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Calculation and analysis of inductive coupling effects for HV transmission lines on aerial pipelines

***Abstract**. Because of the continuous growth of electric energy consumption and the trend with electric lines of high voltages energy transport and metal pipelines which compose the transport of the fluids and liquid or gas hydrocarbons in the same corridor, the parallelism and the proximity of the power lines and the metallic pipelines become increasingly common. Consequently, it was an increasing concern about the possible dangers resulting from the influence of the power lines on the metallic pipelines. Algeria is a country where the problem is increasing due to the existence of a large transport of natural gas and oil. The induced voltages generated in the pipeline should be quantified in order to avoid security problems for the agents working on the pipeline and pipeline equipment. This paper aims at studying inductive coupling between overhead transmission 275 KV lines and an aerial parallel pipeline in steady state conditions and the factors affecting this coupling, modelling and analysis of the coupling is discussed using the mutual impedances of Carson's equation.*

Streszczenie**.W artykule analizowane jest sprzężenie indukcyjne między napowietrznymi liniami przesyłowymi wysokiego napięcia a metalowymi rurociągami. W Problem ten jest szczególnie ważny w Algerii ze względu na liczne rurociągi do transportu gazu lub ropy. Analizowano wpływ linii 275 KV przy wykorzystaniu równań Carsona opisujących indukcyjność wzajemną. **Analiza i obliczenia sprzężenia indukcyjnego miedzy liniami napowietrznymi wysokiego napięcia a rurociągami

Keywords: inductive coupling, induced voltage, Carson, aerial pipeline, power line.
Słowa kluczowe: sprzężenie indukcyjne, równania Carsona, linie przesyłowe, rurociągi.

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Introduction

Energy transport in high voltage level is causing major disturbances. The electric fields and magnetic created by high voltage overhead power transmission lines induce voltages and currents in metallic pipelines running in close proximity to these lines on long distances. This electromagnetic interference is present both during normal conditions and during faults; three types of basic interference between the electric systems of the high voltage and the metal pipelines can exist. The first is the electrostatic coupling where the pipeline acts as one side of a capacitor to the ground; this is only a concern when the pipeline is above ground. Secondly the electromagnetic coupling which may occur when the pipeline is either above or below ground, in this case, the pipeline acts as a secondary circuit of a transformer core. Finally, a resistive coupling is caused by the fault current of the power line; the each interference induced adverse effects on the pipeline. These side effects can pose a risk of electric shock for the operator of maintenance of the pipelines, direct risks to the pipeline, such as corrosion, damage to the pipeline coating and perforation of the steel. They can also threaten the integrity of the equipment used for cathodic protection and counting. Many publications have been made to calculate the voltages induced by the inductive coupling created by lines of power transmission. In most cases, they are interested to the buried pipeline [1-5]; the publications concerning the aerial pipelines are few [6, 7].

The objective of this paper is to evaluate the inductive interference from power lines during steady state operation near the metal aerial pipelines, and factors influencing the interference, using the equations of CARSON. This evaluation is usually done for personnel safety reasons coming into contact with the pipeline and equipment connected to the pipeline, a purpose of ensuring that the induced voltages are within the limits of safety standards.

Inductive coupling

The inductive interference is the result of the magnetic field generated by the power lines (Fig. 1). Aerial and underground pipelines running parallel to or in close proximity to transmission lines are subjected to induced voltages by the time varying magnetic fields produced by the transmission line currents. The induced electromotive forces (EMF) cause currents circulation on the pipeline and voltages between the pipeline and the surrounding earth.

Inductive Coupling Calculation

For calculating the induced voltage appearing on the pipeline due to magnetic field created by the transmission line, we normally should go through two steps. First, determination of the electromotive forces induced along the pipeline, and then the potential difference between the pipeline and the earth, resulting from these induced EMF's is calculated. In case of perfect parallelism between the power line and the above ground metallic pipeline, under steady state conditions, the induced have been calculated using simple power system concepts; this approach is based on the mutual impedances between phase conductors and the pipeline presented by Carson [6, 7, 8]

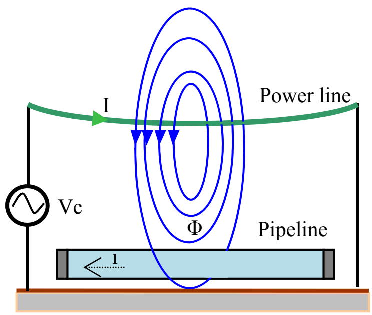

Fig.1. Inductive coupling between a pipeline and a power line

In figure 2, the total longitudinal electromotive forces induced on the pipeline due to the three phase currents and the earth wire current can be found by the following equation:

$$E_p = -I_1.Z_{p1} - I_2.Z_{p2} - I_3.Z_{p3} - I_g.Z_{pg} \quad (1)$$

where: E_p – the longitudinal EMF induced on the pipeline, I_1, I_2 and I_3 – the phase currents, I_g – current in the earth wire. Z_{p1}, Z_{p2}, Z_{p3} and Z_{pg} – the Carson mutual impedance term between phase conductor, earth wire and pipeline.

Assume that the voltage drop across the earth wire conductor is zero; the current in the earth wire is given by the equation:

$$I_g = -\frac{1}{Z_{gg}}\left(I_1.Z_{g1} + I_2.Z_{g2} + I_3.Z_{g3}\right) \tag{2}$$

Substituting this value into equation (1), we obtain the equation of the induced electromotive force:

$$E_p = -I_1.(Z_{p1} - \frac{Z_{pg}}{Z_{gg}} Z_{g1}) - I_2.(Z_{p2} - \frac{Z_{pg}}{Z_{gg}} Z_{g2}) - I_3.(Z_{p3} - \frac{Z_{pg}}{Z_{gg}} Z_{g3}) \tag{3}$$

The mutual impedance between the pipeline and an overhead line phase or earth wire conductor, with earth return, is calculated using Equation (4) as follows:

$$Z_{pi} = \frac{\mu_0.\omega}{8} + j.\frac{\mu_0.\omega}{2.\pi}.\ln\left(\frac{D_e}{D_{pi}}\right) \tag{4}$$

where : D_{pi}– the distance between the centre of the pipeline and line conductor, ω – the angular power frequency (rad/s), D_e– the depth of equivalent earth return conductor (Fig. 3) can be found using equation (5):

$$D_e = 658.87\sqrt{\frac{\rho}{f}} \tag{5}$$

where: ρ – the earth resistivity, μ_0 – the permeability of free space, f – system frequency. The self-impedance of earth wire conductor with earth return is given by:

$$Z_{gg} = R_{gg} + \frac{\mu_0.\omega}{8} + j.\frac{\mu_0.\omega}{2.\pi}.\left[\frac{1}{4} + \log_e\left(\frac{D_e}{R_{GM}}\right)\right] \tag{6}$$

where: R_{gg}–the earth wire conductor ac resistance, R_{GM}–the geometric mean radius of the earth wire conductor. The induced voltage on the pipeline can be found by the following equation:

$$V_p = E_p.L \tag{7}$$

where: L – length of the pipeline in meter.

The shock current that passes through a human body touching the pipeline is limited by the total impedance of the line Z_{pp} plus that of the ground return path R_g and the resistance of the human body R_c. The shock current is given by the expression [9]:

$$I_p = \frac{V_p}{Z_{pp} + R_g + R_c} \tag{8}$$

where: V_p – the induced voltage, Z_{pp} – the impedance in the circuit, the impedance of the pipeline with earth return is the series impedance that consists of the internal impedance and external impedance. According to the American standard IEEE 80:2000, the overall resistance of the human body is usually taken equal to 1000 Ω [10].

For pipelines installed above ground, the series impedance with earth return is given by [1]:

$$Z_{pp} = \frac{\sqrt{\rho_p.\mu_p.\omega}}{2\sqrt{2}.\pi.r_p}(1+j) + \frac{\omega.\mu_0}{8} + j\left[\frac{\omega.\mu_0}{2.\pi}.\log\left(\frac{3.7\sqrt{\rho_p.\mu_0^{-1}.\omega^{-1}}}{2.r_p}\right)\right] \tag{9}$$

where: r_p– the pipeline's radius, μ_p– the relative permeability of the pipeline's metal, ρ_p– the pipeline's resistivity.

Most national regulations insist that safety measures have to be taken when the voltage on the pipeline exceeds 50 or 65V under steady-state conditions [1,6].

By earthing the pipeline with two electrodes at each end of the pipeline, this can reduce the voltages due to inductive coupling. The current flowing to an earth electrode can be calculated from the residual potential of the pipeline at the installation point and the earth resistance [6,7].

$$I_R = \frac{V_p}{Z_T} \tag{10}$$

where: Z_T– the total impedance in the circuit, the total magnitude of impedance can be found by the following equation:

$$Z_T = \sqrt{(2.R)^2 + (Z_{pp})^2} \tag{11}$$

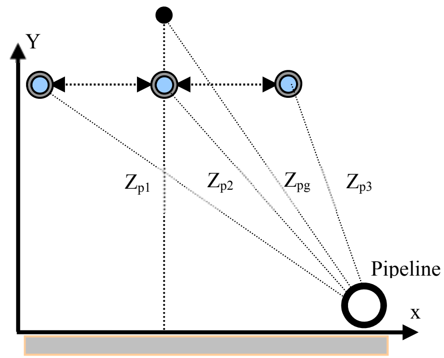

Fig.2. single-circuit overhead line with above pipeline

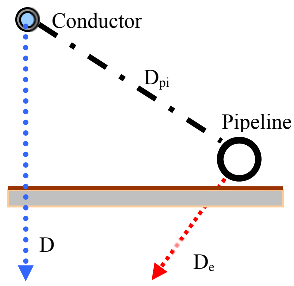

Fig.3. Equivalent distances between conductor and Pipeline

The grounding of the pipeline is an effective measure to reduce the induced voltage. The resistance of the electrode from the ground should be chosen to ensure a voltage drop of less than 50V. Under the condition, the pipeline is grounded with electrodes $R_1 = R_2 = R$. According to figure 4, we have the following relationship:

$$I_R = \frac{V_p}{\sqrt{4 + \left(Z_{pp}/R\right)^2}} \tag{12}$$

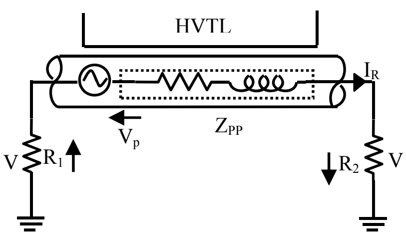

Fig.4. Pipeline and electrode resistance circuit

Inductive Coupling validation

For demonstrating the validity of the proposed method, the calculation results of the induced voltages due to inductive coupling on the pipeline are compared with those obtained by the Passive Loop Conductor.

The basic principal of the induced voltage due to high voltage power lines in the passive loop can be calculated through Faraday's Law. This law explains that magnetic fields that change with time will induce electromotive forces in a pipeline. The total flux Φ_t due to all the currents carrying conductors into the pipeline is calculated as a surface integral as shown in [11].

$$\Phi_t = \int_s B_t . ds \tag{13}$$

where: B_t – the flux density, S – the total surface area. The pipeline conductors form a loop and are located at (x_p, y_p) and (x_p, $-y_p-D_e$) (fig.5), applying the coordinates of the phase conductors and the pipeline as shown in:

$$\phi_t = -\frac{\mu_0 . L.}{4.\pi}\sum_{i=1}^{n} I_i \ln\frac{\left(x_p+x_i\right)^2+\left(y_p+D_e+y_i\right)^2}{\left(x_p+x_i\right)^2+\left(y_p-y_i\right)^2} \tag{14}$$

Using the total flux found in the previous step and making use of Faraday's law, the induced voltage on the pipeline can be found.

$$V_{ind} = -\frac{\partial \phi_t}{\partial t} \tag{15}$$

Combination of equations 14 and 15 gives equation 16 which may be used to calculate the voltage induced in the circuit:

$$V_p = -j.\omega.\phi_t \tag{16}$$

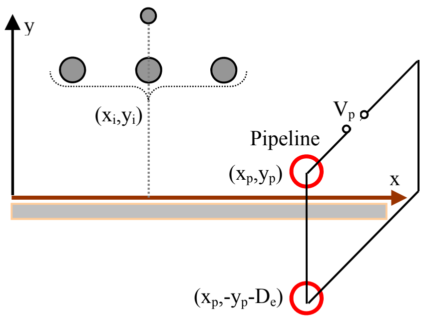

Fig.5. the passive inductive loop conductors

Case study

For the present study, we consider a single-circuit 275 KV horizontal overhead transmission line with one earth wire and an above ground insulated metal pipeline in the vicinity; the geometrical data of the overhead line circuit and pipeline are shown in figure 6. The pipeline is parallel to the axis of the power line at a distance of 30 m, it has an outer radius of 0.3 m and its height above ground is 1 m. The length of parallel exposure of the pipeline and power line is 4 km. The three-phase currents on the power line have been assumed under balanced operation with the magnitude of 500 A. The earth is assumed to be homogeneous with a resistivity of 100 Ω m. Nominal frequency f =50 Hz.

Results and Discussions

Induced voltage due to inductive coupling on the pipeline located at different distances from the midpoint of the line with and without the ground wire is shown in figure 8. As can be seen in this figure, the induced voltage is almost negligible at the central point of the transmission line and maximum where
the pipeline is located at separation distance equal to 15 m, and then it decreases progressively as the transverse position of the pipeline increases. We can also see from this figure that the presence of a ground wire practically has no influence on the value of the induced voltage, because of its location above the phase conductors; it slightly increases the induced voltage of 1 to 2%, on the pipeline. In this study, the induced voltage value on the pipeline obtained during the simulation is 67. 22 V, this value is above than the safety limit.

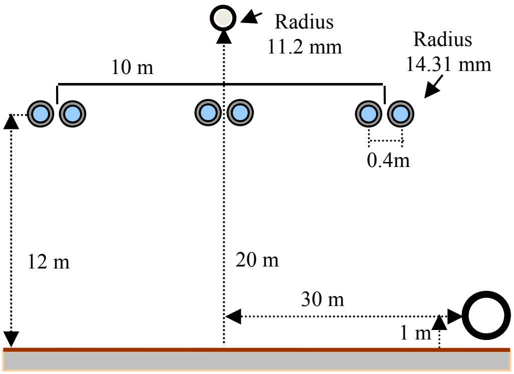

Fig.6. Single circuit horizontal configuration with ground wire and above pipeline

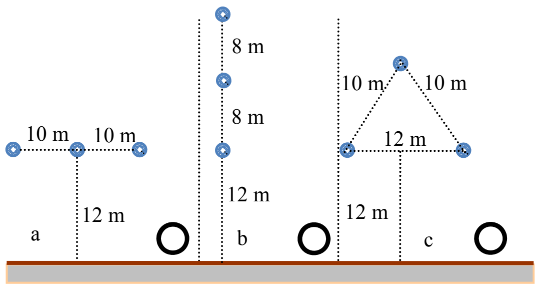

Fig.7. Different geometrical configurations for transmission overhead lines (a) horizontal, (b) vertical, (c) delta

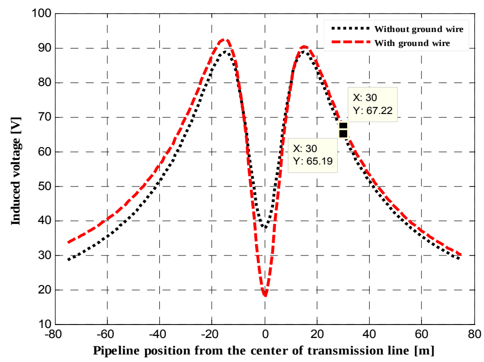

Fig.8. Induced voltage profile on the pipeline with and without the ground wire (d_p=30 m, h_p=1 m)

As can be seen from figure 9, the variation of the instantaneous value of the transverse induced voltage corresponding to the same example for the point in space (d_p, h_p) = (30, 1) [m] is presented for a time interval of [0- (1/ *f*)], in function of the module and the phase angle of the induced voltage.

The relation between the induced voltage on the pipeline and its height above ground is shown in figure 10, if the height of the pipeline is increased above the ground a vertical distance hp, it is noted that the induced voltage increases slightly with approximate direct proportion.

From the figure 11 is clearly noticed as the radius of the pipeline increases, the amplitude of the induced voltage on the surface of the pipeline remains constant for the entire length of parallelism.

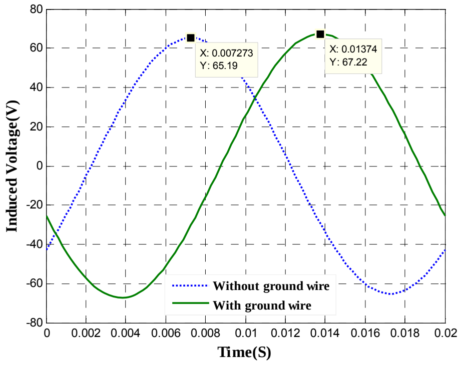

Fig.9. Temporal variation of the instantaneous value of the induced voltage

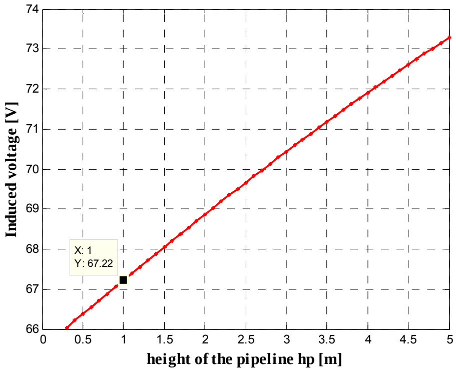

Fig.10. Relation between the induced voltage and the height of the pipeline (x_p=30 m)

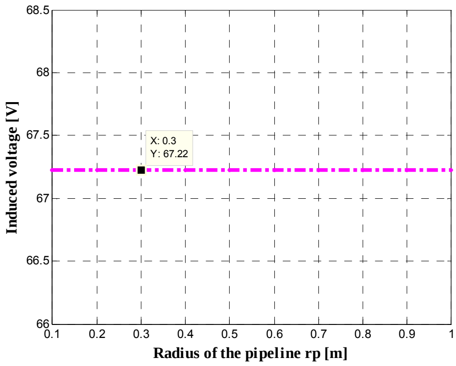

Fig.11. Relation between the induced voltage and the radius of the pipeline (d_p=30 m, h_p=1 m)

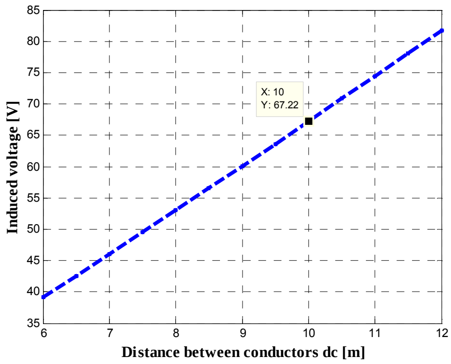

Fig.12. Variation of the induced voltage by varying the distance between conductors (hc=12 m)

Using the geometry of figure 6, we vary the distance between the phase conductors and check the effect on the value of the induced voltage, shown in figure 12, as the distance between the conductor's phases is high, the induced voltage on the pipeline increases.

As we see in figure 13, the variation of the induced voltage with the height of the conductors above the ground, the increase in height of the conductors seems the most effective method to reduce the induced voltage on the pipeline.

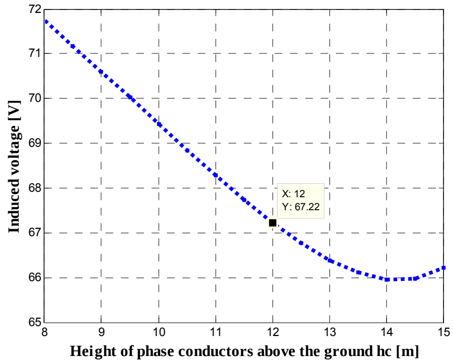

Fig.13. Variation of the induced voltage by varying the height of the conductors from the ground

We can see in figure 14 the effect of soil resistivity on the induced voltage in a pipeline exposed to the parallel transmission line. For a separation distance from the point of symmetry of the line about 30 m, it seems that the induced voltage is insensitive to the resistivity of the soil. But beyond this distance along the transverse axis, the influence of the resistivity is marginal on the induced voltage. In other words, the voltage increases slightly with increasing soil resistivity.

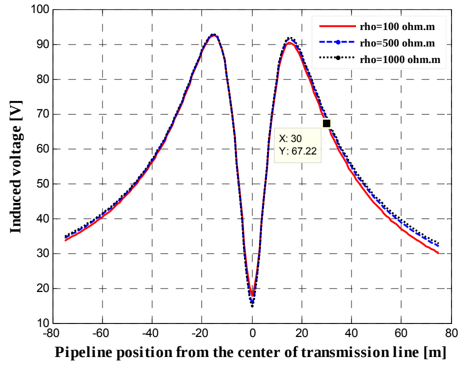

Fig.14. Variation of Induced voltage with the soil resistivity (d_p=30 m, h_p=1 m)

As can be seen in figure 15, a non-linear relation between the effective values of the induced voltage with the soil resistivity, starting from point of symmetry as distances less than 15 metre (y=5 m) , the graph is a horizontal line with a constant slope, outside the zone (y=30 m) the slope of the graph becomes very low.

The induced voltage level depends on the pipeline length exposed to the transmission line. For a parallelism between the pipeline and HV power line, figure 16 shows the induced voltage along the pipeline for different length of a parallel section. As the parallel section increases, the induced voltage on pipeline increases with the exposure length.

It can be seen from figure 17 a proportional linear relationship between the Induced voltage on the pipeline and the exposure length of parallel sections.

A comparison of induced voltages for all the three single circuit configurations (horizontal, vertical, delta) (see fig. 7), it can be seen from figure 18 that the induced voltage on the pipeline for a separation distance between the centre of power line and the pipeline equal to 30 m, the vertical configuration produces the lower magnitude of induced voltage than the horizontal and delta configurations, the horizontal configuration caused the height magnitude of induced voltage for the same distance of separation of the pipeline.

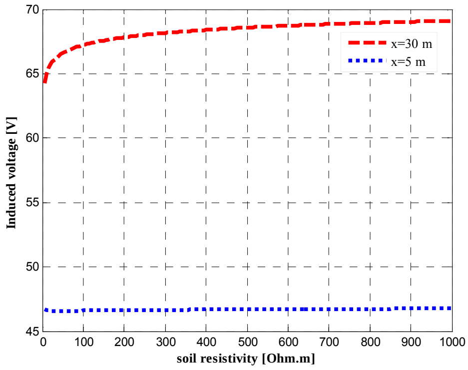

Fig.15. Relation between induced voltage and the soil resistivity (d_p=30 m, d=5 m ,h_p=1 m)

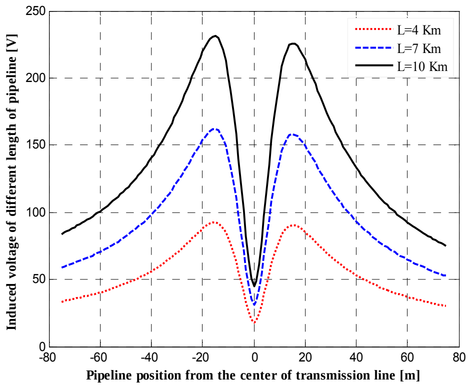

Fig.16. Variation of Induced voltage with the length of parallelism (d_p=30 m, h_p=1 m)

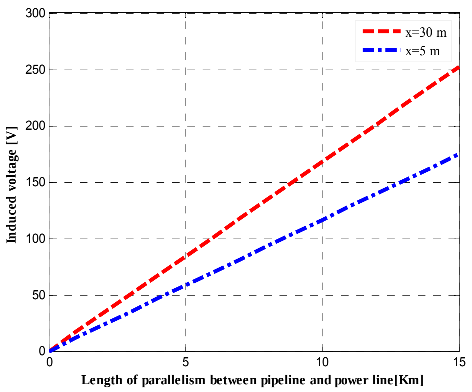

Fig.17. Relation between the induced voltage and separation distance of the pipeline (d_p=30 m, d=5 m ,h_p=1 m)

Figure 19 shows the shock current pass through the human body. The distribution results are similar to the induced voltages; it can be found that from 0 to 15m of the pipeline position, the shock current increases until it reaches a maximum value (peak value of current). From this point, the currents start decreasing gradually. It is interesting to note that if the voltages are higher, the currents are higher because the currents flowing through the human body determined from the ratio of voltage induced to the total longitudinal impedance of the circuit with the contact resistance. In this example, the shock current magnitude is equal to 50 (mA). This high intensity is considered as an unacceptable safety risk. The mitigation technique can be applied in order to reach a negligible value of shock current.

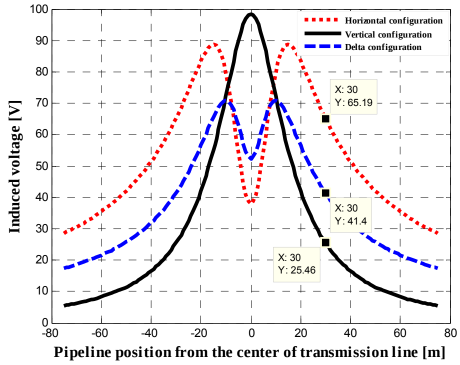

Fig.18. Induced voltage on the pipeline for various phase configurations

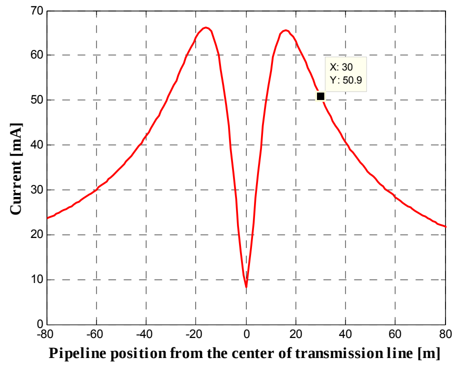

Fig.19. Shock current passing through the human body

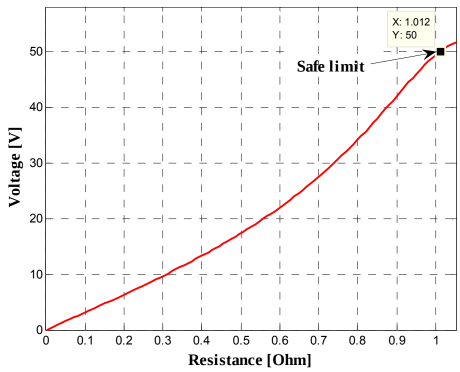

Fig.20. Electrode voltage

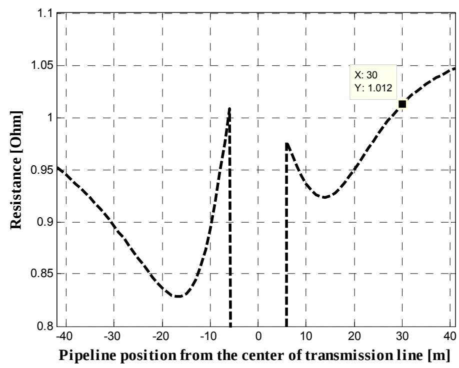

Fig.21. Earth electrode resistance of the pipeline

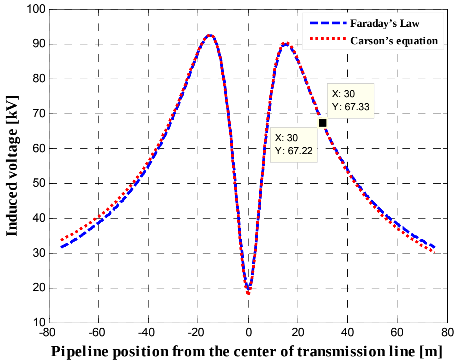

Fig.22. Comparison of induced voltages between the Carson's Formulae and the Faraday's Law

Figure 20 shows the induced voltage in the electrode. In order to achieve a safe induce voltage (50 V), it is required to install the pipeline section between two electrodes, the earth electrode resistance value less than 1.012 ohms.

Figure 21 shows the resistance value for the electrode according to the separation distance of the pipeline in order to reduce the pipeline potential to the safety limit.

As can be seen from figure 21, the earthing resistance decreases to a minimum value then it increases to reach a maximum value. For a beach of separation distance going of -6 m to 6 m, the pipeline does not require an earthing resistance because the induced tension is under the safe voltage limit.

To validate the simulation results in this paper for the same line geometry, the calculated of the induced voltages on the pipeline due to inductive coupling from Carson's equations method were compared with the results obtained from the Passive loop conductor method. Figure 22 shows the simulation results for the inductive interference on the pipeline, the induced voltages obtained for two different methods are compared; the analysis of results has shown that there is a good agreement.

Conclusion

In this paper, the inductive interference of high voltage transmission lines on the nearby pipelines have been computed pipeline using the mutual impedances between phase conductors and the pipeline (Carson's equations), with the effects of various parameters on the generated interference. The separation distance and the length of parallelism between the HV transmission line and the pipeline are important factors that affect the level of the induced voltage. This is reduced by increasing the separation distance and increases linearly with increasing the length of exposure.

It is worth noting that the effect of the earth wire of the transmission line in the state of balance is to slightly increase the induced voltage on the pipeline.

The induced voltage vary with the pipeline heights from ground surface, when the altitude of the pipeline is increased to the level of the conductors of the power line, the amplitude of the induced voltage in the pipeline increases slowly. Induced voltage on the pipeline is calculated at different pipeline radius, the variation of the radius has no significant effect on the voltage induced. The effect of varying the separation distance between the conductors was studied, increasing the distance of separation between lines. The induced voltage increases. Regarding, the effect of the increasing the height of conductors above the ground, the induced voltage decreases as the height of the conductors increases. The effect of soil resistivity on the induced voltage is practically negligible. If the soil resistivity is changed, that does not seem to have any significant effect on the induced voltage.

The Effect of configuration of the phases conductors (the phases arrangement), it has been found that the variation of the configuration has a significant effect on the amplitude of the induced voltage in the pipeline. For the electric shock current, it was found by this calculation that important currents flowing through the body by the inductive effect, causing various effects of an electric shock. To attenuate the induced voltage on the pipeline under the safe touch voltage, an effective technique suggested is to install the two ends of the pipeline with the grounding electrodes. The results presented by the calculation methods used in this study are also compared to results obtained with the results obtained through another numerical method. The comparison shows a good agreement that confirms the validity of the proposed methods.

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