Proceedings of the World Congress on Engineering and Computer Science 2017 Vol I
WCECS 2017, October 25-27, 2017, San Francisco, USA

Low Frequency Induction Simulation of Power Transmission Lines and Pipelines: A Comparative Study

K.B. Adedeji, *Member IAENG*, B.T. Abe, *Member IAENG*, and A.A. Jimoh, *SMIEEE*
*

Abstract—**Water/oil bearing metallic pipelines share common corridor with overhead power transmission lines, with attendant problem of induced voltage on the pipelines. Depending on the conditions of the line, the induced voltage can pose a threat to working personnel safety. Therefore, this necessitates its estimation on metallic pipelines. For the computation of the induced voltage on buried pipelines from nearby high voltage transmission lines using circuit analysis, the mutual impedance between the power line conductors and the pipeline plays a major role. In this paper, the authors present an investigation of the mutual impedance approximations in the computation of the induced open circuit potential on a pipeline. These approximations include Carson, Lucca and Ametani mutual impedance approximations. Two different realistic power line geometries of single circuit horizontal and vertical configurations are considered. The simulation of the induced open circuit potential was performed in MATLAB software environment. The manuscript provides detailed graphs and numeric data which can be useful for the analysis of the induced voltage on pipelines and in choosing the appropriate mutual impedance approximation.**

Keywords: Induce voltage, Mutual impedances, Carson, Ametani, Lucca, Pipeline, Transmission lines

1 Introduction

Over the last decades, alternating current (AC) interference induced on metallic pipelines as a result of closeness to power transmission lines and AC traction systems is acknowledged as one of the major challenges facing water utilities. The ever increasing cost of right of way suitable for pipelines and power transmission lines coupled with the land use regulation has forced utility companies to install pipelines and power lines in the same corridor.

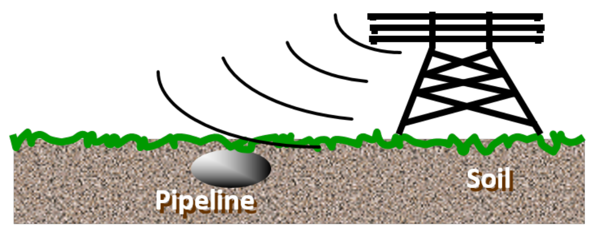

Figure 1: A typical power line-pipeline magnetic field coupling.

The situation is on the increase whereby new pipelines are being installed near an existing power line. The currents flowing through the transmission line conductors create an electromagnetic field which varies in time and space. This field couples with metallic pipelines which are at right angle to the direction of the line of magnetic flux as illustrated in Fig. 1. As a result, voltage is induced in such a structure according to Faraday law. The induced voltage can occur during both the steady state and fault conditions of the lines [1–4]. In extreme cases, especially during fault conditions, a large voltage magnitude can be impressed on the metallic pipeline. Consequently, the pipe and its coating materials can be compromised if this voltage exceeds the stress voltage of the pipe coating material [5]. More importantly it poses a danger to personnel touching the exposed part of the metallic pipe. For personnel safety, several regulations and safety guide have been proposed and published. Among the notable guides are those proposed by CIGRE [6] and the national association of corrosion engineers (NACE) [7]. NACE [7] stated that the induced voltage on pipelines should be mitigated if exceeds 15 V, for personnel safety. Also, previous research works revealed that the induced voltage on pipelines is known to accelerate the corrosion process [8–10] and adversely affects the performance of the cathodic protection systems of pipelines [11–13].

Previous research effort revealed that in order to alleviate the AC corrosion probability on metallic pipelines that is subjected to AC interference from power lines, the induced AC potential on the pipe should not exceed;

*Manuscript received January 18, 2017; revised March 27, 2017. This research work was supported by Rand Water and the National Research Foundation (NRF) of South Africa.
The authors are with the Department of Electrical Engineering, Tshwane University of Technology, Pretoria South Africa.
Corresponding author: Adedeji K.B., Tel: +27622935332, Email: adedejikb@tut.ac.za

ISBN: 978-988-14047-5-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

i. 10 V where the soil resistivity is greater than 25 Ωm;
ii. 4 V where the soil resistivity is less than 25 Ωm [14].

For this regulation to be respected, it is necessary to estimate the induced voltage on the pipelines either through measurements or computations. In the past, the computation of the induced voltage was conducted using circuit analysis method [1, 15–17] or numerical methods using finite element approach [2, 3, 18–20]. This paper focuses on the former approach (circuit analysis). In the circuit analysis approach, the concept of mutual impedances between two circuits (power line conductors to metallic pipelines) is used. In this method, each phase conductor of the line induces a voltage on the metallic pipeline through its corresponding mutual impedances. There are three different mutual impedance formulations in the literature for computing the induced open circuit emfs on pipelines. These include the Carson, Lucca and Ametani mutual impedance approximations [5, 21–23]. The focus of this paper is to compute and compare the induced open circuit potential on a pipeline using these three approximations. The rest of the paper is organized as follows. Section 2 presents the model formulation and methodology used for the work. In Section 3, the results of the comparison of the three approximations are presented, while Section 4 concludes the paper.

2 Methods

2.1 Model description and derivation: power line-pipeline ROW

In this paper, three different mutual impedance approximations for the computation of the induced voltage on a buried pipeline are considered and compared. The computation was performed using a single circuit horizontal and vertical power line geometries. Fig. 2 shows the schematics of the transmission lines and the buried pipeline. The dimensions of the power lines are illustrated in Fig. 2. The phase conductors are labelled R, W, B. The lowest conductor of the line is measured at a height H_t of 17 m to the tower. If the height of the conductor

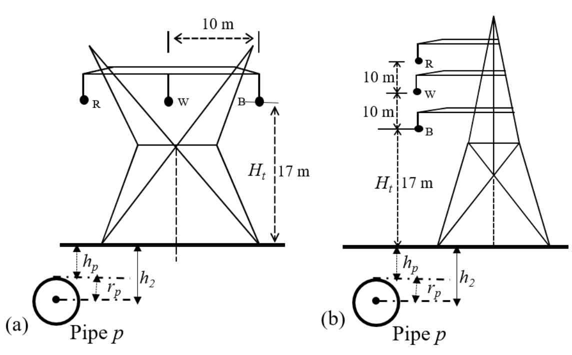

Figure 2: Schematics of the pipeline-transmission line right of way (a) horizontal (b) vertical geometry.

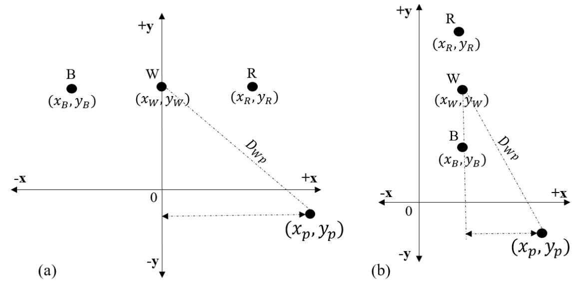

Figure 3: Coordinates of the pipeline-transmission line right of way (a) horizontal (b) vertical geometry.

measured from the ground is H_t and the maximum mid-span sag of Sag_{max}, then the mid-span ground clearance H_g is given by

$$H_g = H_t + Sag_{max} \tag{1}$$

For a maximum mid-span sag of 5 m, the mid-span ground clearance H_g is 12 m. The pipeline, with a radius r_p of 300 mm is buried at a depth h_p of 1 m in a homogeneous soil with a resistivity of 100 Ωm. The pipe is considered to run parallel with the line for a length of 1 km.

For easy analysis, the power line and pipeline configurations are expressed in two dimensional Cartesian coordinate systems as shown in Fig. 3. In Fig. 3,(x_R;x_W;x_B, y_R;y_W;y_B) are the coordinates of the phase conductors while (x_p, y_p) is the coordinate of the buried pipe. For the computation, some assumptions and simplifications were made. The phase conductors of the line are assumed to be parallel to each other and the effect of the earth wire is neglected.

The soil is assumed to be conductive but magnetically transparent [24], flat and homogeneous, of finite resistivity. The computation of the longitudinal induced open circuit voltage on the pipeline, under steady state conditions was performed using simple power system concepts and mutual impedance relations between the phase conductors and the pipeline [15–17, 21, 25].

Under steady state conditions and considering a single circuit overhead line, each current induces a voltage on the pipeline through the appropriate mutual impedance between the pipeline and the phase conductor due to inductive coupling from the transmission line. The longitudinal emf induced on the pipeline due to the three-phase currents I_R, I_W, I_B is given by

$$E_p = \sum I_i Z_{i-p}, \quad \forall i \varepsilon (R, W, B) \tag{2}$$

where I_i is the steady state current in the i^{th} phase conductor, while Z_{i-p} represents the mutual impedance between the i^{th} conductor and the pipe. i is an index which

ISBN: 978-988-14047-5-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

refers to the phase conductors R,W or B, therefore,

$$E_p = I_R Z_{R-p} + I_W Z_{W-p} + I_B Z_{B-p} \quad (3)$$

If the pipeline runs in parallel with the line for a length L, then the induced open circuit potential V_p on the pipeline is expressed as

$$V_p = E_p L \quad (4)$$

From the induced longitudinal emf in equation (3), one can see that the mutual impedance between the power line conductors and the buried pipeline plays a major role in the computation. Several mutual impedance formulas have been proposed in the literature to include the Carson approximation [5, 21], Ametani [23] and Lucca approximation [22]. Considering Carson's approximation [5, 21], the mutual impedance Z_{i-p} (Ω/km) between the i^th phase conductor and the buried metallic pipe is expressed as

$$Z_{i-p} = 9.869f \times 10^{-4} + j2.8935f \times 10^{-3} log_{10}(\frac{\delta_e}{D_{i-p}}) \quad (5)$$

where D_{i-p} is the geometric mean distance between the pipeline and the i^{th} phase conductor of the line, f represents the operating frequency of the line while δ_e is the depth of the equivalent earth return given as

$$\delta_e = 658.37\sqrt{\frac{\rho}{f}} \quad (6)$$

Furthermore, the mutual impedance (Ω/km) formula proposed by Ametani [23] and Lucca [22] are given in equation (7) and equation (8) respectively.

$$\begin{aligned} Z_{i-p} &= j\omega(\frac{\mu_0}{2\pi})[ln(\frac{S}{D_{i-p}}) \\ &-(\frac{2}{3})(\frac{h_e}{S^2})^3 H_{i-p}(H_{i-p}^2 - 3d_{i-p}^2)], \quad \forall i\epsilon(R,W,B) \end{aligned} \quad (7)$$

$$Z_{i-p} = j\omega(\frac{\mu_0}{2\pi})[exp(\frac{-h_2}{h_e})ln(\frac{S}{D_{i-p}})], \ \forall i\epsilon(R,W,B) \quad (8)$$

From the equations (6, 7 and 8),

$$D_{i-p} = \sqrt{h_{i-p}^2 + d_{i-p}^2}, \quad \forall i\epsilon(R,W,B) \quad (9)$$

where d_{i-p} represents the horizontal distance between the i^{th} phase conductor and the pipe while h_{i-p} depicts the height from the i^{th} phase conductor to the centre of the pipe (m). Using the coordinate system in Fig. 3, these are evaluated as

$$\begin{aligned} h_{i-p} &= y_i - y_p \\ d_{i-p} &= x_p - x_i \end{aligned} \quad (10)$$

Therefore, in the equation (9), for $\forall i\epsilon(R,W,B)$, D_{i-p} is evaluated as

$$\begin{aligned} D_{R-p} &= \sqrt{(x_p - x_R)^2 + (y_R - y_p)^2} \\ D_{W-p} &= \sqrt{(x_p - x_W)^2 + (y_W - y_p)^2} \\ D_{B-p} &= \sqrt{(x_p - x_B)^2 + (y_B - y_p)^2} \end{aligned} \quad (11)$$

Also in the equation (7),

$$H_{i-p} = h_{i-p} + 2h_e, \quad \forall i\epsilon(R,W,B) \quad (12)$$

For each phase conductor and the pipe, H_{i-p} becomes

$$\begin{aligned} H_{R-p} &= (x_R - y_p) + 2h_e \\ H_{W-p} &= (x_W - y_p) + 2h_e \\ H_{B-p} &= (x_R - y_p) + 2h_e \end{aligned} \quad (13)$$

where h_e is the complex depth of the skin effect layer [26] given as

$$h_e = \sqrt{\frac{\rho}{j\omega\mu}}, \quad \mu = \mu_0\mu_r \quad (14)$$

In the equation (12), ω is the angular frequency of the line, μ_0 is the permittivity of free space $(4\pi \times 10^-7)$, μ_r is the relative permeability of the soil. Typical values of the relative permeability of various soils and rocks range from 1.00001 to 1.136 except rocks in iron-mining areas [24]. More so, in the equation (7) and equation (8),

$$S = \sqrt{H_{i-p}^2 + d_{i-p}^2},$$

For the i^{th} phase conductor and the pipe,

$$S = S_{i-p} = \sqrt{H_{i-p}^2 + (x_p - x_i)^2}, \quad \forall i\epsilon(R,W,B) \quad (15)$$

And from equation (8), $h_2(= y_p = h_p + r_p)$, represents the height from the ground to the centre of the pipe as shown in the Figure 2. To this end, h_p represents the burial depth of the pipe while r_p is the radius of the pipe.

The induced open circuit potential was computed using the equation (4) and with the mutual impedance formulations for the two transmission line geometries shown in the Fig. 2. MATLAB software was used for the computation and presentation of results. In addition, the correlation between the mutual impedance approximations was conducted by computing the correlation coefficient of the induced potential due to each approximations. The correlation coefficient is a measure of the degree to which two variables (say A and B) are associated. It is the statistical measure of the strength of the relationship between paired data. This can be expressed mathematically using the Pearson correlation coefficient[27, 28] as

$$r = \frac{\sum_{i=1}^{n}(A_i - \bar{A})(B_i - \bar{B})}{\sqrt{[\sum_{i=1}^{n}(A_i - \bar{A})^2][\sum_{i=1}^{n}(B_i - \bar{B})^2]}}, \quad -1 \leq r \leq 1 \quad (16)$$

where A_i and B_i are the values of the two compared variables A and B for the i^{th} individual while A and B represent the mean.

ISBN: 978-988-14047-5-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

3 Results and Discussions

The profile of the induced open circuit potential on the pipeline for both horizontal and vertical power line geometries, due to the mutual impedance approximations is illustrated in Fig. 4 and Fig. 5. Observing Fig. 4, one can see that the Carson's mutual impedance approximation gives a reasonable voltage induction on the pipeline compared to those obtained for Lucca and Ametani approximations. Analysing the profile of the induced open circuit voltage, at the midpoint of the tower (point 0), a large difference in the values of the computed induced open circuit potential (almost 99%) is observed comparing Carson's to both Lucca and Ametani's mutual impedance approximations.

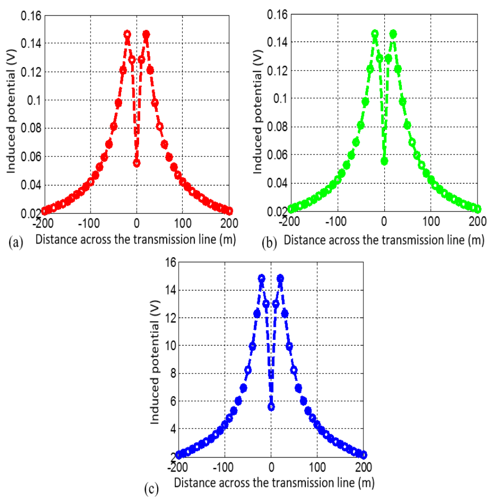

Figure 4: Induced open circuit potential profile due to the mutual impedance approximations for horizontal geometry (a) Ametani (b) Lucca (c) Carson's approximation.

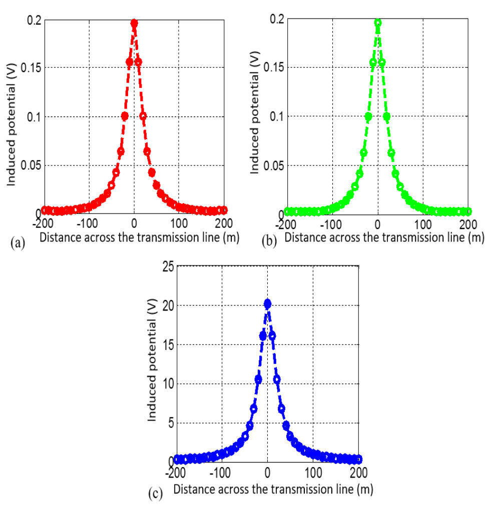

Figure 5: Induced open circuit potential profile due to the mutual impedance approximations for vertical geometry (a) Ametani (b) Lucca (c) Carson's approximation.

Therefore, a careful selection of the mutual impedance formulation is vital in order to avoid underestimation or overestimation of results. More so, the characteristic nature of the profile form due to Ametani (Fig. 4(a)) and Lucca (Fig. 4(b)) mutual impedance approximations is the same.

A similar study of the vertical geometry is illustrated in Fig. 5. In this case and in a similar manner to the results obtained for horizontal configuration, a lager voltage difference is observed at the midpoint of the tower and at other points across the transmission line right of way. The characteristic nature of the induced open circuit potential profile due to Ametani and Lucca mutual impedance approximation is also the same. It should be noted that the results presented are for steady state operation of the power lines. During fault conditions, a different results might be obtained.

In Fig. 6 and Fig. 7, the histogram plot of the induced open circuit potential profile computed using the three mutual impedance approximations, for both horizontal and vertical power line geometries is presented. Observing Fig. 6(a) and (b), one can see that the statistical nature of the induced potential profile computed due to Ametani and Lucca is the same compared to that form by Carson's approximation. A similar result is inferred for the single circuit vertical geometry (Fig. 7).

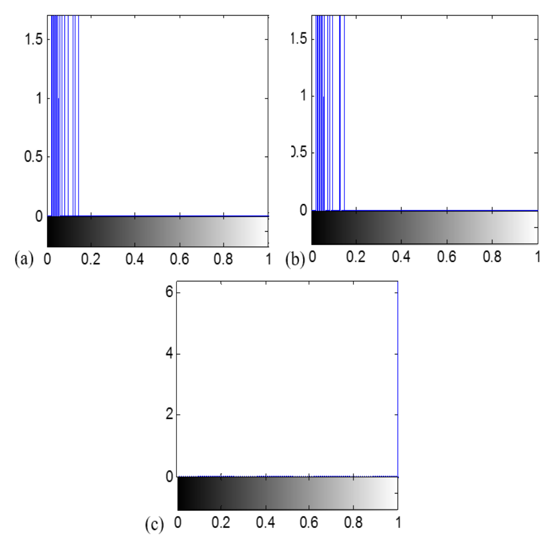

Figure 6: Histogram of the induced open circuit potential profile for the mutual impedance approximations for the horizontal geometry (a) Ametani (b) Lucca (c) Carson's approximation.

To further affirm the correlation existence between the mutual impedance approximations from the induced potential profile, the results of correlation coefficient computed for the studied power line geometries are presented in Table 1.

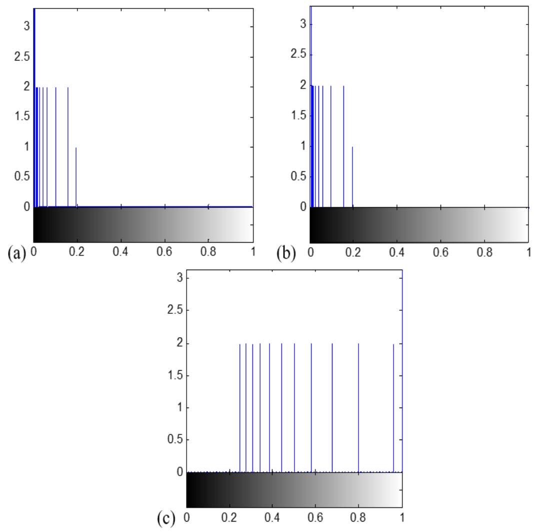

Figure 7: Histogram of the induced open circuit potential profile for the mutual impedance approximations for the vertical geometry (a) Ametani (b) Lucca (c) Carson's approximation.

Table 1: Correlation coefficient of the induced potential due to the mutual impedance approximations.

Mutual impedance approximation	Correlation coefficient	
	Horizontal geometry	Vertical geometry
Ametani-Carson	0.5997	0.5998
Ametani-Lucca	1.0000	0.9999
Lucca-Carson	0.5995	0.5994

Table 1 confirms the existence of a strong relationship for the compared profile due to Ametani-Lucca approximations. The strength of relation varies in degree based on the value of the correlation coefficient obtained. Nevertheless, the compared mutual impedance approximations for the induced potential profile have positive correlation coefficients. This means that a little relationship can be inferred. However, Ametani-Lucca approximations gives better correlation for the power line geometries studied. To this end, the results somewhat differ in the case of vertical geometry (although very close). One major conclusion that can be drawn is that, the computed correlation coefficient of the induced open circuit potential profile for the mutual impedance approximations is somewhat dependent on the power line geometry. Nevertheless, depending on the type of geometry, the correlation between the induced open circuit potential due to Ametani-Lucca mutual impedance approximations is very strong compared to Carson-Lucca or Carson-Ametani approximations.

4 Conclusions

A comparative study of the Carson, Ametani and Lucca mutual impedance approximations used for the computation of induced open circuit potential on pipelines is presented. The overall simulation results show that Carson's mutual impedance approximation gives a reasonable voltage induction on the pipeline compared to those obtained from Lucca and Ametani mutual impedance approximations. The study also affirms a strong relationship between the induced open circuit voltage profile produced by Lucca and Ametani formula for the different power line configurations studied. Although this can somewhat be noticed in the formulae. The statistical analysis results presented revealed a strong relationship between the Lucca and Ametani approximation, even for the different power line configurations. Therefore, care must be taken in selecting a mutual impedance formulation when computing the induced potential on metallic pipelines. This is to avoid overestimation or underestimation of the induced voltage. Also, measurements can be made (if possible) to support the results of any computational approximations used.

References

[1] J.P. Nelson, "Power systems in close proximity to pipelines," *IEEE Transactions on Industry Applications*, vol. 1A-22, no. 1, 1986, pp. 435-441.

[2] G.C. Christoforidis, D.P. Labridis, and P.S. Dokopoulos, "Inductive interference calculation on imperfect coated pipelines due to nearby faulted parallel transmission lines," *Electric Power Systems Research*, vol. 66, no. 2, 2003, pp. 139-148.

[3] G.C. Christoforidis, D.P. Labridis, and P.S. Dokopoulos, "Inductive interference on pipelines buried in multilayer soil due to magnetic fields from nearby faulted power lines," *IEEE Transactions on Electromagnetic Compatibility*, vol. 47, no. 2, 2005, pp. 254-262.

[4] K.B. Adedeji, A.A. Ponnle, B.T. Abe and A.A. Jimoh, "Analysis of the induced voltage on buried pipeline in the vicinity of High AC voltage overhead transmission lines," *Proceedings of the 23rd Southern African Universities Power Engineering Conference*, Johannesburg, Jan. 28-30, 2015, pp. 7-12.

[5] Australian/New Zealand Standard, T.M, "Electric hazards on metallic pipelines," *Standards Australia*, AS/NZS, p. 4853, 2000.

[6] CIGRE, "Guide on the influence of high voltage AC power systems on metallic pipelines," *CIGRE Technical Brochure*, No. 095, 1995.

ISBN: 978-988-14047-5-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

[7] NACE RP0177, "Mitigation of alternating current and lightning effects on metallic structures and corrosion control systems," *NACE International Standard Practice*, Houston, Texas, 2007.

[8] S. Goidanich, L. Lazzari and M. Ormellese, "AC corrosion. Part 2: parameters influencing corrosion rate," *Corrosion Science*, vol. 52, no. 3, 2010, pp. 916-922.

[9] Z. Jiang, Y. Du, L. Dong and M. Lu, "Effect of AC current on corrosion potential of Q235 steel," *Acta Metall Sin*, vol. 47, no. 8, 2011, pp. 997-1002.

[10] Z. Jiang, Y. Du, M. Lu, Y. Zhang, D. Tang and L. Dong, "New findings on the factors accelerating AC corrosion of buried pipelines," *Corrosion Science*, vol. 81, 2014, pp. 1-10.

[11] A. Fu and Y. Cheng, " Effect of alternating current on corrosion and effectiveness of cathodic protection of pipelines," *Canadian Metallurgical Quarterly*, vol. 51, no. 1, 2012, pp. 81-90.

[12] L. Xu, X. Su and Y. Y. Cheng, "Effect of alternating current on cathodic protection on pipelines," *Corrosion Science*, vol. 66, 2013, pp. 263-268.

[13] A. Brenna, L. Lazzari, M. Pedeferri and M. Ormellese, "Cathodic protection condition in the presence of AC interference," *La Metallurgia Italiana*, no. 6, 2014, pp. 29-34.

[14] CEN/TS15280, "Evaluation of AC corrosion likelihood of buried pipelines-application to cathodically protected pipelines," *Technical Specification, CEN European Committee for Standardization*, Germany, 2006.

[15] M. Vakilian, K. Valadkhani, A.A. Shaigan, A.H. Nasiri and H. Gharagozlo, "A method for evaluation and mitigation of AC induced voltage on buried gas pipelines," *Scientia Iranica*, vol. 9, no. 4, 2002, pp.311-320.

[16] A.D.N. Tleis, *Power Systems Modelling and Fault Analysis: Theory and Practice* , Newnes, Oxford, UK, 2008.

[17] R. Djekidel and D. Mahi, "Calculation and analysis of inductive coupling effects for HV transmission lines on aerial pipelines," *Przegld Elektrotechniczny* , vol. 90, no. 9, 2014, pp. 151-156.

[18] G.C. Christoforidis, D.P. Labridis and P.S. Dokopoulos, "A hybrid method for calculating the inductive interference caused by faulted power lines to nearby buried pipelines," *IEEE Transactions on Power Delivery*, vol. 20, no. 2, 2005, pp. 1465-1473.

[19] K.J. Satsios, D.P. Labridis and P.S. Dokopoulos, "Currents and voltages induced during earth faults in a system consisting of a transmission line and a parallel pipeline," *European Transactions on Electrical Power*, vol. 8, no. 3, 1998, pp. 193-199.

[20] K.J. Satsios, D.P. Labridis and P.S. Dokopoulos, "Finite-element computation of field and eddy currents of a system consisting of a power transmission line above conductors buried in nonhomogeneous earth," *IEEE Transactions on Power Delivery*, vol. 13, no. 3, 1998, pp. 876-882.

[21] J.R. Carson, "Wave propagation in overhead wires with ground return," *Bell System Technical Journal*, vol. 5, 1926, pp. 539-554.

[22] G. Lucca, "Mutual impedance between an overhead and a buried line with earth-return," *In: proceedings of the 9th IET International Conference on Electromagnetic Compatibility*, September 1994, pp. 80-86.

[23] B. Yoshihiro, A. Ametani, T. Yoneda and N. Nagaoka, "An investigation of earth-return impedance between overhead and underground conductors and its approximation," *IEEE Transactions on Electromagnetic Compatibility*, vol. 5, no. 3, 2009, pp. 860-867.

[24] J.H. Scott, "Electrical and magnetic properties of rock and soil," *US Geological Survey Technical Letter*, Special Projects-16, 1966.

[25] H. Ahmed, M. Wael and A. Ehab, "Effects of electromagnetic field from power line on metallic objects and human bodies," *International Journal of Electromagnetics and Applications*, vol. 2, no. 6, 2012, pp. 151-158.

[26] G. Mazzanti, "The role played by current phase shifts on magnetic field established by AC double-circuit overhead transmission lines-part I: static analysis," *IEEE Transactions on Power Delivery*, vol. 21, no. 2, 2006, pp. 939-948.

[27] T.D.V. Swinscow, *In: Statistics at Square One*, 9th edition, M.J. Campbell edition, University of Southampton, BMJ Publishing Group, 1997.

[28] D.E. Hinkle, W. Wiersma and S.G. Jurs, *Applied Statistics for the Behavioural Science*, 5th edition, Boston, Houghton Mifflin, 2003.

ISBN: 978-988-14047-5-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)