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AC CORROSION PHENOMENON AND MITIGATION IN BURIED PIPELINE DUE TO VERY-HIGH-VOLTAGE (VHV) OVERHEAD TRANSMISSION LINE EFFECT

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Abstract. *The presence of a very-high-voltage (VHV) electricity transmission line nearby a metallic pipeline can be a source of dangerous effects for this pipeline due to the electromagnetic field generated by this power line, it can induce a considerable voltage which may threaten the safety of operating personnel and the integrity of the pipeline. The main purpose of this paper is to evaluate the electromagnetic coupling effect in a buried metallic pipeline located in close proximity to a very-high-voltage (VHV) overhead transmission line using the Faraday's law and nodal network analysis under steady state conditions, as well as to estimate the possibility of AC induced corrosion of the metallic pipeline. The obtained results show that the induced voltage on the metallic pipeline exceeds the maximum threshold value recommended by the international regulations CENELEC and NACE, the AC corrosion current density surpasses the allowable value indicated by the specialized majority of corrosion studies. Therefore, a mitigation technique based on a pipeline grounding system is proposed to reduce the voltage induced on the pipeline to safe limits, in order to remedy the hazardous potential effects. The adopted mitigation technique has achieved better efficiency by reducing the induced voltage well below the safety limit.*

Key words: *buried metallic pipelines, AC corrosion, electromagnetic coupling, mitigation, very-high-voltage, overhead power line*

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Acronyms:

AC	Alternating Current	F	Faraday Constant
AS/NZS	Australian/New Zealand Standards	Fe	Iron Element
CENELEC	European Committee for Electrotechnical Standardization	H	Hydrogen Element
CIGRE	International Council on Large Electric Systems	NACE	American National Association of Corrosion Engineers
DC	Direct Current	O	Oxygen Element
EMF	Electromotive Force	VHV	Very High Voltage
EMI	Electromagnetic Interference	π	Pi alphabet grec

1. INTRODUCTION

The buried metallic pipelines that transport natural gas and oil situated in immediate vicinity to sources of interference, such as power lines and electric railways which produce electromagnetic fields and stray currents through electrical interferences occur mainly from

capacitive, electromagnetic and conductive coupling. Indeed, these different coupling modes generate electromagnetic disruptions which can cause dangerous effects concerning the safety of the intervention and maintenance operators, the pipeline integrity and its electrical equipment connected to it, under normal and abnormal operating conditions of the electrical network [1-6].

The power transmission lines generate electric and magnetic fields due to the electric charges and the varying currents flowing in the conductors [7, 8], which are injected into the neighboring pipeline through the physical phenomenon of induction, while the electric railways produce galvanically injected stray currents which penetrate into the pipeline via the ground. Consequently, induced stray voltages and currents can result from these different sources of disruption through the mechanism of electromagnetic coupling [8 -15]. In some cases, these induced voltages can reach high levels which can present a electric shock risk for the safety of operators touching the metallic pipeline, they can also threaten the integrity of the pipeline and the associated cathodic protection equipment; they also tend to cause and accelerate the AC corrosion process of the steel composing this pipeline [16, 17].

The corrosion of a metal is a natural phenomenon which affects the metal constituting the metallic pipeline by a generalized and uniform attack resulting in the degradation of the material making up the metal, in particular steel and its chemical properties following an electrochemical reaction with its surrounding environment. The corrosion due to the alternating current (AC) discharge is the most common adverse effect of the electromagnetic interference (EMI) [18].

Under normal operating conditions, the maximum allowable induced voltage levels on metallic pipeline vary to various international standards and national regulations, based on the results and recommendations reported by its research studies and scientific investigations, such as CENELEC, CIGRE and AS/NZS regulations. The findings showed a permissible induced voltage range from 50 to 65 V [19-21], while the NACE standard has recommended a very strict limit of 15V [22]. These international standards and guidelines highly recommend reducing the AC voltage in the pipeline to a minimum to combat possible adverse effects, which makes it possible to maintain the lower value of 50V. When the maintained limit values are exceeded, a corrective action procedure should be considered to collapse these induced voltages to safe levels to ensure the personnel safety and the metallic pipeline integrity. There are various mitigation techniques which can be applied to reduce the AC voltage induced on the buried pipelines to much lower levels, in order to protect the entire pipeline against the electromagnetic coupling effects. One of the most common and effective mitigation measures is the protection by the grounding installation; its basic principle consists in connecting the both ends of the pipeline to the ground through very suitable resistances [23-26].

Indeed, under normal operating conditions of the electrical network, it appears very important to accurately assess the electromagnetic interference between the overhead power line and the buried pipeline for reasons of maintenance operators' safety and pipeline integrity. Moreover, the need to implement the most appropriate preventive measure, in order to eliminate the risks of undesirable consequences in accordance with designated standards [25, 26].

In previous works [27, 28], the capacitive and inductive coupling modes between an overhead electricity transmission line and an aerial neighboring metallic pipeline have been treated using numerical simulation methods. This present paper proposes an electromagnetic modeling making it possible to evaluate the electromagnetic coupling effect between a very-high-voltage (VHV) overhead power line and a buried metallic pipeline collocated in immediate proximity to this power line using Faraday's law of electromagnetic induction and nodal network analysis. Firstly, by determining the profiles of disturbed magnetic induction and AC induced voltage on the buried pipeline and, second, to compute the AC corrosion current density that passes through the metal constituting this pipeline, in order to estimate the likelihood and degree of AC induced corrosion and finally to analyze the effectiveness of the proposed electromagnetic coupling mitigation technique. A program developed using the Matlab version R2014a environment was used in this present work.

2. Inductive Coupling Mechanisms

Electromagnetic coupling is considered the most important of all possible modes of coupling between the metallic pipeline and the power transmission lines. It occurs when alternating currents flowing through overhead power line conductors generate a time-varying magnetic field, as shown in Figure 1. This magnetic field in turn creates an electromotive force (EMF) of induction, hence the appearance of induced voltage and current in the metallic pipeline installed near this power line. This coupling is represented by a mutual inductance; its operating principle is quite similar to that of the single-phase transformer [19, 20].

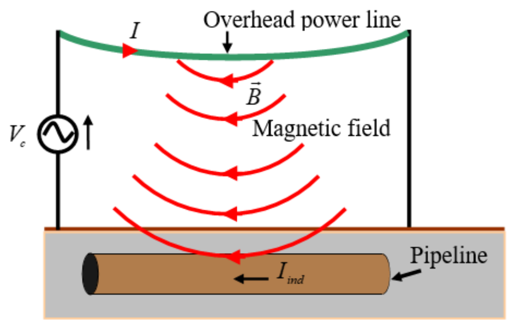

Fig. 1 Electromagnetic coupling from a very-high-voltage (VHV) power line to a metallic buried pipeline

3. MAGNETIC FIELD CALCULATION

The Biot-Savart law is one of the fundamental laws of magnetostatics allowing to calculate the intensity of the magnetic induction created by a stationary current distribution, the magnetic induction translates the effect of the displacement of the electric charges. Let us consider an elementary length $d\vec{\ell}$ along a supposed infinite rectilinear conducting wire traversed by a constant current I, as shown in Figure 2. This element creates at point M at a distance r an elementary magnetic induction given by the Biot-Savart law, as mentioned in the following equation [29-32]:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{\ell}\times\vec{r}}{r^2}, \quad (1)$$

where $d\vec{\ell}$ is the elementary length on the path C oriented in the direction of current I; r is the distance separating the element $d\vec{\ell}$ at the point M where the magnetic induction $d\vec{B}$ is evaluated; $\vec{r}$ is a unit vector in the direction of r; μ_0 is the permeability of free space.

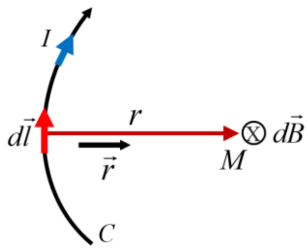

Fig. 2 Description of Biot and Savart's law for magnetic induction created by an element of conductor

Generally, to obtain the resulting magnetic induction $\vec{B}$, it is necessary to sum over the entire length of the conductor, the different vectors $d\vec{B}$ created by each vector element $d\vec{\ell}$ from an integral along this conductor. For a straight and finite length current carrying conductor at a point M, located a distance r, the total magnetic induction intensity is given by the following relation [29-32]:

$$\vec{B} = \frac{\mu_0}{4\pi}\int_C \frac{I\,d\vec{l}\times\vec{r}}{r^2} \Rightarrow B = \frac{\mu_0\,I}{2\pi r}. \quad (2)$$

For the magnetic induction evaluation generated by a multi-conductors overhead line with a balanced system, the conductors of the power line carrying the currents are generally assumed to be straight horizontal wires of infinite length and parallel to the flat ground. In addition, it is possible to consider in effect the presence of a conductive earth due to the return current induced by the alternating magnetic field that the power transmission line creates it, which is represented by the conductors images located at a depth in the ground equal to their height above the ground plus the complex penetration depth, as shown in Figure 3 [33-40]. Also, in this calculation, the effect of currents induced in ground wires and metallic pipeline by power line currents is taken into account, the metallic pipeline can be treated as a long conductor with additional loss [33-40].

According to Cartesian coordinates in a two-dimensional system, the horizontal and vertical components of the magnetic induction at the observation point M can be expressed as [33-40]:

$$B_x = -\frac{\mu_0}{2\pi}\sum_{i=1}^{n} I_i\left[\frac{y_j - y_i}{d_{ij}^2} - \frac{y_j + y_i + D_e}{d_{ij}^{'2}}\right],$$
$$B_y = \frac{\mu_0}{2\pi}\sum_{i=1}^{n} I_i\left[\frac{x_j - x_i}{d_{ij}^2} - \frac{x_j - x_i}{d_{ij}^{'2}}\right], \tag{3}$$

Where I_i are the currents flowing through the conductors of power line; n is the number of power line conductors; (x_i, y_i) are the coordinates of the power line conductors, and (x_j, y_j) are the coordinates of the observation point; d_{ij} is the distance between each conductor and the observation point, and $d_{ij}^{'}$ is the distance between each image conductor and the observation point; D_e is the complex penetration depth; μ_0 is the permeability of free space.

As indicated in Figure 3, the both distances d_{ij} and $d_{ij}^{'}$ are calculated using the formulas given below:

$$d_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} ,$$
$$d_{ij}^{'} = \sqrt{(x_j - x_i)^2 + (y_j + y_i + D_e)^2} . \tag{4}$$

The total magnitude of magnetic induction due to current contributions through all conductors of the power line is expressed by the equation below [33-40]:

$$B_T = \sqrt{B_x^2 + B_y^2} . \tag{5}$$

The penetration depth of equivalent earth return is given by [41]:

$$D_e = 658.87\sqrt{\frac{\rho_s}{f}} , \tag{6}$$

where ρ_s is the soil resistivity; f is the frequency of the source current.

The induced currents in the ground wires and the metallic pipeline can be determined using the matrix given below [15]:

$$\left[I_g\right] = -\left[Z_{ii}^{-1}\right]\left[Z_{ij}\right]\left[I_c\right] , \tag{7}$$

where Z_{ii} are the self impedances of the (earth wires/pipeline); Z_{ij} are the mutual impedances between phase conductors and (earth wires / pipeline); I_c are the currents passing through the phase conductors.

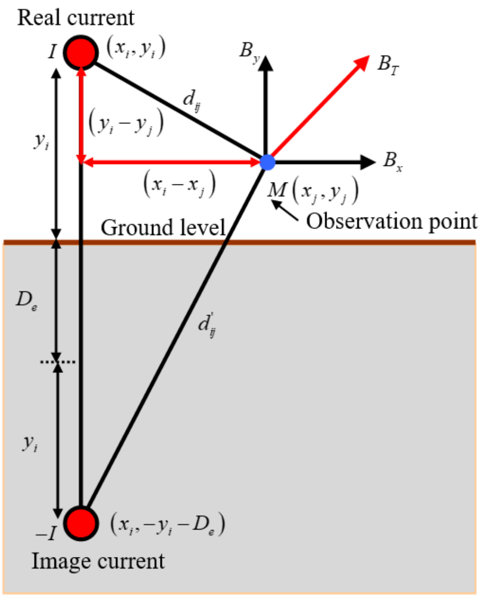

Fig. 3 Magnetic induction intensity generated by a single conductor at an observation point

The mutual and self longitudinal impedances of the conductors can be obtained by the Carson-Clem's expression, respectively [15]:

$$Z_{ii} = R_i + \frac{\mu_0 \omega}{8} + j\frac{\mu_0 \omega}{2\pi} \ln\left(\frac{D_e}{R_G}\right), \tag{8}$$

$$Z_{ij} = \frac{\mu_0 \omega}{8} + j\frac{\mu_0 \omega}{2\pi} \ln\left(\frac{D_e}{d_{ij}}\right), \tag{9}$$

where R_i is the DC resistance of conductor; R_G is the geometric mean radius of the conductor; d_{ij} is the distance between the conductor (i) and the conductor (j); ω is the angular frequency.

4. Inductive Coupling Analysis

The amplitude of the induced voltage appearing between the terminals of the metallic pipeline which constitutes a closed circuit, due to the time variation of the electric currents passing through the overhead power line conductors can be calculated using Faraday's law. This law explains that an induced electromotive force in a closed loop is proportional to the variation over time of the magnetic flux linkage within the conducting loop. This magnetic flux generated by the varying currents which flows in a surface S is calculated as the integral of the magnetic induction on this surface, as follows [42-45]:

$$\phi_T = \int_S B_T \, dS. \tag{10}$$

By applying the coordinates of the power line conductors (x_i, y_i) and the metallic pipeline (x_p, y_p) in order to determine the surface of flux calculation, this magnetic flux can be expressed as follows [42-45]:

$$\phi_T = -\frac{\mu_0}{4\,\pi}\sum_{i=1}^{n} I_i \ln\left[\frac{(x_p - x_i)^2 + (y_p + y_i + D_e)^2}{(x_p - x_i)^2 + (y_p - y_i)^2}\right]. \tag{11}$$

The induced electromotive force on the buried metallic pipeline can be found as [42-45]:

$$E_{ind} = -j\,\omega\,\phi_T. \tag{12}$$

For calculating the induced voltage on buried pipeline, the nodal network analysis is often used which is based on the impedance matrix of the π concentrated equivalent circuit type, as represented in Figure 4. The basic pipeline-earth circuit equations can be written as follows [46-50]:

$$V(x) - z\,dx\,I(x) + E(x)\,dx - \left[V(x) + dV(x)\right] = 0, \tag{13}$$

$$I(x) - dI(x) = y\,dx\,V(x) + I(x), \tag{14}$$

where E (x) is the induced electromotive force (EMF) on the pipeline per unit length; V (x) is the voltage from sending end point of the power line; V (x) + dV (x) is the voltage from receiving end point of the power line; I (x) – $d\,I$ (x) is the current at the sending end point of the power line; I (x) is the current at the receiving end point of the power line; z is the series impedance of the pipeline per unit length; y is the shunt admittance of the pipeline per unit length.

These two first-order differential equations (13 and 14) are called the fundamental equations of the transmission line. By differentiating these two equations above with respect to the longitudinal coordinate and combining them, it is possible to conclude two second-order differential equations (15 and 16), as given below [46-50]:

$$\frac{d^2V(x)}{dx^2} - y\,z\,V(x) - \frac{dE(x)}{dx} = 0, \tag{15}$$

$$\frac{d^2I(x)}{dx^2} - y\,z\,I(x) + y E(x) = 0. \tag{16}$$

Finally, for a pipeline section that continues to run for a several kilometers beyond the both ends A and B of the parallel influence length, which are perpendicular on the very-high-voltage (VHV) without earthing. The general solution possible resulting from these two differential equations determines the variation of the potential and the current induced along the pipeline, it is given by the following expressions [46-50]:

$$V_{ind}(x) = \frac{E_{ind}}{2\,\gamma}\left(e^{\gamma(x-L)} - e^{-\gamma x}\right), \tag{17}$$

$$I_{ind}(x) = \frac{E_{ind}}{2\,Z_c}\left(2 - e^{\gamma(x-L)} - e^{-\gamma x}\right), \tag{18}$$

Where x and L are the positions of the ends of the section of pipeline; γ is the propagation constant of the buried pipeline; Z_c is the characteristic impedance of the buried pipeline, they are given by [19, 50]:

$$\gamma = \sqrt{z\,y}, \tag{19}$$

$$Z_c = \sqrt{\frac{z}{y}}. \tag{20}$$

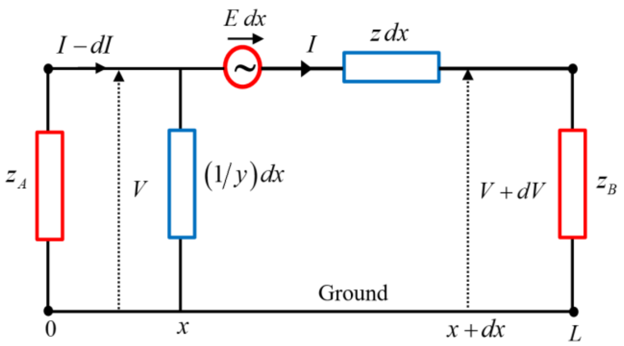

Fig. 4 Modeling of equivalent electrical circuit between buried pipeline and ground

The series impedance per unit length with ground return of the pipeline, it is given by [19, 50]:

$$z = \frac{\sqrt{\rho_p\,\mu_p\,\mu_0\,\omega}}{\sqrt{2}\,\pi\,D_p} + \frac{\mu_0\,\omega}{8} + j\left[\frac{\sqrt{\rho_p\,\mu_p\,\mu_0\,\omega}}{\sqrt{2}\,\pi\,D_p} + \frac{\mu_0\,\omega}{2\,\pi}\ln\left(\frac{3.7\sqrt{\rho_s\,\omega^{-1}\mu_0^{-1}}}{D_p}\right)\right], \tag{21}$$

Where D_p is the pipeline's diameter; μ_p is the relative permeability of pipeline's metal; ρ_p is the resistivity of metal pipeline.

The parallel admittance per unit length of the pipeline to ground is computed using the following formula [19, 50]:

$$y = \frac{\pi\,D_p}{\rho_c\,\delta_c} + j\,\omega\frac{\varepsilon_0\,\varepsilon_r\,\pi\,D_p}{\delta_c}, \tag{22}$$

where ρ_c is the resistivity of the pipeline's coating; ε_r is the coating's relative permittivity, and δ_c is the coating's thickness.

5. AC Induced Corrosion of Pipeline

Corrosion is an electrochemical oxidation-reduction reaction with transfer of electrons between a metal and its environment which leads to a degradation of the metal and its properties, such as hardness or resistance. It forms when two materials in a structure have different electrical potentials. The potential difference often results from heterogeneity in the metal, in the surrounding medium or the existence of an external electrical source [51-54]. In the case of iron corrosion, the process consists of two reactions [55, 56].

The anodic oxidation half- reaction, with loss of electrons:

$$2Fe\ (s) \rightarrow 2Fe^{2+}(aq) + 4e^{-}. \tag{23}$$

The cathodic reduction half- reaction, with electron gain:

$$O_2(g) + 2\ H_2O\ (l) + 4\ e^{-} \rightarrow 4\ OH^{-}(aq). \tag{24}$$

The overall redox reaction is:

$$2\ Fe\ (s) + O_2(g) + 2\ H_2O\ (l) \rightarrow 2\ Fe\left(OH\right)_2 (s). \tag{25}$$

For the buried metallic pipeline, corrosion is a phenomenon caused by the induced current exchange between the ground and the metal of the pipeline, this exchange of current depends on the induced voltage appears at the terminals of the pipeline, it poses a serious threat to pipeline structural integrity, affecting pipeline reliability and lifetime, causing pipeline safety accidents. In the long term, corrosion can lead to a significant loss in the metal of the pipeline of more than 1 mm per year. The probability of AC induced corrosion can be predicted on the basis of current density levels, the international NACE standard summarizes conclusions regarding current densities associated with corrosion risks based on various previous studies; these ranges are summarized below [57-66]:

– AC corrosion does not occur at AC current densities below 20 A /m^2.
– AC corrosion is unpredictable for AC current densities between 20-100 A /m^2.
– AC corrosion occurs at AC current densities greater than 100 A /m^2.

On the other hand, a majority of studies have indicated that AC corrosion is possible at AC current densities between 20 and 30 A /m^2.

At a coating circular holiday point, the metallic pipeline has a resistance to remote earth, which can be formulated as follows [67]:

$$R_s = \frac{\rho_s}{2\,D_h}\left(1 + \frac{8\,\delta_c}{D_h}\right). \tag{26}$$

Generally, the induced AC current density for a given location is mainly depends to the AC induced voltage on the pipeline, the soil resistivity and the size of coating holiday, it can be calculated according to Ohm's law as follows [67]:

$$J_{ac} = \frac{V_{ind}}{R_s\,S_h} = \left(\frac{\dfrac{2D_h^2\,V_{ind}}{\rho_s\left(D_h + 8\,\delta_c\right)}}{\pi\left(\dfrac{D_h}{2}\right)^2} \right) = \frac{8\,V_{ind}}{\pi\rho_s\left(D_h + 8\delta_c\right)}, \tag{27}$$

Where J_{ac} is the AC current density; ρ_s is the soil resistivity; D_h is the diameter of the circular holiday; R_s is the area spreading resistance of a circular holiday; S_h is the surface area of the circular holiday.

The corrosion current can be related directly to the corrosion rate of a material, which is defined as the average rate at which a surface of the metal corrodes uniformly over the entire area that has been exposed to corrosion, it depends on the properties of the metal and the environmental conditions, can be calculated according to Faraday’s law [68-73]:

$$CR = \frac{t \times J_{AC} \times M_m}{z_e \times F \times \rho_m}, \tag{28}$$

where M_m is the atomic weight of the metal, for iron element (Fe) M_m = 55.847 *g / mol*; ρ_m is the specific density of metal, for (Fe) element ρ_m = 7.85 g /cm^3; z_e is the charge number which indicates the number of electrons exchanged in the dissolution reaction, for (Fe) element z_e = 2; *F* is the Faraday constant, which corresponds to the amount of electricity carried by 1 mol of electrons, it is equal to *F* = 96.485 *C / mol*; *t* is the corrosion time, for one year *t* = 3.16 x 10^7 (s).

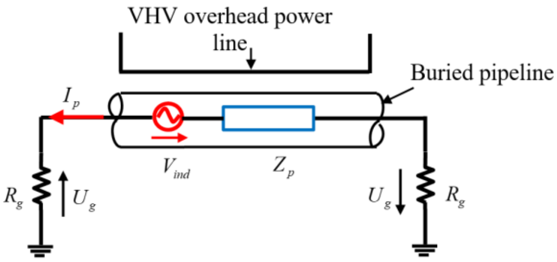

Fig. 5 Grounding of metallic pipeline by an electrode resistance

In the case, where the AC induced voltage due to the electromagnetic coupling between the pipeline and the ground exceeds the recommended safety limit, a mitigation system aimed at reducing this induced voltage to safe levels must be applied, the most common method consists of connecting both ends of the pipeline to ground through resistances of suitable values, as illustrated in Figure 5 [74-78]. Therefore and according to this figure, the grounding resistance suitable for reducing the induced voltage in the pipeline to the safe voltage limit U_g is calculated using the following formula [79, 80]:

$$R_g \prec Z_p \left(\frac{U_g}{V_{ind} - 2U_g} \right). \tag{29}$$

Consider a very-high-voltage (VHV) overhead single circuit transmission line of 275 kV, with a buried metallic pipeline in the immediate vicinity; the arrangement and geometric coordinates of the overhead power line and metallic pipeline are shown in Figure 6. The metallic pipeline length of exposure to the AC power line is 10 km. The three-phase currents have been assumed under balanced operation with the magnitude of 1000 A; the nominal system frequency is 50 Hz. The earth is assumed to be homogeneous with a resistivity of 100 (Ωm), the AC resistance of the phase conductor is 0.1586 (Ω / km), for the earth wire is 0.1489 Ω / km and 0.1 Ω / km for the metallic pipeline. The physical parameters of the buried pipeline are given as follows: the relative permeability of the pipeline μ_r = 300; the resistivity of pipeline coating ρ_c = 0.25 x 10^7 (Ωm); the resistivity of pipeline ρ_c = 1.7 x 10^{-7} (Ωm); the relative permittivity of the pipeline coating ε_r = 5; the thickness of the coating δ_c = 5 mm.

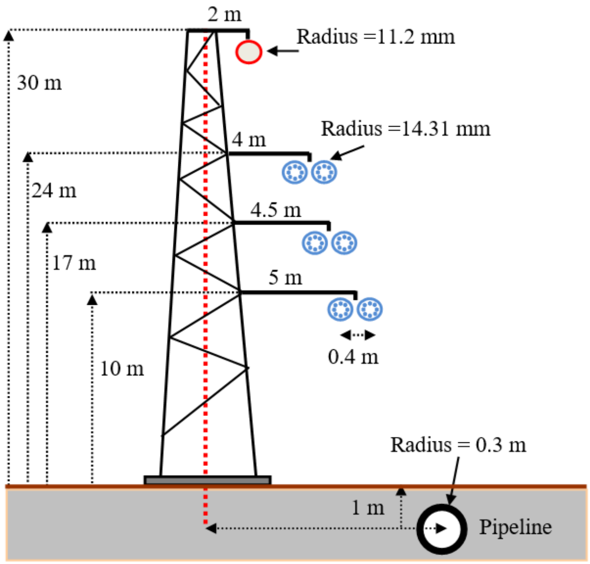

Fig. 6 Single circuit very-high-voltage (VHV) configuration with a buried metallic pipeline

6. Results and Discussions

The first step is to calculate the induced current on the ground wire caused by the variation of the magnetic field produced by the transmission line, using the Eq. (7), and the following value is obtained $I_g = 102.16\, e^{j(-22.75)^\circ}$ A.

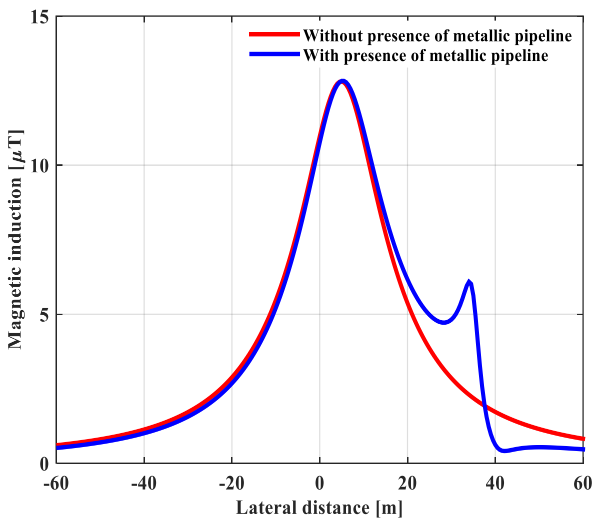

Fig. 7 Magnetic induction profile at 1 m above the ground level without and with the presence of a buried pipeline

Figure 7 shows the lateral distribution of the magnetic induction at 1 m above the ground without and with the presence of a metallic pipeline. It is observed that the presence of this metallic pipeline in the vicinity of a power line disturbs the distribution of the magnetic induction lines; this disturbance is reflected by a sudden rise in the magnetic induction at the location where the pipeline is installed, this is due to the induced current effect in the pipeline, which in turn produces its own magnetic induction which is added to that produced by the power line.

The profile of the induced voltage in the buried pipeline caused by the electromagnetic coupling influence, as a function of its lateral location from the pylon center is shown in Figure 8. It can be seen that the maximum value of induced voltage is obtained at a lateral distance of 5 m which is directly below the lateral phase conductor furthest from the pylon. From this point the value of the induced voltage decreases progressively with the lateral distance on either side of the right-of-way to reach very low values very far from the pylon. The AC induced voltage value obtained in this case study is equivalent to 54.65 volts; it is slightly higher than the allowed threshold authorized by the CENELEC and CIGRE standards.

Figure 9 illustrates the AC induced voltage profile along the buried metallic pipeline according the influence area of the electromagnetic coupling. It can be seen from this figure that the induced voltage is maximum at the two terminals of the buried pipeline, and negligible at the mid-point of the influence area, this is due to system symmetry, where the induced voltage value in the middle point of the influence area represents the difference between the two peak values at both ends of the buried pipeline, which makes it equal to the ground surface voltage value.

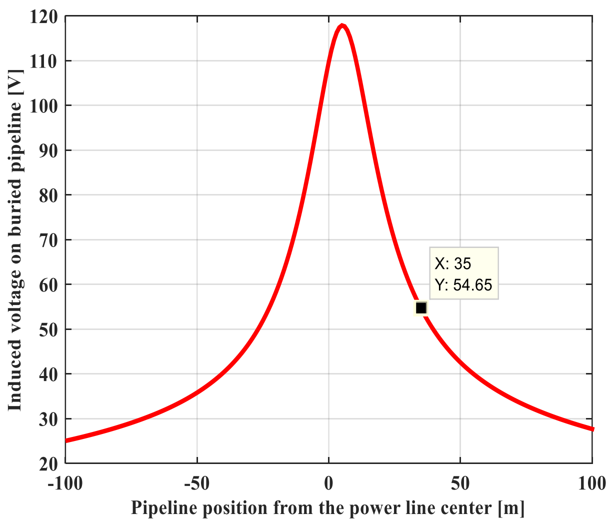

Fig. 8 Induced voltage profile on the buried metallic pipeline

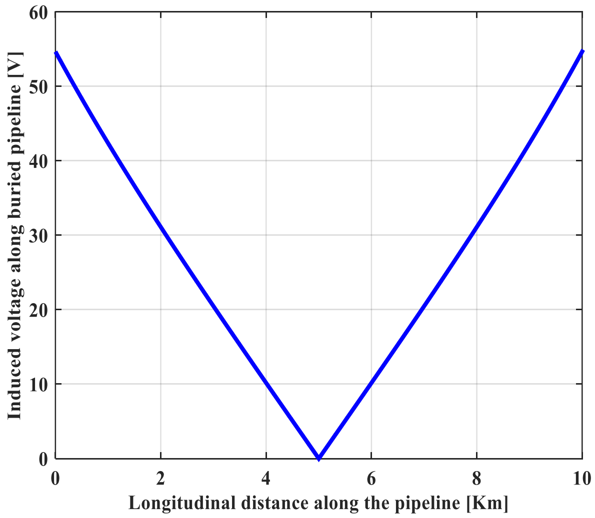

Fig. 9 Induced voltage profile along the buried metallic pipeline

The profile of the induced longitudinal current flowing in the buried metallic pipeline is shown in Figure 10. It clearly appears that the induced current reaches its maximum at the middle of the influence zone with a peak value of 46.16 A, at the two terminals of the buried pipeline, it decreases significantly at a lower value of 28.17 A.

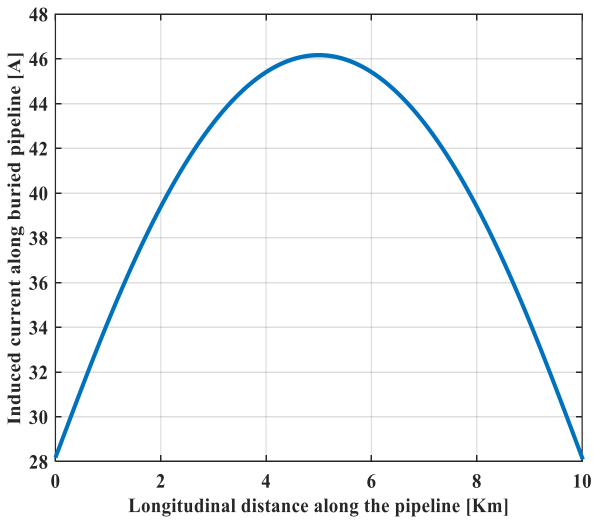

Fig. 10 Induced current profile on the buried metallic pipeline

In this case, a coating defect of a buried pipeline made of ferrous metal, with a diameter of a circular holiday having an area of 1cm2 (d = 0.015 m) is considered in corrosion evaluating.

Figure 11 shows the variation of the AC corrosion current density as a function of the induced voltage imposed in the pipeline; it is clearly observed that this intensity is directly proportional to the induced voltage applied to the terminals of the pipeline, when the induced voltage gradually raises, the AC current density increases linearly. In this case study, the AC corrosion current density value obtained is in the order of 25.3 A/m2, this value can produce and significantly increase the uniform corrosion of the ferrous metal.

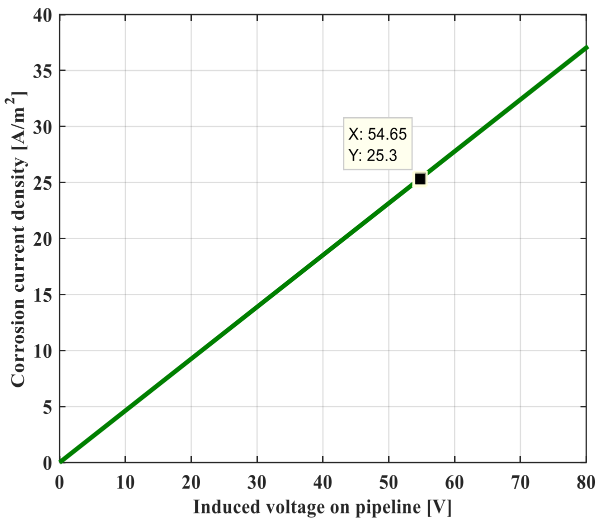

Fig. 11 AC corrosion current density as a function of the AC induced voltage

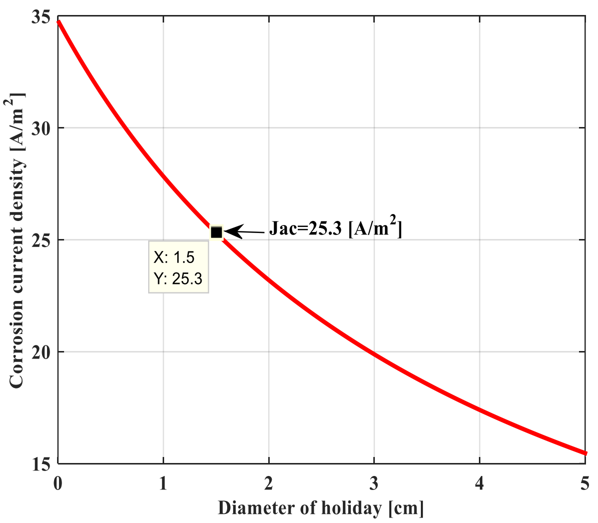

Fig. 12 AC corrosion current density as a function of the holiday diameter

Figure 12 shows the variation of the AC corrosion current density as a function of the coating defect size, it can be observed that this current density decreases inversely proportional with the increase in the coating defect diameter. The buried pipeline which has a coating defect a small diameter may be subject to a higher risk of uniform corrosion processes due to the high value of the AC corrosion current density.

The uniform corrosion rate of a metallic material can be expressed by a decrease in thickness of the metal per unit time (or a loss of mass per unit area and time).

Figure 13 represents the evolution of the metal corrosion rate as a function of the AC corrosion current density. One can notice that the corrosion rate is proportional to the AC corrosion current density which runs through the corroded metal. When the AC current density increases, the corrosion rate increases linearly. Therefore, for a significant AC corrosion current density, the corrosion rate is greater as the surface of the metal coating defect exposed to the corrosion is small.

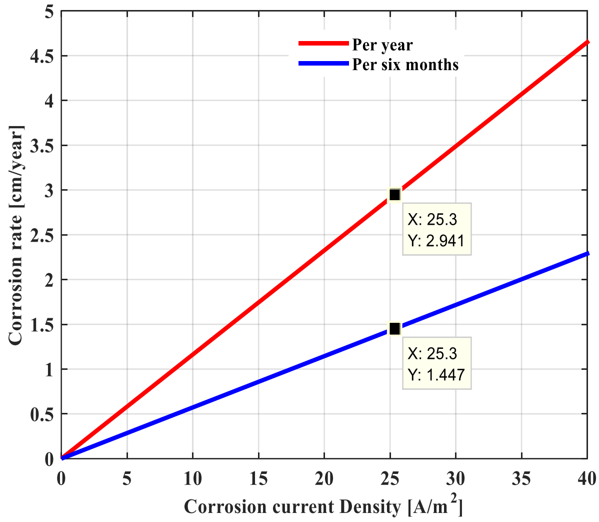

Fig. 13 Corrosion rate as a function of the AC corrosion current density

Figure 14 illustrates the earthing resistances values of the buried pipeline according to its separation distance from the pylon center, in order to reduce the AC induced voltage in the buried pipeline to the safety limit set by the CENELEC and NACE regulations. As can be seen from this figure, the graphical behavior depicted by the grounding resistance is the shape is clearly reversed to that of the AC induced voltage. For the range of the pipeline location where the induced voltage is above the recommended value, the shape is almost similar, the grounding resistance is maximum, and then decreases to a minimum value, again it increases to a maximum value.

By calculating the levels of AC voltage and current induced on the buried pipeline, which exceeded the allowed value specified by the international standards and most field investigations, it is concluded that the possibility for electric shock hazard to workers and corrosion of the pipeline metal is very high. Therefore, the induced voltage on the buried pipeline must be reduced to acceptable and safe limits to prevent various possible risks. The most suitable mitigation system suggested is to install adequate earthing resistances at both ends of the pipeline.

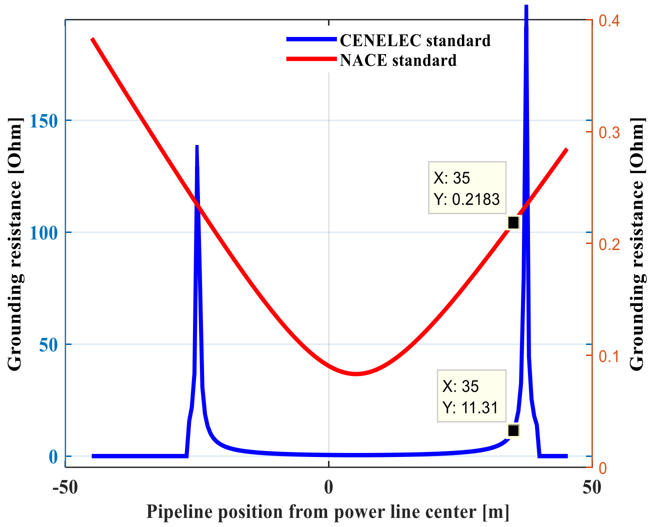

Fig. 14 Earth electrode resistance of the buried pipeline

Figure 15 shows the voltage induced in the earth electrode, in order to obtain a safe induction voltage according to the desired standard (50 V or 15 V). For the CENELEC standard, it is necessary to connect the pipeline to ground with a resistance value of less than 11.31 ohms, while for the NACE standard; the resistance value must be less than 0.2183 ohms.

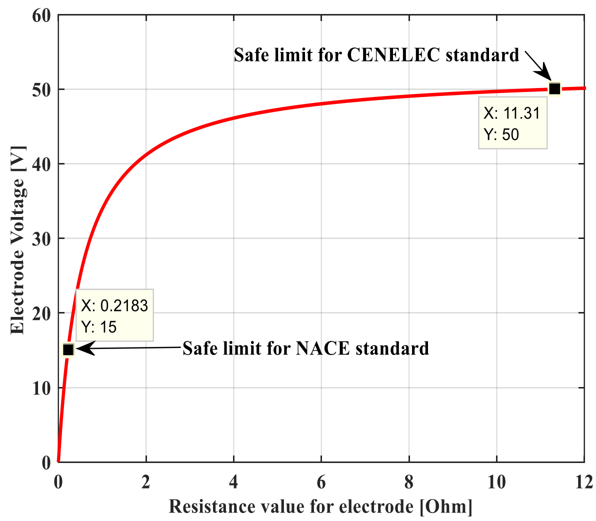

Fig. 15 Induced voltage against the electrode resistance

Figure 16 represents the AC induced voltage profile appearing in the buried pipeline before and after the mitigation installation, it can clearly be seen that the AC induced voltage is reduced below the permitted limit by placing earthing resistances at low values at the ends of the buried pipeline.

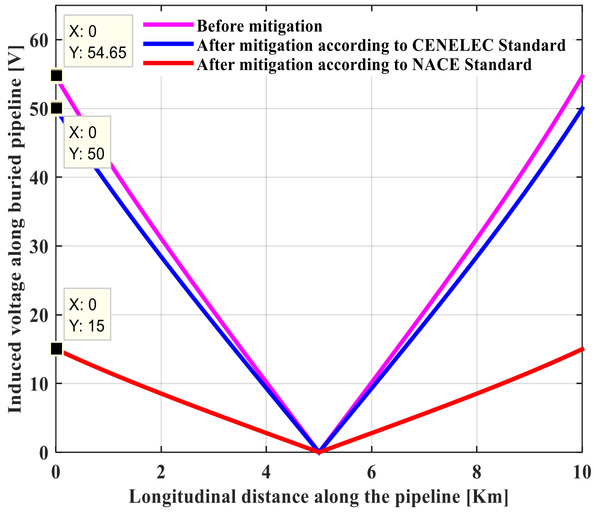

Fig. 16 Induced voltage profile along the pipeline before and after mitigation system

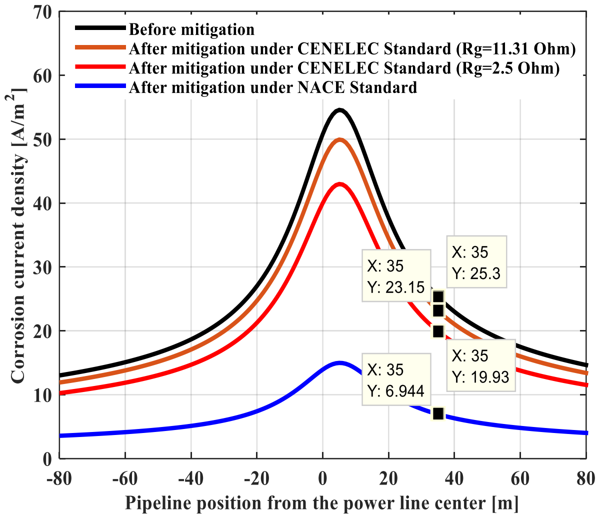

Fig. 17 AC corrosion current density before and after mitigation system

Figure 17 depicts the AC corrosion current density induced in the buried pipeline before and after the mitigation installation, it can be observed that the AC current density is limited under the threshold levels that can be tolerated by the electrical safety system, regarding the operating personnel and the overall integrity of buried oil and natural gas pipelines. Indeed, the adopted mitigation of earthing system appears to be an appropriate and very effective approach to eliminate the undesirable effects due to electromagnetic coupling.

7. CONCLUSION

In this paper, an electromagnetic modeling based on the Faraday's law and nodal network analysis is represented for electromagnetic coupling analysis between a buried metallic pipeline and a Very-High-Voltage overhead power line, under normal operating conditions.

From the results, it is very evident that the presence of a metallic pipeline in the vicinity of an overhead power line causes the distortion of the magnetic field intensity at the pipeline's surface due to the induced current in the pipeline generated by the electromagnetic induction effect. The induced voltage generated in the metallic pipeline as a function of its lateral position with respect to the pylon center reaches a maximum value in a pipeline location directly adjacent to the most lateral phase conductor, and then decreases rapidly with increasing position of the metallic pipeline on both sides of the transmission line right-of-way. The longitudinal induced voltage applied to the metallic pipeline is higher at its two ends and zero in the mid-point of the pipeline length, while the longitudinal current value is maximum on the mid-point of the pipeline length and is greatly reduced at its both ends.

The AC corrosion current density is directly proportional to the AC induced voltage on metallic pipeline and inversely proportional to the coating defect size of metal. In our case study, the current density traversing the metal is above the threshold value prescribed by studies of corrosion investigations, it can be concluded that the possibility of AC corrosion risk of the metal is highly anticipated. For safety considerations, a mitigation technique using pipeline earthing resistances has been simulated to reduce the AC induced voltage on the buried pipeline to the safe limit following to CENELEC/NACE guidelines to eliminate the possibility of harmful risks. Therefore, this implemented mitigation system has clearly proven to be more effective whilst ensuring the proper functioning of the complex electrical system.

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