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RESEARCH ARTICLE

Optimum Phase Configuration and Location of the Aerial Pipeline in the Vicinity of a High Voltage Overhead Line

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Abstract
Metallic pipelines above-ground installed near high voltage power lines are subject to an electromagnetic interference caused by the capacitive coupling, inductive and conductive. Due to the interference, voltages and currents are induced in an aerial metallic pipeline, which may present a risk of electric shock to the operator safety; they can also threaten the integrity of the pipeline equipment. This paper aims is to analyze the capacitive coupling between the transmission lines operating at steady state and the neighboring aerial metallic pipelines, also to determine the optimal arrangement of the phase conductors, which produces a lower induced alternating voltage, and suitable location for the pipeline, where the induced voltage has a relatively low value, using a modeling based on the admittance matrix method combined with the Genetic Algorithm (GA). The simulation results are compared with those obtained from the CIGRE Method, a good agreement has been obtained.

Keywords
Aerial Pipeline, Admittance Matrix Method, Capacitive Coupling, HV Power Lines, Induced Voltage, Genetic Algorithms (GAs)

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1 Introduction

Transporting hydrocarbons from pipelines remains the most secure means for conveying large amounts of oils and gas over long distances. These pipelines are expensive constructions due to the quantity and quality of the steel tubes that they require. The proximity of these gas pipelines with electrical high voltage lines is sometimes unavoidable for reasons of bulk density of the soil and subsoil; it can be a source of harmful electromagnetic interference for these pipelines, under both normal power line operating conditions and short-circuit. There are three coupling modes of interference to be considered, the capacitive coupling; inductive coupling and conductive coupling. The associated risks induced are [1-6]:

- breakdown of the pipeline coating and risk of perforation;
- electrocution of emergency responders and people in contact with the pipeline;
- Dysfunction counting devices and measuring also the cathodic protection system connected to the pipeline.

Evaluation of capacitive interferences is generally done for security reasons of property and agents of intervention, to ensure that the values of variables induced on pipelines by HV power lines are not dangerous to people in contact with the pipeline and for the pipeline equipments [7].

The admittance matrix technique is an analytical calculation method, fast, accurately and efficiently in the capacitive interference simulation [1, 3, 8], its principle is purely based on the matrix of the self and mutual potential coefficients for a multi-conductor system.

Concerning the optimization problems, it is imperative to use the evolutionary methods such as Genetic Algorithms (GAs) and evolutionary algorithms (EAs), and Particle swarm optimization (PSO). In recent years, Genetic algorithms have been successfully applied in various areas of electric power and high voltage engineering.

The Genetic Algorithm (GA) was introduced in the mid 1970s by John Holland and his colleagues and students at the University of Michigan. The GA is inspired by the principles of genetics and evolution, and mimics the reproduction behaviour observed in biological populations [9].

In this work, we are interested in computing the capacitive coupling occurs between the high-voltage power line and aerial pipeline, the objective is also to optimize an optimal configuration of the phase conductors of transmission line producing a minimum induced voltage on the pipeline, in order to arrive at a suitable location of the pipeline so that the induced voltage is close to zero, using a combination of admittance matrix method with Genetic algorithms. The simulation results of the proposed method are compared with those reported in the literature obtained from the CIGRE method.

2 Capacitive Coupling Mode

Any metallic pipeline above ground insulated from ground run parallel to or in close proximity to High Voltage AC Power Transmission Line is subject to the capacitive coupling, voltages and currents may be induced on pipelines. It is a form of voltage divider running across the capacitances between the power line conductors and the pipe, and between the pipe and ground as shown in the figure below (Fig. 1). For a buried pipeline, the capacitive coupling is negligible; because the ground acts as an electrostatic shield [1-3, 5, 10].

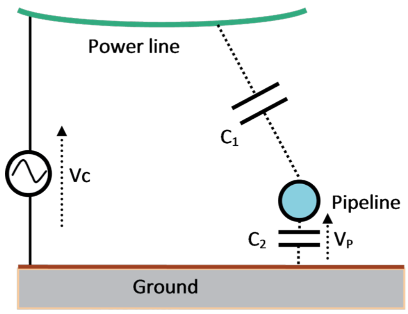

Fig. 1 Capacitive coupling between pipeline and power line

Where:
V_c: transmission line voltage; V_p: induced voltage in pipeline; C_1: capacitance between power line and pipeline; C_2: capacitance between pipeline and ground.

3 Capacitive Coupling Calculation

During normal steady state conditions, due to the effect of capacitive coupling from the power line, induced voltages appearing on the insulated pipelines running in proximity to overhead power lines. The induced voltage for a parallel exposure between pipelines and power lines can be easily calculated using the admittance matrices analysis. This method is based on the principle of self and mutual potential coefficients of the electric system.

Consider a set of a three phase overhead line and a parallel pipeline. The steady state current phasor with the operating voltages is given by [1, 3, 8]:

$$[I]=[Y]\cdot[V] \tag{1}$$

For a balanced three-phase power system with the earth wires and above metal pipeline under steady state conditions, the shunt Admittance matrix is given by the following equation [3, 8]:

$$\begin{bmatrix} I_c \\ I_p \\ I_g \end{bmatrix} = \begin{bmatrix} Y_c\, Y_{cp}\, Y_{cg} \\ Y_p\, Y_{pc}\, Y_{pg} \\ Y_{gc}\, Y_{gp}\, Y_g \end{bmatrix} \cdot \begin{bmatrix} V_c \\ V_p \\ V_g \end{bmatrix} \tag{2}$$

Where: c, p and g represent respectively the phase conductors, pipeline and ground wires.

Because the ground wire is grounded, the current I_g is equal to zero, substituting this value in Eq. (2) the matrix can be reduced to [3, 8]:

$$\begin{bmatrix} I_c \\ I_p \end{bmatrix} = \begin{bmatrix} Y'_c Y'_{cp} \\ Y'_{pc}\ Y'_p \end{bmatrix} \cdot \begin{bmatrix} V_c \\ V_p \end{bmatrix} \tag{3}$$

With:

$$\begin{cases} Y'_c = Y_c - Y_{cg}\cdot Y_g^{-1} Y_{gc} \\ Y'_{cp} = Y_{cp} - Y_{cg}\cdot Y_g^{-1} Y_{gp} \\ Y'_{pc} = Y_{pc} - Y_{pg}\cdot Y_g^{-1} Y_{gc} \\ Y'_p = Y_p - Y_{pg}\cdot Y_g^{-1} Y_{gp} \end{cases} \tag{4}$$

For an insulated pipeline, (I_p = 0) and from Eq. (3), the induced voltage to earth on the pipeline due to capacitive coupling with the power lines is given by:

$$\left[V_p\right] = -\cdot\left[Y'_{pc}\right]\cdot\left[Y'_p\right]^{-1}\cdot\left[V_c\right] \tag{5}$$

Where: V_c are the known phase voltages to earth of the power lines.

Recalling that the charging admittance per unit length associated with a sinusoidal variation in capacitive (inverse of the potential coefficient) is expressed as [3, 8]:

$$[Y] = j\cdot\omega\cdot[P]^{-1} \tag{6}$$

Where: P is the potential coefficient matrix of the power line conductors; ω: is the pulsation frequency.

Using Fig. 2, the self and mutual Maxwell's potential coefficients of system (conductors and pipeline) are defined as follows:

$$P = \begin{cases} P_{ii} = \dfrac{1}{2\cdot\pi\cdot\varepsilon_0}\cdot\ln\left[\dfrac{2\cdot h_i}{r_i}\right] \\ P_{ij} = \dfrac{1}{2\cdot\pi\cdot\varepsilon_0}\cdot\ln\left[\dfrac{h_i}{r_i} + \sqrt{\left(\dfrac{h_i}{r_i}\right)^2 - 1}\right] \rightarrow \text{Pipeline} \\ P_{ij} = \dfrac{1}{2\cdot\pi\cdot\varepsilon_0}\cdot\ln\left[\dfrac{D_{ij}}{d_{ij}}\right] \rightarrow \text{Conducteur} \end{cases} \tag{7}$$

Where:
h_i :is the height of conductor/ pipeline above the ground;

r_i : the real radius of conductor/ pipeline ;
ε_0 : the permittivity of free space;
d_{ij} :the distance between conductors i and j;
D_{ij} : the distance between the real conductor i and the image of the conductor j.

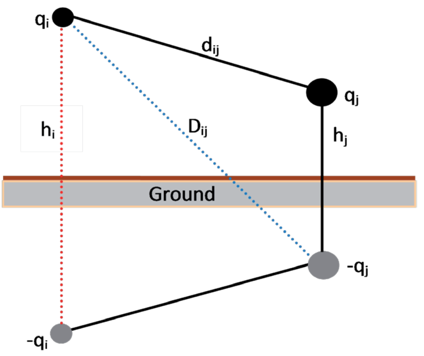

Fig. 2 Two Conductors i and j with their images

The electric field intensity distortion of the power line on the pipeline is obtained from the negative gradient scalar potential In the Cartesian coordinate system this relationship is of the form [11]:

$$\left[E_x, E_y\right] = -grad\,V_p = -\left(\frac{dV_p}{dx}a_x + \frac{dV_p}{dy}a_y\right) \tag{8}$$

Where: a_x, a_y are the base unit vectors of the coordinate axes.

The electric discharge current through the body of a person, which touches the pipeline can be represented as the rate at which the electric charge transferred through the body in some time t, the discharge current is given by [3, 8]:

$$I_{dis} = P_p^{-1} \cdot L_p \cdot \frac{dV_p}{dt} = j \cdot \omega \cdot P_p^{-1} \cdot L_p \cdot V_p \tag{9}$$

Where:
V_p is the induced voltage on the pipeline; L_p is the length of the pipeline exposed to capacitive coupling. If the discharge current magnitude is higher than the admissible exposure limit recommended by the international standards IEC 60479-1:2005 in steady state conditions at 50 Hz, which equal to 10mA for adult males [12], it is required to earthed the pipeline through a low resistance Re to reduce the current below the admissible limit, this earthing resistance (see Fig. 3) must be lower:

$$R_e < \frac{R_b}{\beta - 1} \tag{10}$$

Where:
R_b is the body resistance; Z_P is the pipeline impedance.
β is the ratio and it is given by Eq. (11).

$$\beta = \frac{I_{dis}}{I_{adm}} \tag{11}$$

According to the American standard IEEE 80:2000 [13], the overall resistance of the human body is usually taken equal to 1000 Ω.

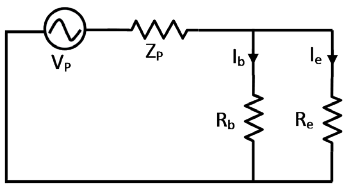

Fig. 3 Technical mitigation of the pipeline for personal security

4 Genetic algorithms (GAs)

The genetic algorithm (GA) is a search heuristic; a robust adaptive optimization method based on biological principals, GA is an efficient algorithm to solve combinatorial optimization problems by exploring a large and complex search space in an adaptive way guided by the mechanics of natural selection and natural genetics: reproduction of an original population, performance of crossover and mutation, selection of the best. GA combines the adaptive nature of natural genetics or the evolution procedures of organs with functional optimizations. An initial population is provided, which is represented by bit strings that evolve randomization through successive generations in order to obtain an optimum for a particular objective function [14-17].

This can be in the following form:

$$OF = -\left|\frac{V_p(\max) - V_p(x_p)}{V_p(\max)}\right| \cdot 100 \tag{12}$$

Where:
$V_p(\max)$ is the maximum induced voltage produced by the configuration of the power line; $V_p(x_p)$ is the desired minimum induced voltage according to the separation distance of the pipeline.

5 Results and Discussion

We consider in this application two types a single circuit, the horizontal and vertical configurations of the transmission line a 400 kV, with an above parallel pipeline of radius 0.3 m. Each phase has a two conductor bundle separated by 40 cm, with a sub-conductor radius of 1.43 cm and 1.12 cm for the earth wire. The spacing of the conductors and the pipeline relative to the centre of the tower and earth are shown in Fig. 4. The length of parallel exposure of the pipeline and power line is 10 km.

For a constant separation distance between the power line and metal pipeline, this is kept at 40 m from the central phase of the power line.

Figure 5 shows the transverse profile of induced voltage at pipeline level surface for the two configurations, one can see in this figure that the horizontal configuration provides a higher induced voltage than the vertical and triangular configuration for the pipeline location.

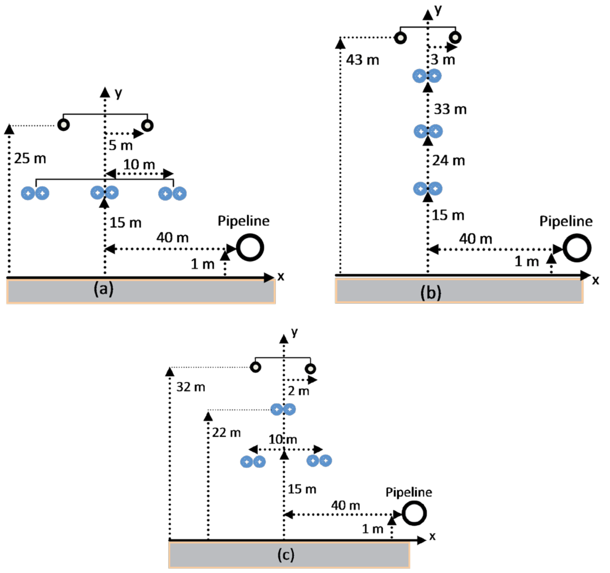

Fig. 4 Single circuit line configurations with an above pipeline (a): horizontal; (b): vertical; (c) triangular

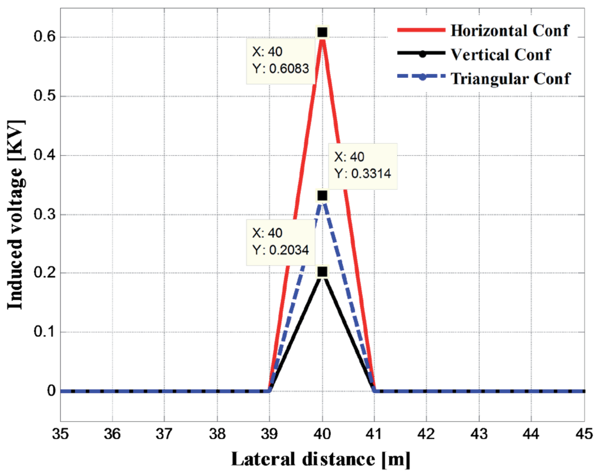

Fig. 5 Induced Voltage at pipeline level surface for three phase configurations

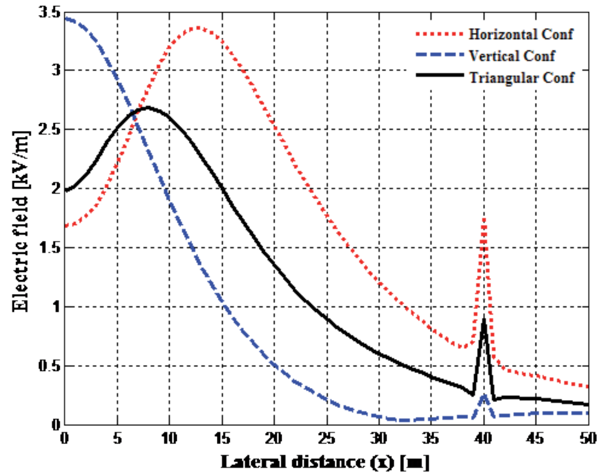

Fig. 6 Electric field stress at pipeline level surface for three phase configurations

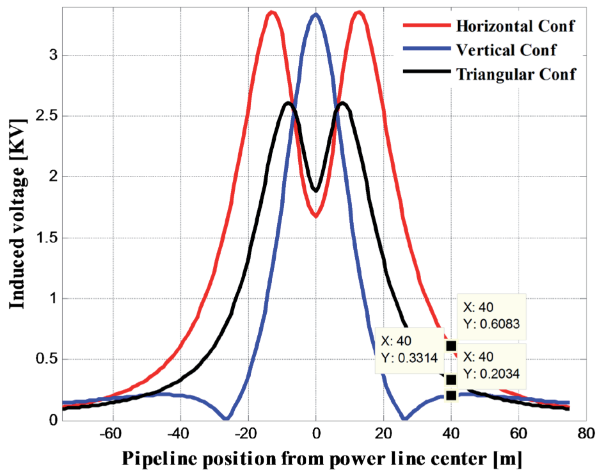

Fig. 7 Induced Voltage at pipeline level surface three phase configurations in function of the location of the pipeline

Figure 6 shows the electric field distribution as a function of lateral distance from the centre of the power line at pipeline's surface, it is clear from the graph that the presence of the parallel pipeline in the vicinity of an overhead power line introduces a distortion of the electric field on the pipeline surface, the electric charges induced on the surface of the pipeline increases significantly the electric field.

For a variable separation distance for the pipeline along the corridor, the induced voltage profile on the pipeline for the three configurations is presented in Fig. 7. For horizontal configuration, the induced voltage has a lower value at the center of the power line and increases to a maximum value at separation distance of 13 m and then progressively reduced as one moves away from the power line, in which it is becoming negligible at a distance far from the power line center.

For vertical configuration, the induced voltage is maximum at the center of the power line and decreases to a negligible value at about 26 meters, from this distance, the induced voltage increases slightly again then gradually decreases with separation distance to reach very small values.

For triangular configuration, the profile is similar to that for the horizontal configuration, the lower value of induced voltage is obtained at the center of the power line and increases to a maximum value at separation distance of 8 m and then rapidly decreases with separation distance continuously to achieve away from the power line center to much neglected values.

The shock current by capacitive coupling in a worker touching the metal pipeline located at different distances from the center of the power line is shown in Fig. 8. It is important to note that the current intensity is directly proportional to the induced voltage, if the induced voltage is intense on the pipeline, the induced current also increases and vice versa. The shock current profile is similar to that of the induced voltage. In our case study, the values of the current for the horizontal, vertical and triangular configurations are respectively (56.05, 18.74, 30.54) mA. These values were considered unacceptable for personnel safety.

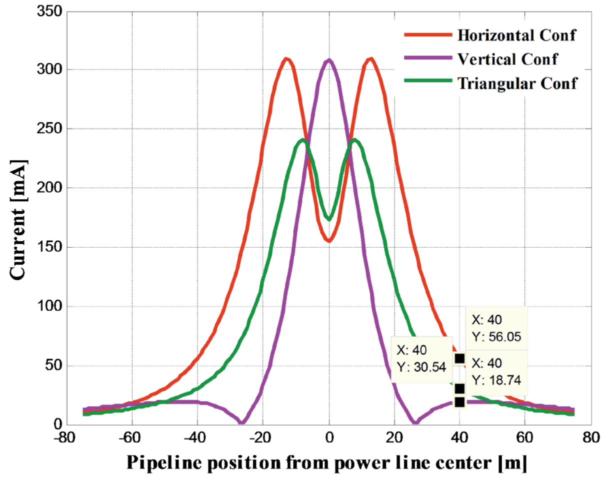

Fig. 8 Discharge current profiles passing through the human body three phase configurations in function of the location of the pipeline

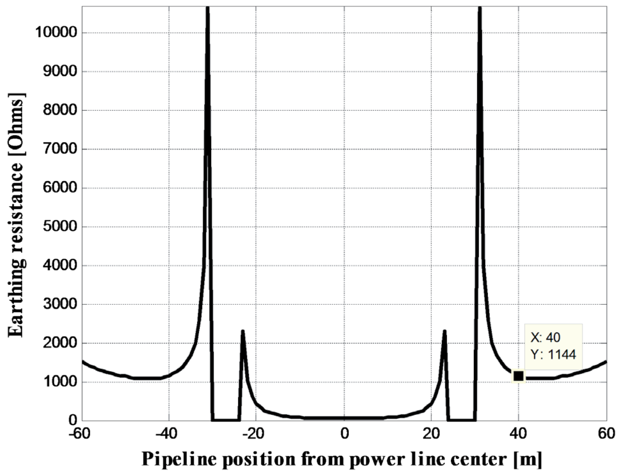

Fig. 10 Calculation of the earthling resistance of pipeline for vertical configuration

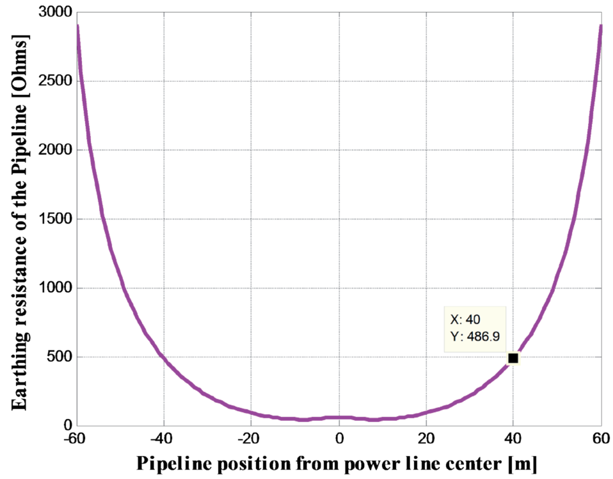

Fig. 11 Calculation of the earthling resistance of pipeline for triangular configuration

Generally, if the current is higher than the permissible safety value recommended by the standards under steady state conditions, which equal to 10 mA for adult males. Therefore, the pipeline must be grounded through adequate resistance.

According to the American standard IEEE 80:2000, the overall resistance of the human body is usually taken equal to 1000 Ω, in this example the pipeline would generally be earthed through an resistance equal to 217.2 Ω for the horizontal configuration, 1144 Ω and 486.9 Ω respectively for the vertical and triangular configurations.

Earthing resistance of pipeline as a function of the pipeline separation distance for the tree configurations is shown in Figs. 9, 10 and 11. According to these figures, we see that the behavior of the grounding resistance is inversely proportional to the induced voltage and current. When these parameters are minimal, the resistance is maximal and vice versa.

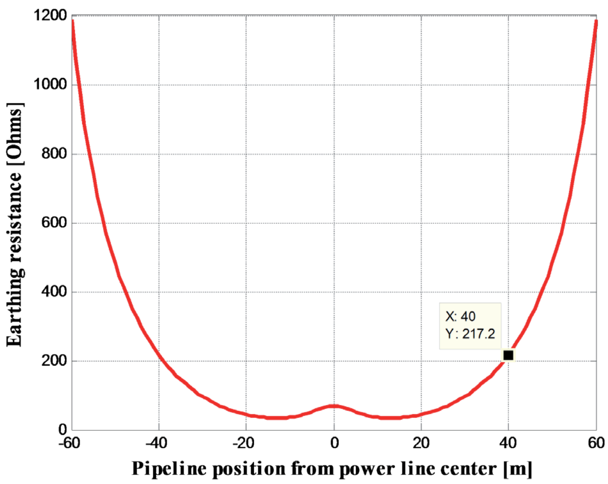

Fig. 9 Calculation of the earthling resistance of pipeline for horizontal configuration

Based on the above results, it is possible to determine optimum configuration which provides lowest induced voltage as a function of the separation distance of the pipeline under the power line, also noting the optimum separation distance for the implementation of the pipeline which corresponds to a minimum induced voltage or a voltage close to zero, as shown in Fig. 12.

For pipeline separation distances ranging from 0 to 6 m on both sides of the transmission line corridor ±[0-6] , it is noted that the horizontal configuration of the phase conductors gives an induced voltage lower than the vertical and triangular configurations, whereas, for a range of separation distances including between 7 and 50 m ±[7-50], One can observe that the vertical configuration gives a minimum induced voltage than other configurations. From a separation distance between 51 and 84.5 m ±[51-84.5], the triangular configuration is the preferred configuration, the values obtained indicate that a significant reduction in the induced voltage in that range.

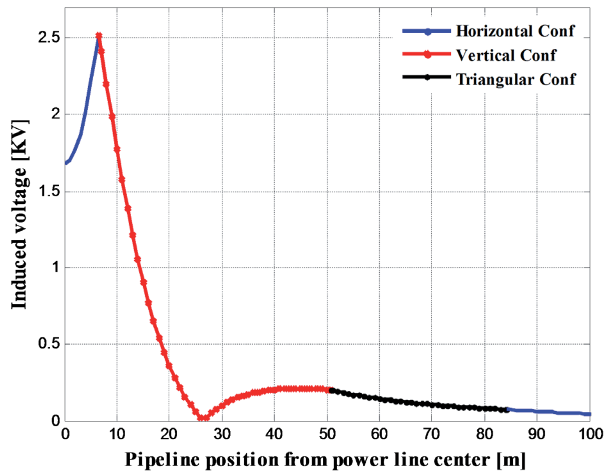

Fig. 12 Optimum configurations of the phase conductors and position of the pipeline from the power line center configurations

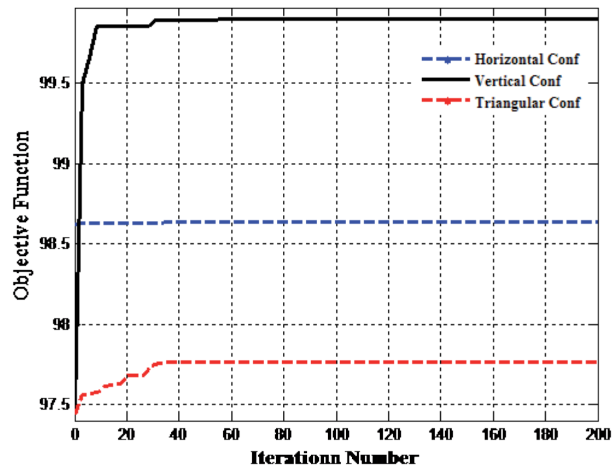

Fig. 13 Evolving process of GA algorithm with optimum parameters

For a separation distance greater than 84.5 m, the horizontal configuration still provides values of the induced voltage slightly more than the other configuration, but in general they are much reduced.

In order to optimize the optimum location of the pipeline based on the optimum phase configuration of the power line, the *parameters optimization* AG used in the numerical calculation are shown below: Population size N=20, Mutation probability Pm=0.1, crossover probability Pc=0.9, Number of bits Nb=14, Maximum number of generations 200.

The Objective Function (OF) varies with the iteration number as shown in Fig. 13. The typical change in value of this Function over the generations, illustrating the searching and optimisation processes undertaken by the algorithm, the objective of the optimization algorithm is to maximize the function given in Eq. (12), the evolution of the algorithm is increased in order to determine the smallest value of the induced voltage on the pipeline according to the search space. The simulation results are shown in Figs. 14, 15 and 16, where it becomes obvious that the algorithms converge rapidly to these values.

The results of applying the GA to estimation the optimum parameters for ppipeline are summarized in Table 1.

Table 1 Optimum phase configuration and the suitable location of the pipeline with the corresponding values induced

	Range of the separation distance		
	±[0-6] and ±[84.5-100]	±[7-50]	±[51-84.5]
Optimum Configuration	Horizontal Configuration	Vertical Configuration	Triangular Configuration
Optimum Separation Distance	100 m	26.47 m	84.39 m
Induced voltage	45.82 V	17.36 V	75.22 V
Shock current	4.22 mA	1.6 mA	6.85 mA

The last step is devoted to validate this modelling by comparing the simulation results obtained by the Admittance matrix method with those obtained in the literature, based on the work presented in the CIGRE Guide [1]. This is a specialized guide in the electromagnetic interference between electrical power lines and nearby metallic pipelines.

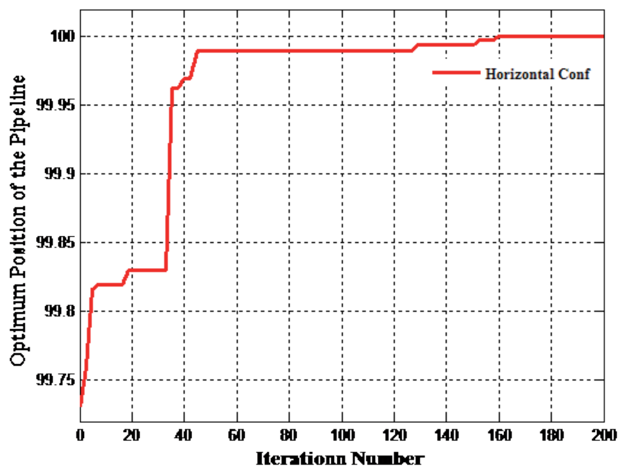

Fig. 14 Convergence of the Optimum Value for horizontal configuration

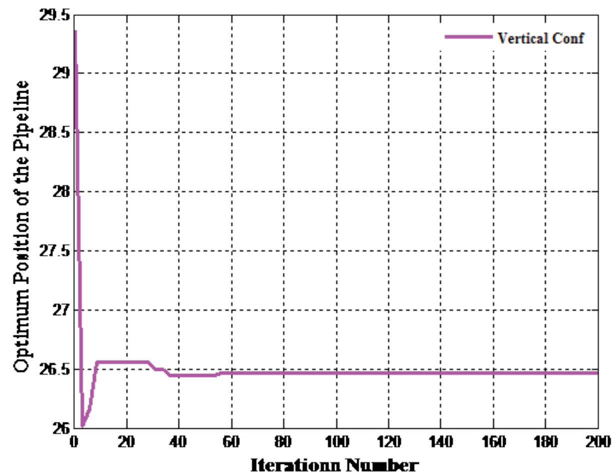

Fig. 15 Convergence of the Optimum Value for vertical configuration

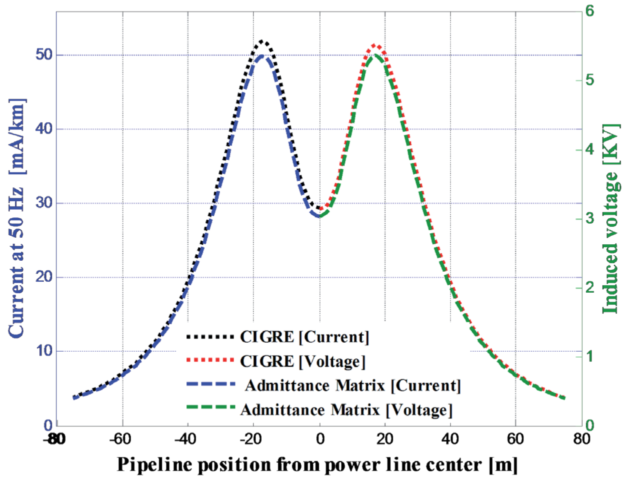

Fig. 16 Convergence of the Optimum Value for triangular configuration

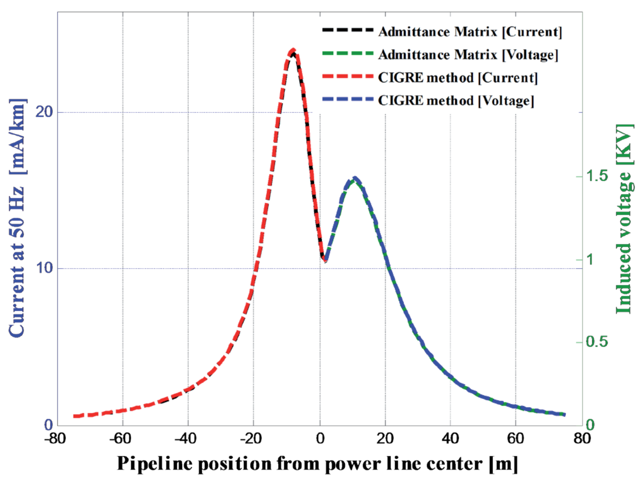

Fig. 19 Comparison of the results between the proposed Method and the CIGRE Method for the triangular configuration 220 kV

By comparing the graphs of Figs. 17, 18 and 19, we note that the distribution of the induced voltage and the discharge current is almost identical. It is also observed that these induced physical parameters (voltage and current) obtained are very close, despite the slight difference that emerges from the comparison of these profiles at the maximum values.

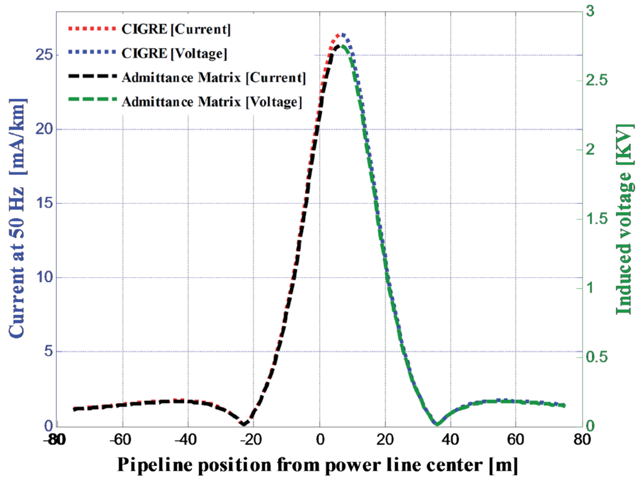

Fig. 17 Comparison of the results between the proposed Method and the CIGRE Method for the horizontal configuration 750 kV

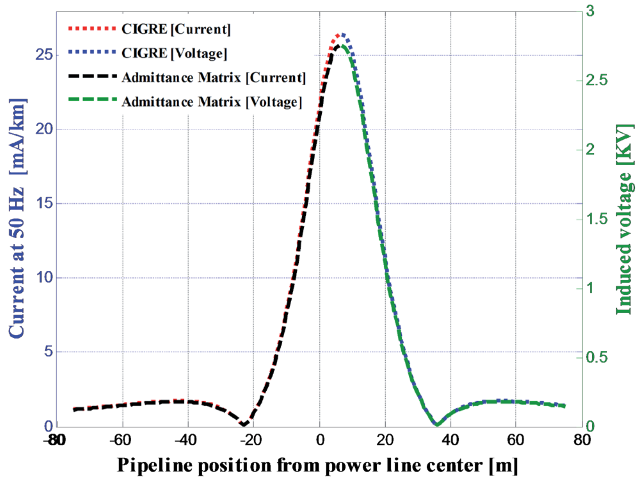

Fig. 18 Comparison of the results between the proposed Method and the CIGRE Method for the vertical configuration 400 kV

This procedure ensures the effectiveness of the proposed method and to validate the simulation. The comparison results of the maximum values between the simulation method and the CIGRE Method are given in Table 2.

Table 2 Comparison between the proposed Method and the CIGRE Method

	HVTL Horizontal Configuration 750 kV		HVTL Vertical Configuration 400 kV		HVTL Triangular Configuration 220 kV	
	Induced Voltage kV	Shock Current mA/km	Induced Voltage kV	Shock Current mA/km	Induced Voltage kV	Shock Current mA/km
CIGRE Method	5.513	51.92	2.833	26.42	1.491	24.07
Admittance Matrix Method	5.353	49.93	2.75	25.65	1.477	23.83

6 Conclusion

In this paper, the capacitive interference of high voltage transmission lines on the aerial pipeline has been analysed using the Admittance Matrix approach. According to the results presented, the induced voltage is affected by the nature of the configuration of the overhead power line and the distance of the location of the pipeline. It was noted by this analysis that the high induced voltages can induce dangerous currents for the safety of persons in contact with the pipeline, that it often exceeds the authorized limit; where it is necessary to reduce the current to the acceptable limit by directly connecting the pipeline to the ground with an appropriate resistance.

The results also analyze the optimal configuration giving the minimum induced voltage for pipeline, and the suggested location to implement the pipeline using genetic algorithm optimization.

The Induced voltages and currents calculated by this method were compared with those obtained using CIGRE Method; a very good agreement was obtained. This comparison allows to properly validating this simulation method.

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