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ASSESSMENT OF ELECTRICAL INTERFERENCE ON METALLIC PIPELINE FROM HV OVERHEAD POWER LINE IN COMPLEX SITUATION

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Abstract. *Sharing corridors between high voltage alternating current (HVAC) power lines and metallic pipelines has become quite common. Voltages can be induced on pipelines from HV power lines, which may cause a risk of electric shock to the operator and serious corrosion damage on metallic pipelines. This paper aims to examine the capacitive coupling between aerial metallic pipelines and HV power lines in perfect parallelism case and in general situation which is formed by parallelism, approaches and crossings, using a combination of charge simulation method and Artificial Bee Colony (ABC) algorithm. The electric field at the pipeline's surface and the induced voltage on the pipeline are strongly affected by the pipeline separation distance. The presented simulation results are compared with those obtained from the admittance matrix analysis, a good agreement has been obtained.*

Key words: *Charge Simulation Method (CSM); Artificial Bee Colony Algorithm (ABC), Capacitive Coupling, H-V Overhead Power Line, Aerial Pipelines*

1. INTRODUCTION

Aerial and buried metallic pipelines are typically designed to share common corridors for long distances with HV overhead power lines, the electric and magnetic fields emitted by these HV power lines result in AC interferences to metallic pipelines located in close proximity. Therefore, in many cases, the adjacent metallic pipelines are subjected to the impact of high induced AC voltages and currents [1-6]. There are three different mutual interferences, capacitive, inductive and conductive coupling. These electrical interferences present three main subjects of concern, a risk of electrocution for intervention agents of the pipeline, a damage of the pipeline's insulation coating, a risk to the integrity of the pipeline

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and its associated protective equipment, which puts in many cases the need to make a careful verification of these induced voltages levels and to adopt in some cases mitigation systems and safety measures [1-6].

In simple case, where the metallic pipeline runs perfectly in parallel situation with the conductors of the HV power line, this parallel exposure is termed a perfect parallelism. Generally, for the complex situation, the exposure length of the zone of AC interference influence is composed by parallelism, approaches and crossings [1].

In this regard, the purpose of the present paper is to assess the AC induced voltages due to capacitive coupling between the HV power lines and adjacent aerial metallic pipelines that are located in the same corridor in perfect case of parallelism, and in complex situation. The AC induced voltage assessment will be done using the charge simulation method (CSM), this technique accuracy depends strongly on the number and location of the both simulating charges and the contour points. In order to solve this major constraint, the Artificial Bee Colony Algorithm (ABC) is one of the most commonly used evolutionary algorithms for solving these optimization problems [7, 8]. The performance of the adopted hybrid technique will be verified by a comparison with results obtained by the admittance Matrix analysis.

2. Capacitive Coupling Mechanism

Only metallic pipelines installed above ground are subject to the capacitive coupling from the HV power line. The capacitive coupling is produced by the electric field strength due to the HV power line by inducing electric charges in the aerial metallic pipeline. It is a voltage divider formed by the capacitance between the HV overhead power line and the aerial pipeline, which is insulated from the ground, in series with the capacitance between the aerial pipeline and the adjacent earth, as shown in the Fig. 1 below [1,5,9,10].

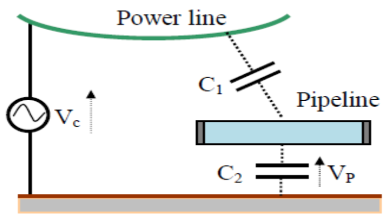

Fig. 1 Electrostatic coupling from a HV power line to a metallic pipeline

3. Charge Simulation Method (CSM)

In this technique, the real distributed charges on the surface of a conductor are replaced by a system of discrete fictitious charges arranged inside the conductor. The values of these fictitious charges are evaluated by satisfying the boundary conditions at a number of selected points called contour points on the surface of the conductor. Once these values of the fictitious charges are known, the potential of any point in the region outside the conductors can be determined using the superposition principle as follows [9-17].

$$V_i = \sum_{j=1}^{n_c} P_{ij} \times q_j \tag{1}$$

Where n_t is the number of discrete fictitious charges and P_{ij}, called the potential coefficient, means the potential at point (i) caused by a unit charge of q_j. It depends on the relative distance between the contour point (i) and the fictitious charge (j), which can be expressed by the following equation [9-17].

$$P_{ij} = \frac{1}{2.\pi.\varepsilon_0} \ln \frac{\sqrt{(x_i - x_j)^2 + (y_i + y_j)^2}}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} \tag{2}$$

where,
(x_i, y_i): Coordinates of the boundary contour point;
(x_j, y_j): Coordinates of the discrete fictitious charge.

Firstly, the values of the fictitious charges are determined by solving the linear system given in equation (3) below [9-17]:

$$[q_j] = [P_{ij}]^{-1}.[V_{ci}] \tag{3}$$

where $[P_{ij}]$ is the potential coefficients matrix; $[q_j]$ is the column vector of discrete fictitious charges; $[V_{ci}]$ is the column vector of known potentials at the contour point (Boundary conditions).

After calculating the values of the fictitious charges, we choose then n_c several verification points located at the contour of the conductors, and we calculate the new electrical potential V_{vi} given by the simulation charges, the relative error calculated between this new calculated electrical potential and the real potential applied to the phase conductors V_{ci} represent the accuracy of the simulation. The simulation is acceptable if this relative error value is less than the selected precision. If not, the simulation procedure should be repeated by changing the number and/ or the position of the simulation charges [9-17].

In electric field calculation due the HV power line; each conductor of the power line is considered as an infinite line type charge. The two-dimensional (2-D) coordinates of the fictitious charges and contour points in the cross section of the conductor/pipeline are shown in Fig. 2 [9,10,16,17]:

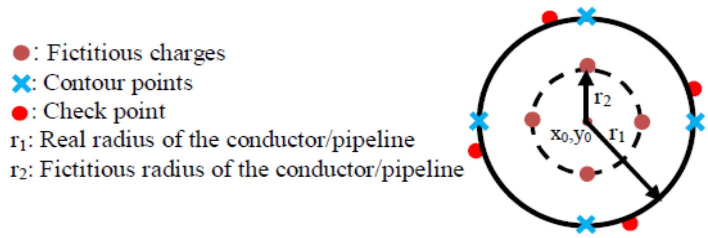

Fig. 2 2-D arrangement of simulation charges and contour points for the line conductor and the metallic pipeline

The general equations of the coordinates of contour points and fictitious charges are obtained very simply using the following two formulas [9,10,16,17].

$$x_k = x_0 + R \times \cos\left(\frac{2.\pi}{n_k} \times (k-1)\right)$$
$$y_k = y_0 + R \times \sin\left(\frac{2.\pi}{n_k} \times (k-1)\right) \tag{4}$$

where, $R = r_1$ *if* $k = i$, r_2 *if* $k = j$, y_0 is the vertical coordinates of conductors and metallic pipeline above ground, x_0 is the horizontal coordinates of conductors and metallic pipeline.

The components of the electric field are calculated using the superposition principle of all the vector components of this electric field. For a Cartesian coordinate system, the horizontal and vertical components E_x and E_y of the electric field for a number of n_t discrete fictitious charges would be given by [9-17].

$$\begin{cases} E_x = \left(\dfrac{1}{2.\pi.\varepsilon_0}\right)\displaystyle\sum_{j=1}^{n_t} q_j \left[\dfrac{x-x_j}{(x-x_j)^2+(y-y_j)^2} - \dfrac{x-x_j}{(x-x_j)^2+(y+y_j)^2}\right] \\ E_y = \left(\dfrac{1}{2.\pi.\varepsilon_0}\right)\displaystyle\sum_{j=1}^{n_t} q_j \left[\dfrac{y-y_j}{(x-x_j)^2+(y-y_j)^2} - \dfrac{y+y_j}{(x-x_j)^2+(y+y_j)^2}\right] \end{cases} \tag{5}$$

Where, (x,y) are the coordinates of the observation point; (x_j,y_j) are the coordinates of the discrete fictitious charges.

The resulting strength of the electric field at the observation point P is obtained by the sum of the intensities of the horizontal and vertical components, it can be written in the form [9-17].

$$E_{res} = \sqrt{E_x^{\ 2} + E_y^{\ 2}} \tag{6}$$

Under steady state condition of the HV power line, the AC induced voltage on the metallic pipeline due to the fictitious charges is determined using Equation (7) given below [1,12].

$$V_{ind} = \frac{1}{2\,\pi\,\varepsilon_0}\sum_{j=1}^{n_t} q_j.\ln\left(\frac{\sqrt{(x-x_j)^2+(y+y_j)^2}}{\sqrt{(x-x_j)^2+(y-y_j)^2}}\right) \tag{7}$$

When a person touches this metallic pipeline, the human body is charged and undergoes an electric shock, the discharge current that would flow through its body is given by the following relation [1, 12,18]:

$$I_{shock} = j \cdot C_p \cdot L_p \cdot \frac{dV_{ind}}{dt} \tag{8}$$

where, L_p is the length of the metallic pipeline exposed to the capacitive coupling (electrostatic coupling); C_p is the metallic pipeline's capacitance to earth per unit length is given by the inverse of the pipeline potential coefficient given above.

If the discharge current magnitude is higher than the admissible exposure limit authorized by the international standards IEC 60479-1:2005 in steady state conditions at industrial frequency of 50 Hz, which equal to 10mA for adult males [1,19], it is required to earthed the metallic pipeline through a low resistance R_s to reduce the discharge current below the acceptable limit, this earthing resistance must be lower than[1,5,12,14]:

$$R_s \prec \frac{R_{body}}{\beta - 1} \tag{9}$$

where, R_{body} is the body resistance; β is the ratio $\beta = \left(I_{shock} / I_{adm}\right)$.

In accordance with the American standard IEEE 80: 2000, the overall resistance of the human body is typically taken equal to a value of 1000 Ω[1,20].

4. General Situation

In General Situation (complex situation) of parallelism between an overhead HV power line and metallic pipeline, the area of influence is generally made up of three different cases: parallelism, approaches and crossings. This situation is illustrated in Fig. 3.

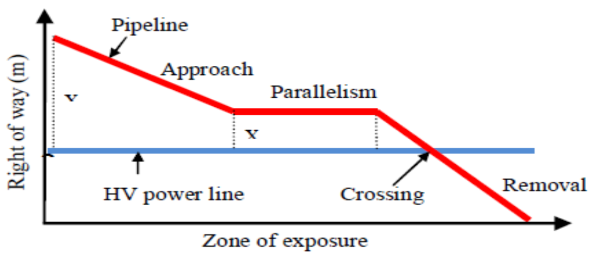

Fig. 3 Zone of influence

In this case, the distance separating the metallic pipeline, or a section of the metallic pipeline, and the different conductors of the overhead HV power line is no longer constant. Two such situations are illustrated in Fig. 4.

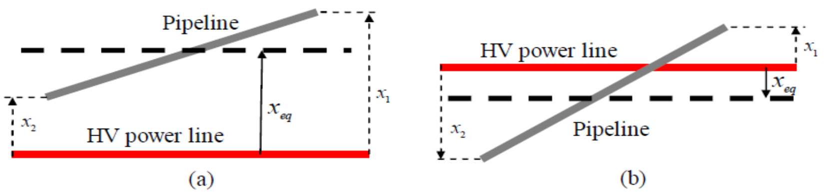

Fig. 4 Conversion of non-parallel exposures to parallel exposures between a HV power line and a metallic pipeline: (a) - oblique exposure, (b) - crossing exposure

In both cases, the non-parallel pipeline exposure can be converted to a perfect parallelism where the aerial pipeline is parallel to the HV power line and is at an equivalent distance from the HV power line given by the following equation [1,18]:

$$x_{eq} = \sqrt{x_1 . x_2} \qquad (10)$$

with,

$$\frac{1}{3} \le \frac{x_1}{x_2} \le 3 \qquad (11)$$

Where, x_{eq} is the geometric mean distance to the HV power line and x_1 and x_2 are the minimum and maximum distances of the metallic pipeline to the HV power line.

The resulting AC voltage of the metallic pipeline to earth can be evaluated as the average of the voltages in each section weighted by its length to the pipeline's complete length as follows[1,18]:

$$V_p = \frac{1}{L} \sum_{i=1}^{N} V_{p(i)} . L_i \qquad (12)$$

where, Vp is the AC induced voltage per unit length in section i; L_i is the length of section i; N is the number of sections of the aerial pipeline; L is the complete length of the zone of influence.

5. Artificial Bee Colony (ABC)

For improving the simulation accuracy in charge simulation method (CSM), the artificial bee colony (ABC) is proposed in order to find the optimal position and number of both discrete fictitious charges and contour points.

The artificial bee colony algorithm was introduced by Dervis Karaboga in 2005 for continuous optimization problems, it is a recent metaheuristic algorithm inspired by the natural pattern of honey bee behavior in foraging. The artificial bee colony contains three groups, Scouts, Onlookers and Employed bees. In the ABC algorithm, the initial solution population consists of a SN number of food sources generated randomly in the search space, each food source v_{mi} is generated according to the following equation [7,8,21,22]:

$$v_{mi} = x_{mi} + \phi_{mi} \, (x_{mi} - x_{ki}) \qquad (13)$$

where, x_k is a randomly selected candidate solution ($m \neq k$), k is a randomly selected parameter index; ϕ_{mi} is a random number within the range [-1,1].

Each food source is associated with a fitness function which characterizes the amount of nectar; this value is calculated according to the following Equation (14) [7,8,21,22].

$$fit_m(x_m) = \frac{1}{1 + f_m(x_m)}, \quad f_m(x_m) \succ 0 \qquad (14)$$

The choice of a food source is carried out in a probabilistic manner by evaluating the probability P_m, which depends on the nectar content of this food source, this probability is determined as follows [7,8,21,22]:

$$P_m = \frac{fit_m(x_m)}{\sum_{m=1}^{SN} fit_m(x_m)} \tag{15}$$

Finally, if the solution is abandoned, then, a new solution x_m will be produced randomly by the scout bees using the following expression [7,8,21,22]:

$$x_m = l_i + rand\ (0,1) * (u_i - l_i) \tag{16}$$

where, *rand* (0,1) is a random number within the range [0, 1], u_i and l_i are the upper and lower bound of the solution space of objective function.

The objective function used in this method is based on the relative error; its form is given by the following equation [9,10,16,17]:

$$OF = \frac{1}{n_t}\left|\sum_{i=1}^{n_t} \frac{V_{c_i} - V_{v_i}(n_t, r_f)}{V_{c_i}}\right| \tag{17}$$

where, V_{vi} is the real voltage which is subjected the phase conductors of the HV power line; V_{ci} is the new electrical voltage obtained by the verification points (check points); n_t is the total number of verification points.

6. ADMITTANCE MATRIX METHOD

For problems related to electrical charges, the pipeline AC voltage to earth due to the capacitive coupling for a given pipeline exposure length with the high voltage (HV) overhead power lines can be assessed using the admittance matrix technique, the resulting matrix consisting of the self and mutual admittances of the HV overhead power line conductors and aerial metallic pipeline. The advantages of this approach are that it is very simple and quite easy to be implemented; it can process very fast and provides an accurate solution. For a balanced (symmetrical) three phase AC power system with an aerial pipeline under steady-state conditions of the HV power line (the three phases have the same amplitude and are phase shifted by120°), the power line admittance per phase per unit length is obtained from the following formula [18,23]:

$$[Y] = j \cdot \omega \cdot [P]^{-1} \tag{18}$$

where, P is the potential coefficients matrix (the inverse of impedance to earth per unit length).

The AC currents in the HV power system are represented in the matrix form as follows,

$$[I] = [Y] \cdot [V] \tag{19}$$

The resultant matrix of shunt admittance per unit length for the three-phase system with the ground wires and aerial metallic pipeline is given by applying the following system of equations [18,23]:

$$\begin{bmatrix} I_c \\ I_p \\ I_g \end{bmatrix} = \begin{bmatrix} Y_c & Y_{cp} & Y_{cg} \\ Y_{pc} & Y_p & Y_{pg} \\ Y_{gc} & Y_{gp} & Y_g \end{bmatrix} . \begin{bmatrix} V_c \\ V_p \\ V_g \end{bmatrix} \tag{20}$$

Where, the subscripts 'c', 'p', and 'g' represent the three phase conductors, pipeline and ground wires, respectively.

The matrix can be reduced by eliminating the earthed ground wires, by replacing the current (Ig =0) in equation (20), giving [18]:

$$\begin{bmatrix} I_c \\ I_p \end{bmatrix} = \begin{bmatrix} Y_c^{'} & Y_{cp}^{'} \\ Y_{pc}^{'} & Y_p^{'} \end{bmatrix} . \begin{bmatrix} V_c \\ V_p \end{bmatrix} \tag{21}$$

With,

$$\left.\begin{array}{l} Y_c^{'} = Y_c - \dfrac{Y_{cg}.Y_{gc}}{Y_g}, Y_{cp}^{'} = Y_{cp} - \dfrac{Y_{cg}.Y_{gp}}{Y_g} \\ Y_{pc}^{'} = Y_{pc} - \dfrac{Y_{pg}.p_{gc}}{p_g}, Y_p^{'} = Y_p - \dfrac{Y_{pc}.Y_{cp}}{Y_g} \end{array}\right\} \tag{22}$$

For an aerial insulated pipeline by substituting (Ip=0) in Equation (21), it can be deduced from this simplification the pipeline AC voltage to earth due to capacitive coupling with the HV power lines, which is expressed by the equation below[18]:

$$\left[V_p\right] = -\left[Y_{pc}^{'}\right].\left[Y_p^{'}\right]^{-1}.\left[V_c\right] \tag{23}$$

Where, V_c are the known three-phase voltages to earth of the HV overhead power line.

7. RESULTS AND DISCUSSIONS

We consider in this study a 400 kV AC overhead power transmission line arranged in single horizontal configuration, with an aerial isolated metallic pipeline in close proximity under operating conditions for two types of situations. The first presents the simple situation (perfect parallelism between the HV overhead power line and the aerial metallic pipeline), and the second presents the general situation (the complex case) as illustrated in Fig. 5. The physical data and the geometric coordinates for the HV power line are shown in Fig. 6.

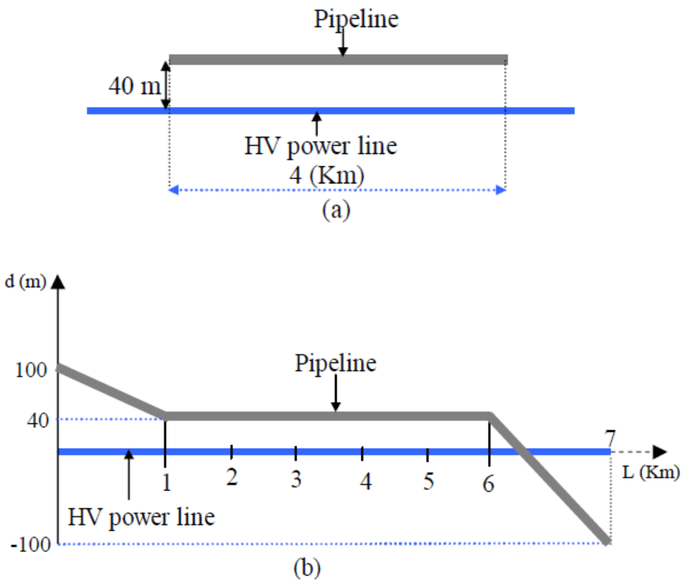

Fig. 5 Representation of situation between HV overhead power line and aerial pipeline, (a) - Case of perfect parallelism, (b) - Case of general situation

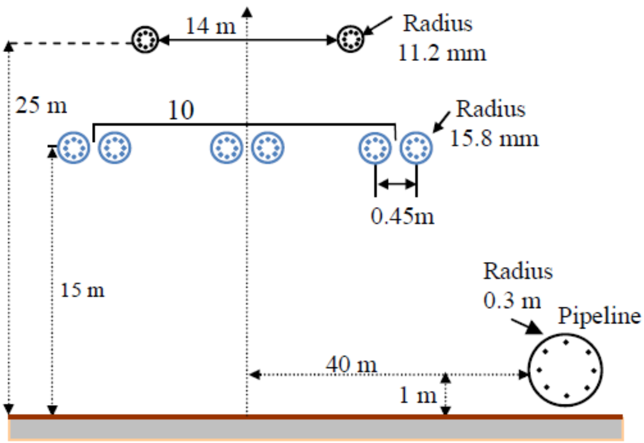

Fig. 6 Single circuit overhead HV horizontal configuration with an aerial pipeline

At first, the Artificial Bee Colony is applied in order to determine the optimal position and number of discrete fictitious charges and contour points used in charge simulation method (CSM), which makes it possible to obtain very sufficient precision in the simulation.

Figure 7 shows the continuous decrease in the objective function value (OF) given in equation (17) as a function of the number of iterations in this minimization algorithm.

The simulation result for the optimal values of parameters versus iteration number is shown in the Fig. 8, where it becomes apparent that this optimization algorithm converges quickly to the best optimal solutions. The indices 'PC', 'EW' and 'PL' represent respectively the phase conductors, earth wires and metallic pipeline.

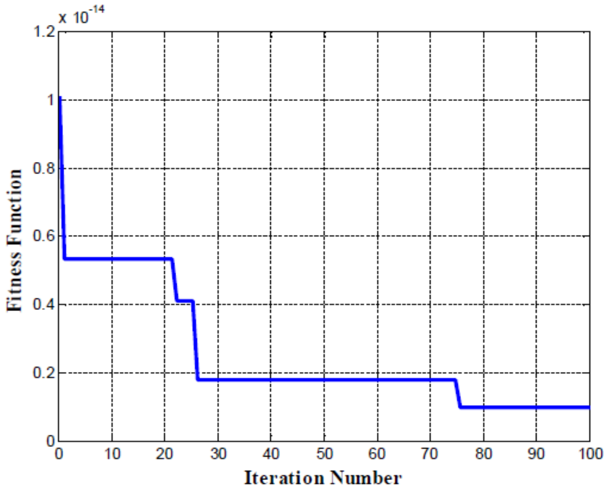

Fig. 7 The optimization process of the objective function with the number of iterations

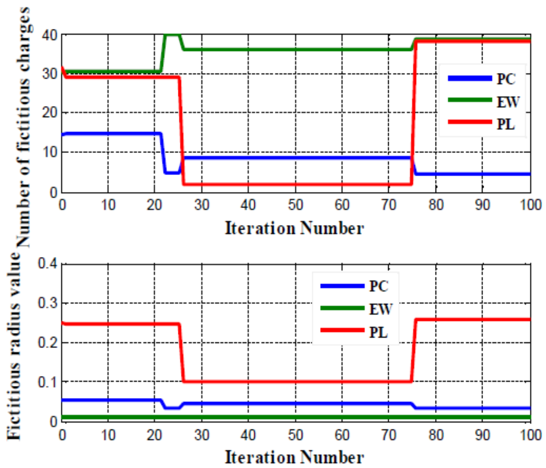

Fig. 8 Convergence of search parameters towards the optimal values

In case of perfect parallelism, Fig. 9 shows the lateral profile of electric field strength at metallic pipeline surface. It is clear from the graph that the presence of the metallic pipeline disturbs the electric field distribution, this electric field is subjected to a significant increase in the zone of the pipeline location, and this is caused by the accumulated induced electric charges on the pipeline surface.

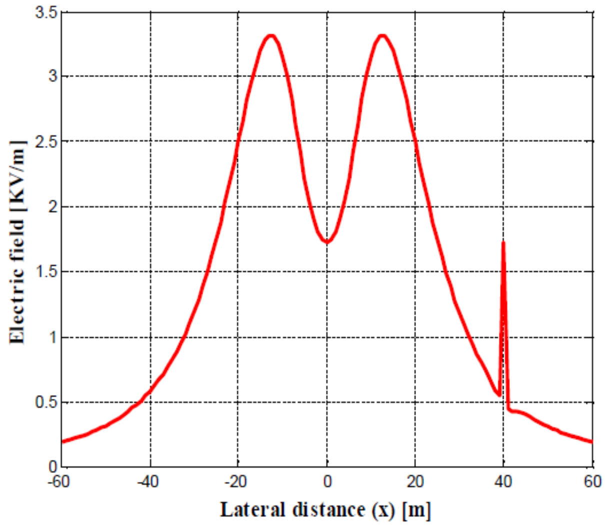

Fig. 9 Perturbed electric field strength on the metallic pipeline surface

The perturbed intensity of the electric field on the metallic pipeline's surface localized at varying separation distances from the HV power line center is shown in Fig. 10. It can be observed that the electric field strength has a low value under the middle phase conductor, and then increases progressively to a maximum value at a critical location of the pipeline, at this point, it starts to decline rapidly as one moves away from the HV power line center. As a result, the electric field strength on the metallic pipeline surface is effectively minimized when the pipeline is located as far away from the power line center as possible.

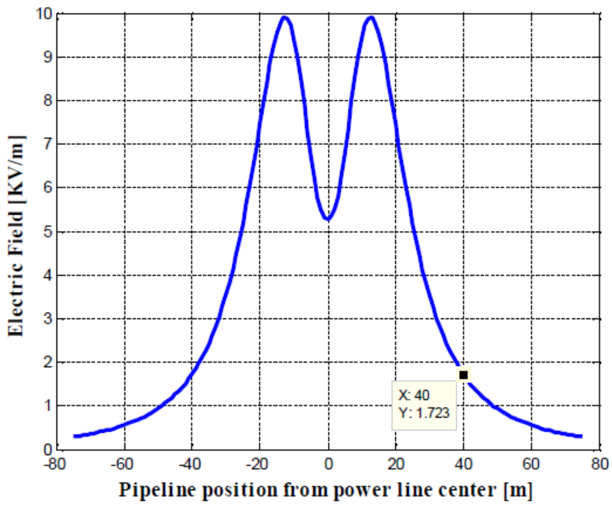

Fig. 10 Perturbed electric field strength as a function of the pipeline separation distance

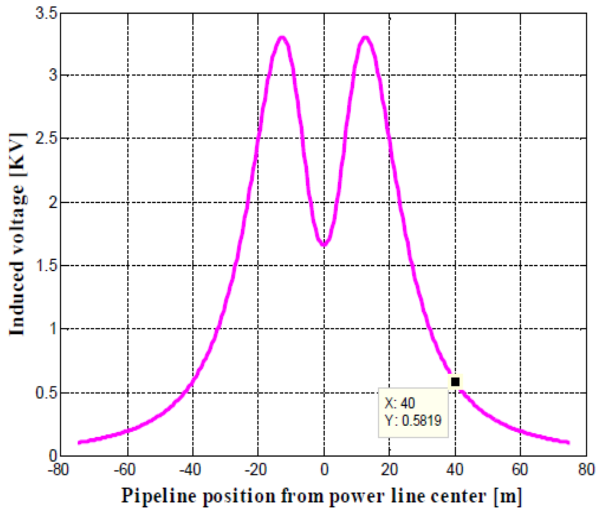

Fig. 11 Induced voltage values as a function of the pipeline separation distance from the power line center

Fig. 11 presents the induced voltage values on the metallic pipeline's surface as a function of its separation distance. It is evident from this figure that the induced voltage profile is generally similar to that of the electric field. From the mid-point of the HV power line, the induced voltage rises until it reaches its maximum value, and then declines gradually with increasing the pipeline separation distance from the mid-point of the HV power line. It is very strongly recommended that the pipeline should be maintained at a proximity distance called critical distance where the induced voltage is very close to zero.

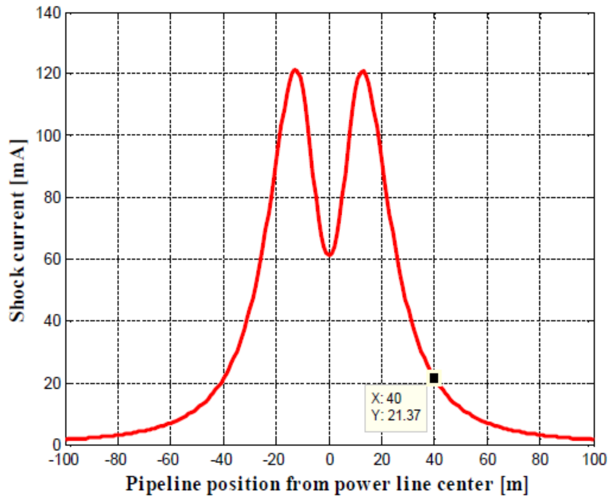

Fig. 12 Strength of shock current flowing through the human body

Under normal operating conditions, the shock current due to the capacitive coupling in a worker when it touches accidentally the metallic pipeline sited at different distances from the HV power line center is shown in Fig. 12. It is important to note that the current intensity is directly proportional to the AC induced voltage level, if this voltage is intense on the metallic pipeline, resulting in high value of shock current in contact with the metallic pipeline.

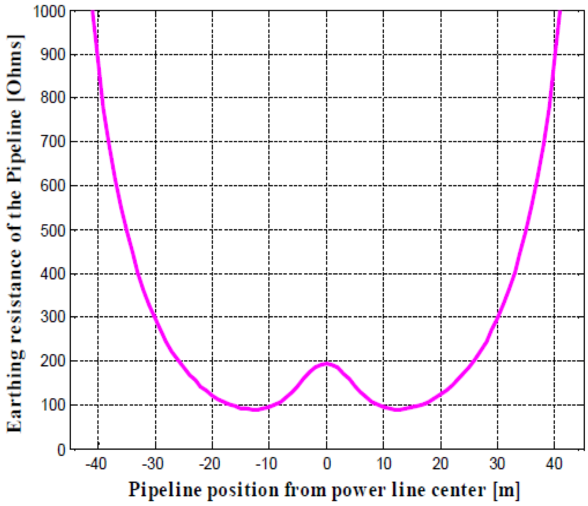

Fig. 13 Calculation of the earthing resistance of metallic pipeline

For shock currents values greater than the safety limit for operating personnel, the limit value which is advised by the CIGRE standard is equal to 10 mA. A concrete preventive measure must be applied: It is enough simply connect the metallic pipeline to the ground through an appropriate resistance calculated properly in accordance with the equation (9) mentioned above. Earthing resistance of the metallic pipeline as a function of its separation distance from the HV power line center is presented in Fig. 13. As can be noted from this figure, the behavior of earthing resistance profile is inversely to that of electric shock current.

In general situation, as shown in Fig. (5-b) above, the zone of influence of the circuit (HV overhead power line and metallic pipeline) is divided into parallel sections, so that the geometrical condition represented by the equation (11) is respected. The results of the calculation of the different separation distances (power line-pipeline) and lengths of parallelism (longitudinal and transverse coordinates), for each section are presented in Table (1) given below.

Table 1 Dimensions of the sections of the zone of influence: HV power line – metallic pipeline

Points coordinates (m) (x,y)		Ratio $ra=(y_i/y_{i+1})$	Separation distance (m) $y_{éq}=\sqrt{y_i \times y_{i+1}}$	Length Equivalent (m) $L_{éq}=\sqrt{(x_i-x_{i+1})^2+(y_i-y_{i+1})^2}$
0	100	/	/	/
500	70	1.43	83.67	500.9
1000	40	1.75	52.91	500.9
2000	40	1	40	1000
3000	40	1	40	1000
4000	40	1	40	1000
5000	40	1	40	1000
6000	40	1	40	1000
6050	20	2	28.28	53.85
6075	10	2	14.14	26.93
6190	-10	-1	6	116.73
6280	-20	0.5	14.14	90.55
6550	-50	0.4	31.62	271.66
7000	-100	0.5	70.71	452.77

Fig. 14 illustrates the variation of the AC induced voltage in each section of the zone of exposure influence, as a function of the equivalent length of parallelism. It can be noted from this figure that the magnitude of the AC induced voltage increases with decreasing in the separation distance between the metallic pipeline and the HV overhead power line, then it remains constant for a constant separation, when the aerial pipeline approaches to the HV power line, this AC induced voltage reaches a maximum value, and then decreases when the metallic pipeline crosses the HV power line, when this metallic pipeline moves away from the HV overhead power line, the AC induced voltage again reaches its maximum value for the same separation distance. In addition, the further we

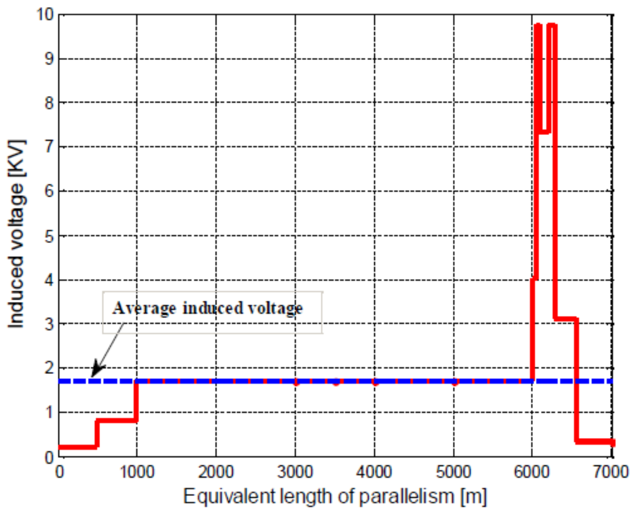

Fig. 14 Illustration of AC induced voltage along the metallic pipeline in complex case

get from the HV overhead power line, the induced voltage decreases to achieve very lower values. It can be concluded that the magnitude of AC induced voltage depends directly on the separation distance between the metallic pipeline and the HV overhead power line, and is significantly influenced by the equivalent length of exposure along the area of influence.

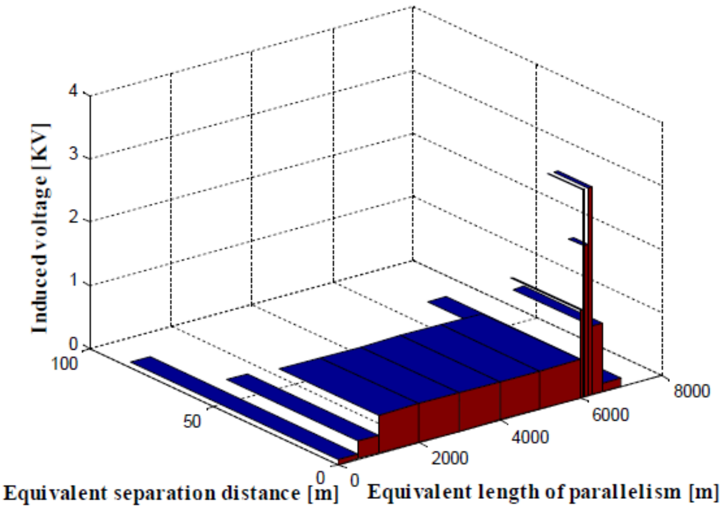

Fig. 15 3-D representation of the AC induced voltage along the metallic pipeline in complex case

Fig. 15 describes the (3-D) three-dimensional variation of the average total pipeline AC voltage to earth profile, as a function of the equivalent length of parallelism and the pipeline separation distance. It is evident from this figure that the AC induced voltage on metallic pipeline is directly proportional to the equivalent length of exposure; on the other hand, this AC induced voltage is in inverse proportion to the separation distance between the HV overhead power line and the metallic pipeline.

The last step is devoted to validate this modelling by comparing the simulation results obtained by the combined approach (CSM +ABC) with those obtained by the admittance matrix analysis, this simple method is strongly recommended in calculating the AC induced voltage on the metallic pipeline from the HV overhead power line; it presents a fast simulation tool. In Fig. 16, we see a good agreement between the values of the induced voltage. This procedure allows to confirm the obtained results.Moreover, it validates and ensures the effectiveness and accuracy of the adopted approach. It is important to note that the validation of simple case of perfect parallelism is sufficient to validate the complex case, since the complex case is a series combination of simple cases of parallelism.

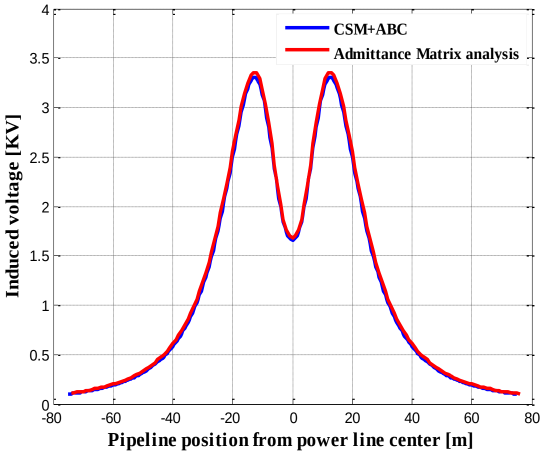

Fig. 16 Comparison of the AC induced voltage values by the two calculation methods

7. Conclusion

In this study, an improved method is used to evaluate the capacitive coupling between the HV overhead power line and an aerial metallic pipeline, based on the charge Simulation Method (CSM) combined with the Artificial Bee Colony (ABC). From the results, the perturbed electric field on the metallic pipeline located at different separation distances from the HV power line center has a lower value at the HV power line center and increases to reach its peak value, and then gets progressively decreased significantly as one moves away from this center. The AC induced voltage on the metallic pipeline is directly proportional to the electric field; its graphic representation is similar to that of the electric field. Generally, if the shock current in a human body touching the metallic pipeline exceeds the authorized limit; therefore, this metallic pipeline must be earthed through an adequate resistance, this protection and mitigation measure is necessarily compulsory to reduce these AC induced voltage levels to accepted limits that are safe for personnel touching the metallic pipeline. In general situation, the magnitude of the AC induced voltage on the metallic pipeline is considerably influenced by the distance separating the HV power line and the metallic pipeline, also the equivalent length of parallel exposure. The performance of the coupled method (CSM+ ABC) is assured by the comparison between its results and those obtained by the admittance matrix analysis, the comparison shows a good agreement.

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