground surface while their horizontal position is represented by $x_k \, \forall k \in (\mathrm{R,W,B,g}_i)$ on the x-coordinate.

More so from (4), Z_{ggi} denotes the self-impedance of the i^{th} earth wire conductor and can be expressed as [25, 26]

$$Z_{gg_i} = R_{g_i} + \frac{\mu_0\omega}{8} + j\left[\frac{\mu_0\omega}{2\pi}\left(\frac{1}{4} + \log_e\left(\frac{\delta_e}{R_{GM_i}}\right)\right)\right] \quad (8)$$

where R_{gi} and R_{GMi} denote the AC resistance and the geometric mean radius of the i^{th} earth wire conductor respectively.

The equation (4) can be used to estimate the longitudinal emf (V/m) induced on the pipe length exposed to the transmission line in parallel route. Moreover, a pipeline has a finite impedance to earth, which is strewn along its length. Therefore, to estimate the pipe-to-soil potential at points along its length, the magnetic field coupling from the transmission lines to the pipeline can be pictured as a distributed induced emf source on the pipeline [25]. To this end, the pipeline can be modelled as a lossy transmission line having a series impedance Z (Ω/m) and a shunt admittance Y (Ω^{-1}/m) as shown in Figure 2.

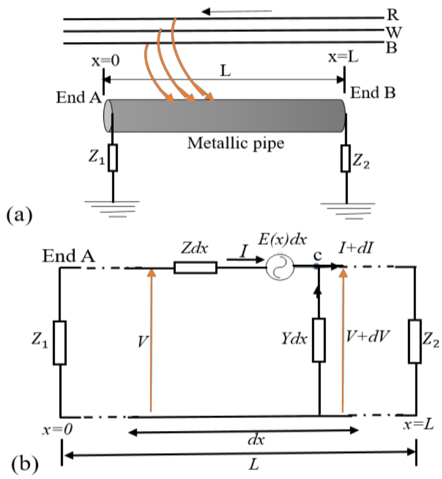

Figure 2: Schematics of a pipeline-power line inductive coupling (a) pipeline section parallel to a power line and (b) pipeline equivalent circuit [25, 28].

In Figure 2, $E(x)$ represents the induced emf (V/m) derived from (4) while Z_1 and Z_2 are the impedance at the termination ends of the pipeline (ends A and B). Analysing Figure 2(b) using Kirchhoff's law,

$$V(x) - ZdxI(x) + E(x)dx - \left[V(x) + dV(x)\right] = 0 \quad (9)$$

And from (9),

$$dV(x) = E(x)dx - ZdxI(x) \quad (10)$$

Dividing (10) by dx, therefore,

$$\frac{d}{dx}V(x) = E(x) - ZI(x) \quad (11)$$

More so, considering the Figure 2(b) and applying Kirchhoff's current law to node c,

$$I(x) - \left(I(x) - dI(x)\right) = YdxV(x) \quad (12)$$

$$dI(x) = -YdxV(x)$$

Dividing through by dx,

$$\frac{d}{dx}I(x) = -YV(x) \quad (13)$$

Differentiating (13) with respect to x, results to

$$\frac{d^2}{dx^2}V(x) = \frac{d}{dx}E(x) - Z\frac{d}{dx}I(x) \quad (14)$$

By substituting (13) into (14),

$$\frac{d^2}{dx^2}V(x) = ZYV(x) + \frac{d}{dx}E(x) \quad (15)$$

If $\gamma = \sqrt{ZY}$, then (15) can be re-written as

$$\frac{d^2}{dx^2}V(x) = \gamma^2 V(x) + \frac{d}{dx}E(x) \quad (16)$$

where γ represents the propagation constant of the pipe. The Z and the Y of a buried coated pipe is expressed as [29]

$$Z = \frac{1}{\pi D_p}\sqrt{\pi f \rho_p \mu_0 \mu_p} + \frac{\pi f \mu_0}{4} + j\left[\frac{1}{\pi D_p}\sqrt{\pi f \rho_p \mu_0 \mu_p} + \mu_0 f \ln\left(\frac{3.7}{D_p}\sqrt{\frac{\rho_{soil}}{2\pi f \mu_0}}\right)\right] \quad (17)$$

$$Y = \frac{\pi D_p}{\rho_c t_c} + j\left(2\pi f \frac{\varepsilon_0 \varepsilon_c \pi D_p}{t_c}\right) \quad (18)$$

In (17), D_p denotes the pipe diameter, ρ_p represents the resistivity of the pipe material (Ω.m), ρ_{soil} is the resistivity of the soil (Ω.m), μ_0 is the permeability of free space, μ_p is the relative permeability of the pipe material and f denotes the operating frequency of the line. While in (18), t_c, ρ_c and ε_c represent the coating thickness, coating resistivity and the relative permittivity of the coating material respectively. ε_0 is the permittivity of free space.

Along the length of the parallel section of the pipeline, the induced emf is constant under both steady state and fault conditions of the line [25], that is, $E(x)=E_p$. Therefore, to appraise the pipe-to-soil potential $V(x)$ along the length of the pipeline section at any point $0 \le x \le L$, the equation (16) has a solution given by (19) [25, 28]. Where in (19),

$Z_0 = \sqrt{\frac{Z}{Y}}$, denotes the pipeline characteristic impedance in (Ω).

In order to adhere strictly to the safety regulations and protection of pipeline from AC corrosion cases, the level of the estimated potential along the length of the pipe must be reduced. Several efforts for reducing the AC potential effect using pipe grounding conditions have been proposed. As reported earlier in previous section, pipeline grounding is an equivalent of a reduction in the coating resistance of a pipe and has been reported to be

$$V(x)=\frac{E_p}{\gamma}\left\{\frac{\left[Z_2(Z_1-Z_0)-Z_1(Z_2+Z_0)e^{\gamma L}\right]e^{-\gamma x}-\left[Z_1(Z_2-Z_0)-Z_2(Z_1+Z_0)e^{\gamma L}\right]e^{-\gamma(L-x)}}{(Z_1+Z_0)(Z_2+Z_0)e^{\gamma L}-(Z_1-Z_0)(Z_2-Z_0)e^{-\gamma L}}\right\} \tag{19}$$

an effective means of reducing AC induced potentials [23]. At the ends of the parallel routing (ends A and B), impedances Z_1 and Z_2 are usually chosen to represent the electrical characteristics of the pipeline parallel section [25, 28]. The different conditions for choosing these impedances were compared in this paper. These conditions are highlighted as the following cases [25];

- Case (i): The pipeline continues for several kilometres after the end of the parallel route with the power line (ends A and B); $Z_1=Z_2=Z_0$.
- Case (ii): The pipeline continues at $x \leq 0$ and it's isolated at $x=L$ (terminal B in figure 2) with an insulating flange; $Z_1=Z_0$; $Z_2=\infty$.
- Case (iii): The pipeline is grounded at $x=0$ (terminal A) and continues beyond $x \geq L$; $Z_1=0$; $Z_2=Z_0$.
- Case (iv): The pipeline is isolated at both ends of the parallel region (terminal A and B) with an insulating flange; $Z_1=Z_2=\infty$.

2.1 Case study parameters.

Table 1 shows the case study parameters used for the simulation. In the computation, the longitudinal induced emf on the buried pipeline below the power lines was obtained for a balanced system in which the current in the conductors is at a phase angle of 120° to one another. More so, a symmetrical load current and homogenous soil with a measured resistivity of 12.96 Ωm were considered. The longitudinal induced emf was evaluated for the pipeline placed at a horizontal distance of up to 24 m measured from the centre line of the power line being the transmission line servitude stipulated by Eskom in South Africa for 275 kV–400 kV lines [30]. The computations of the pipe-to-soil potential was performed and compared for the four pipe grounding conditions. MATLAB software was used for the computation and presentation of result.

Table 1: Parameters of the studied transmission line and pipeline.

Transmission line configuration type	Single circuit horizontal
Operating voltage	275 kV
Number of bundle conductors	2
Conductor type	Zebra
Template temp.	50°C
Thermal rating	676 MVA
Max. allowable current at 275 kV	410 A per conductor
Earth wire parameters	
Type	19/2.65 mm galvanised steel
Diameter	13.48 mm
Resistivity	45×10^{-8} Ωm
AC resistance	3.44×10^{-3} Ω/m
Pipeline parameters	
Material type	Steel
Parallel exposure length	1000 m
Diameter	1000 mm
Burial depth	1 m
Coating type	FBE
Coating thickness	4 mm
Coating resistivity	2×10^{6} Ωm

3. RESULTS AND DISCUSSIONS

Figure 3 shows the profile of the pipe-to-soil potential on the pipeline placed at the transmission line servitude distance of 24 m suggested by Eskom [30] for the case (i). Observing the figure, one can see that the maximum potential occurs at both ends of the pipeline section, that is, point $x=0$ and $x=L$. Beyond the point x=0 along the pipe length, the potential reduced drastically until it reaches zero at the midpoint of the pipeline. Afterwards, it increases with distance till the other terminal end (end B) of the pipe. One can deduce from this result that, with this type of condition, the maximum level of the potential will occur at the start and end points of the parallel route.

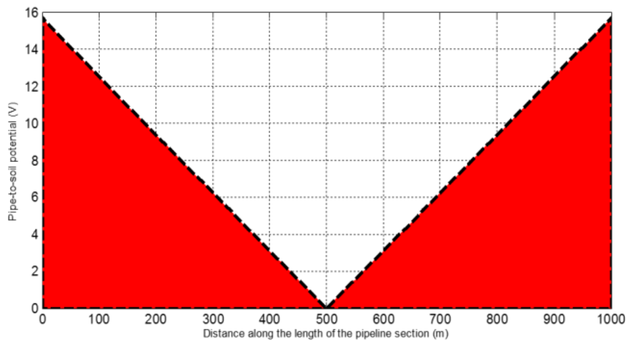

Figure 3: Pipe-to-soil potential on pipeline due to case (i) for the pipe grounding.

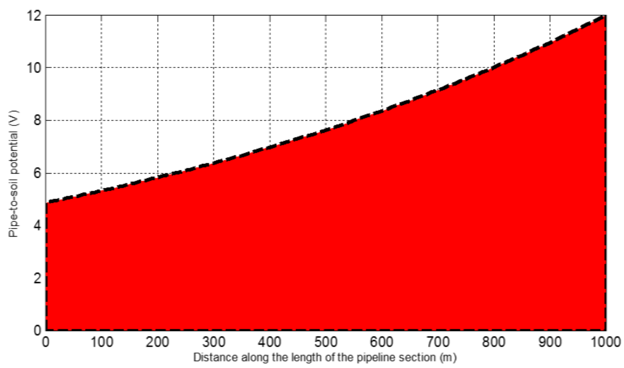

Figure 4: Pipe-to-soil potential on pipeline due to case (ii) for the pipe grounding.

In Figure 4, the profile of the AC potential on the pipeline with the same condition of placing the pipeline in the transmission line servitude, for the case (ii) is presented. Analysing Figure 4, the AC potential for this case increases gradually from a level, say 5 V, at the start (point A) to the end (point B) of the parallel route. The maximum induced AC potential at this point is lower compared to the one in Figure 3.

A similar result is obtained for the case (iii) as depicted in Figure 5. In Figure 5, the profile of the AC potential increases drastically from a level, say 3, at the start to end point of the parallel route. While the potential at the start point (point A) is lesser than that of the case presented in Figure 4, the potential at the other end of the parallel route (point B) is relatively high.

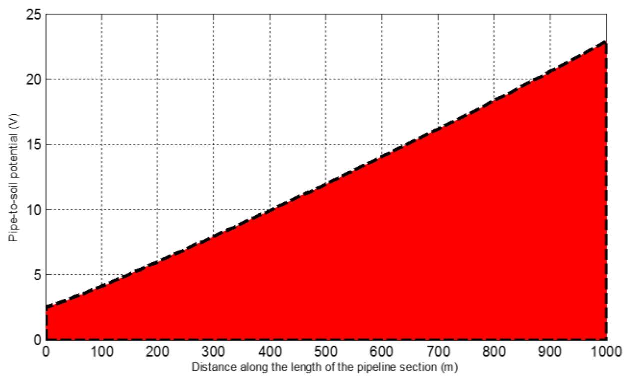

Figure 5: Pipe-to-soil potential on pipeline due to case (iii) for the pipe grounding.

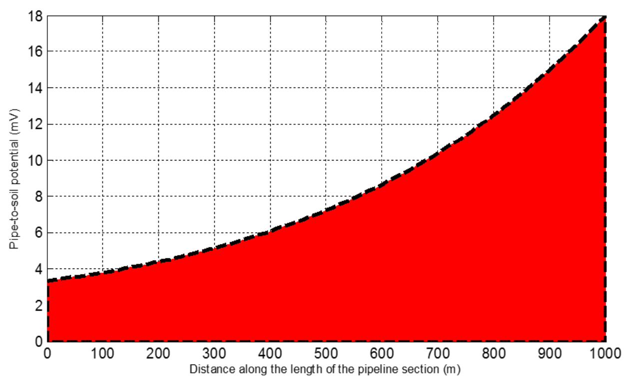

Figure 6: Pipe-to-soil potential on pipeline due to case (iv) for the pipe grounding.

In Figure 6, the profile of the pipe-to-soil potential on the pipeline placed at the transmission line servitude for the case (iv) is presented. A detailed analysis showed that in this case, a large reduction in AC potential on the pipeline is achieved compared to cases (i to iii). The potential is near zero level and with the large magnitude at the end of the parallel route (point B from Figure 2).

The above analysis leads to the recommendation that, in any case where the pipeline length has a parallel route with the transmission lines, pipe grounding condition (iv) should be adopted. Also, other AC mitigation techniques such as Faraday cage can be installed along the parallel route, though at the expense of cost of mitigation. Moreover, choosing an appropriate AC reduction condition shall take into account a careful selection of the pipe coating materials as it has an effect on the AC potentials on pipelines [28]. A detailed study on the effect of pipe coating on the AC induced potential can be found in [28].

4. CONCLUSION

A comparison of the pipe grounding conditions for curbing the effect of AC potential on pipelines is presented. The case study further affirmed that a reduced potential on pipeline can be achieved with different pipe grounding conditions. The model simulation results of the studied network show that the case (iv) of the pipe grounding conditions gives better performance in terms of potential reduction on pipelines. The potential is greatly reduced to near zero level with this condition. This, in conjunction with other AC mitigation techniques can adversely reduce the level of AC potential to the barest minimum or below a threshold in which AC corrosion possibilities are lower.

5. ACKNOWLEDGEMENT

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