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Capacitive Interferences Modeling and Optimization between HV Power Lines and Aerial Pipelines

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ABSTRACT

Metal pipelines are widely used for the transport of fluids and liquid and gaseous hydrocarbons. When these pipelines are installed near overhead power transmission lines, AC interference can occur between the high voltage power lines and pipelines. This interference can cause the appearance of induced voltages that present a risk of electric shock to the operator safety, direct effects on the pipeline, such as corrosion of the coating and steel. Evaluation of this coupling is necessary to ensure the safety of personnel and equipment connected to the pipeline. In this paper, an optimization method combining PSO with CSM is proposed to simulate the capacitive coupling between the HV power lines and aerial pipelines and analyze the different factors that affect the level of this coupling, the simulation results were compared with a previous study of specialty, the results are found in good agreement.

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1. INTRODUCTION

Because of the continuous growth of energy consumption and of the increased tendency to locate the high voltage electric transmission lines, and pipelines along the same corridors, the metallic pipelines are generally buried at shallow depths but they can also be aerial [1]-[3]. The presence of a HV power line parallel or close to the pipeline can be a source of dangerous electrical interference for this structure, under normal and post-fault conditions of power system operation. There are three predominant types of electromagnetic interference such as capacitive, inductive, and conductive. Each of these phenomena induces voltage on the pipeline, causing harmful effects. These effects may present a risk of electric shock to the operator safety. They can also threaten the integrity of cathodic protection equipment, the pipeline coating, and the pipeline steel [4]-[6].

Several international standards provide a method for determining the maximum acceptable contact and the measured voltages to protect workers pipeline. They are all based on the minimum current required to induce ventricular fibrillation (VF). In the normal operating conditions in IEC 60479-1:2005 for adult males, a current available greater than or equal to 10 (mA) would generally be considered unacceptable from the point of view of personal safety [7].

In this context, this study presents the simulation and modeling of a capacitive coupling between aerial pipeline and power line, operating in the steady state, using charge simulation method coupled with stochastic optimization techniques (PSO) for the optimization of the problem parameters.

In this method, the fictitious linear charges are used for the modeling of the line conductors; which are placed inside conductors; the values of these fictitious charges are determined by satisfying the boundary conditions on the conductors' surfaces [6] , [8]-[11], it is very important to determine the optimal position and number of fictitious charges, especially with respect to the realized accuracy and convergence with the number of the fictitious charges.

The choice of the position and the optimal number of fictitious charges was been carried out empirically by using the assignment factor [12], or according to the experience of the investigator [13].

Recently a genetic algorithms (GAs) as a search method has been used to determine the arrangement of fictitious charges in charge simulation method [14]-[16]. Similar to Genetic algorithms (GAs) and evolutionary algorithms (EAs), PSO is a population-based optimization tool, which searches for optima by updating generations. However, unlike GAs and EAs, PSO does not need evolutionary operators such as crossover and mutation [17], [18].

2. CAPACITIVE COUPLING FROM POWER LINES TO PIPELINES

The pipelines installed above earth are subject to capacitive coupling from the conductors of overhead lines. The electric field of the high voltage transmission line generates the capacitive coupling by inducing electric charges in the aerial pipelines. This represents a form of capacitive coupling operating across the capacitance between the overhead power lines and the pipeline, in series with the capacitance between the pipeline and the adjacent earth as shown in Figure 1.

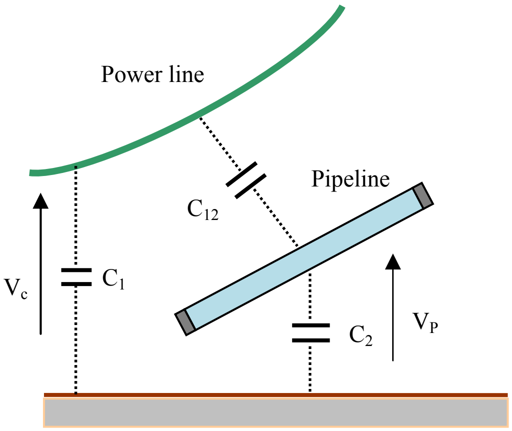


Figure 1. Capacitive coupling from a power line to a pipeline

The induced voltage between the pipeline and the earth, due to capacitive coupling is equal to:

$$V_p = \frac{C_{12}}{C_{12} + C_2} V_c \tag{1}$$

Buried pipelines are not exposed to capacitive coupling from the power line because the earth acts as an electrostatic shield [6], [19].

3. CAPACITIVE COUPLING CALCULATION

The charge simulation method is used to calculate the electric field distribution and the induced voltage on aerial pipeline due to high voltage transmission line, the transmission lines conductors and the pipeline are represented by infinite line charges. Each transmission line phase conductor is modeled by a number n_c infinite line charges kept slightly inside the periphery of the conductor/wire, pipeline is modeled by a number n_p infinite line charges also kept slightly inside the periphery of the pipeline [10], the simulation charges and the contour points are equally arranged on the circles with radius r_2 and r_1 respectively. Simulation charges for line conductors and the pipeline is shown in Figure 2.

The coordinates of the simulation charges and contour points in the cross section of the conductor and the pipeline are given by [20]-[22].

$$x_k = x_0 + R.\cos(k\theta_k)$$
$$y_k = y_0 + R.\sin(k\theta_k) \qquad (2)$$

Where: $R=\{r1 \text{ if } k=i,\ r2 \text{ if } k=j\}$;
y_0: heights of conductors and pipeline above ground;
x_0: horizontal coordinates of conductors and pipeline.

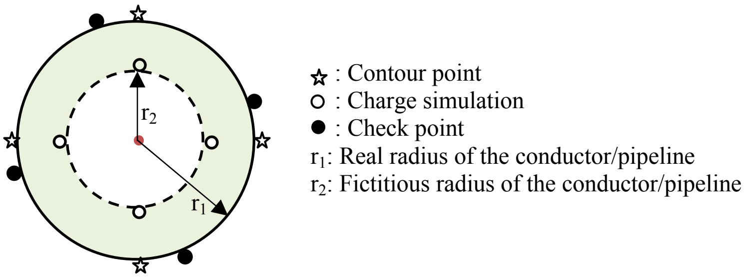


Figure 2. Arrangement of the simulation charges and the contour points (Conductor/ Pipeline)

The potential resulting from a set of fictitious charges of magnitude (Qj) can be computed easily using the superposition principle [20], [21], is given at point (i) as:

$$V_i = \sum_{j=1}^{n} P_{ij} Q_j \qquad (3)$$

Where: n is the total number of 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 only on the type of the charge and the relative distance between (i) and charge (Q_j) [20], [21].

$$P_{ij} = \frac{1}{2.\pi.\varepsilon_0} \ln \frac{\sqrt{(x_i - x_j)^2 + (y_i + y_j)^2}}{\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}} \qquad (4)$$

Where:
(x_i, y_i): coordinates of the contours point;
(x_j, y_j): coordinates of the simulations charges.

The Dirichlet boundary condition is satisfied at the boundary points chosen on the phase conductors and the ground wires. The values of the simulation charges are calculated by the resolution of the system:

$$[Q_j] = [P_{ij}]^{-1}.[V_{ci}] \qquad (5)$$

Where:
P_{ij} : The potential coefficients matrix;
Q_j : The column vector for simulation charges;
V_{ci} : The values of the potential are known values at the contour points.

After having determined the values of the simulation charges we choose then n other checking points placed on the contour of the conductors, and we calculate the new potentials (V_{vi}) given by the simulation charges (Q_j).

$$[V_{vi}] = [P_{vi}].[Q_j] \qquad (6)$$

The difference between the new potential calculated (V_{vi}) and the exact potential (V_{ci}) to which is subjected the conductor represent the precision of calculation [20], [21].

$$\varepsilon = \sum_{i=1}^{n} \left| \frac{V_{vi} - V_{ci}}{V_{vi}} \right| .100 \tag{7}$$

Where: n is the total number of contour points (n = 3.nc+2.ng+ np). Also nc is the number of the infinite line charges for each transmission line phase (for three phases) conductor, ng is the number of the infinite line charges for each earth wire (for two wires) and np is the number of the infinite line charges for the pipeline (for one pipeline).

The equation (7) must be minimized over nc, ng, np, rc, rg and rp.

Where: rc, r_g and r_p are the fictitious radius of phase conductor, earth wire and pipeline respectively.

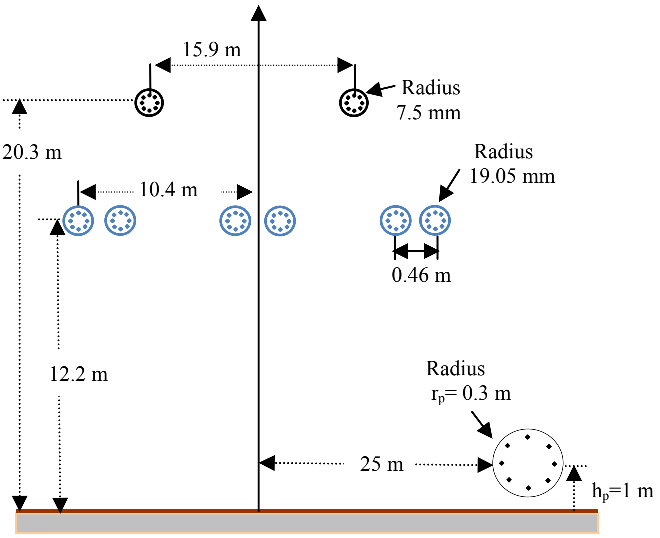


Figure 3. Single horizontal configuration with above pipeline

The electric field (Ei) at point contour is the sum of the electric field contributions of all simulation charges (Qj). The horizontal and vertical components of the electric field intensity at any point (x, y) for a number of charges (Qj) can be calculated by the following equations:

$$\left. \begin{aligned} E_{x_i} &= \sum_{j=1}^{n} Q_j \frac{\partial P_{ij}}{\partial x} \\ E_{y_i} &= \sum_{j=1}^{n} Q_j \frac{\partial P_{ij}}{\partial y} \end{aligned} \right\} \tag{8}$$

The resulting electric field at the contour point is expressed by:

$$E_i = \sqrt{E_{x_i}^2 + E_{y_i}^2} \tag{9}$$

In the presence of a power line parallel to on aerial pipeline, the voltages are induced in the pipeline through the electric fields produced by high voltage power transmission lines. The induced voltage on the metallic pipeline located at (xp, yp) due to capacitive coupling with the power lines under normal steady state along the right-of-way have been calculated using the charge simulation method (CSM). This induced voltage is given by the expression [10]:

$$V_{ind} = \int_{r=D}^{r=D'} \bar{E}_i . r . \hat{a}_r = \frac{1}{2\pi\varepsilon_o} \sum_{j=1}^{n} Q_j . \ln\left(\frac{D'}{D}\right)$$

Where: D' is the distance from the image of conductor to pipeline, D is the distance from conductor to pipeline. The earth is assumed to be a perfect conductor, so that the images are the same distance below the earth as are the conductors above the earth.

If a person touches a pipeline whose voltage is Vind, the discharge current that would flow through his body is given by [6], [23]:

$$I_p = j..\omega.C_p.L_p.V_{ind} \tag{13}$$

Where: L_p is the length of the pipeline exposed to capacitive coupling. C is the pipeline's capacitive.

If the current is above the admissible limit, the earth resistance required R_E to reduce the current below the admissible limit, applying the relationships circuit system shown in Figure 4, we have the equation [6]:

$$R_E \prec \frac{R_c}{\beta - 1} \tag{14}$$

Where: R_E the earth resistance required; R_c is the body resistance; ß is the ratio $ß = \left(I_p / I_{adm}\right)$.

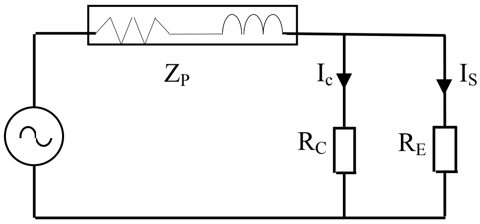


Figure 4. Technical mitigation: grounding pipeline for personal security

4. PARTICLE SWARM OPTIMIZATION

PSO optimizes an objective function by undertaking a population-based search. The population consists of potential solutions, named particles, which are a metaphor of birds in flocks. These particles are randomly initialized and freely fly across the multidimensional search space. During flight, each particle updates its own velocity and position based on the best experience of its own and the entire population. The updating policy drives the particle swarm to move toward the region with the higher objective function value, and eventually all particles will gather around the point with the highest objective value. The detailed operation of particle swarm optimization is given below:

- Step 1: Initialization. The velocity and position of all particles are randomly set to within pre-defined ranges.
- Step 2: Velocity updating at each iteration; the velocities of all particles are updated according to:

$$V_i = W\ V_i + c_1.R_1.(P_{i,besti} - P_i) + c_2.R_2.(g_{i,besti} - P_i) \tag{15}$$

Where: P_i and are V_i the position and velocity of particle i, respectively; $P_{i,best}$ and $g_{i,best}$, is the position with the 'best' objective value found so far by particle i and the entire population respectively; W is a parameter controlling the flying dynamics; R_1 and R_2 are random variables in the range [0, 1]; c_1 and c_2 are factors controlling the related weighting of corresponding terms. The inclusion of random variables endows the PSO with the ability of stochastic searching, the weighting factors, c_1 and c_2; compromise the inevitable trade-off between exploration and exploitation. After updating V_i should be checked and secured within a pre-specified range to avoid violent random walking.

- Step 3: Position Updating. Assuming a unit time interval between successive iterations, the positions of all particles are updated according to:

$$P_1 = P_i + V_i \tag{16}$$

After updating, P_i should be checked and limited to the allowed range.

- Step 4: Memory updating. Update $P_{i,best}$ and $g_{i,best}$, when condition is met.

$$\begin{cases} P_{i,besti} = P_i & if \quad f(P_i) < f(P_{i,besti}) \\ g_{i,besti} = g_i & if \quad f(g_i) < f(g_{i,besti}) \end{cases} \tag{17}$$

Where: f(x) is the objective function subject to minimization.

- Step 5: Termination Checking. The algorithm repeats Steps 2 to 4 until certain termination conditions are met, such as a pre-defined number of iterations or a failure to make progress for a certain number of iterations. Once terminated, the algorithm reports the values of $g_{i,best}$ and $f_{(gi,best)}$ as its solution.

Estimation the number of charges using PSO technique PSO mentioned above is used to select parameters of CSM: the Number of charges, which are attributes of each particle. In PSO operation, the fitness function of the particles group with test cases was evaluated using the Eq. (7).

Consider for the case study a single circuit transmission line a 400 kV, frequency of the system is 50 Hz, the phase conductors and ground wires are assumed parallel to a large flat conducting ground plane, the geometrical parameters of the line configuration are shown in Figure 3, the length of parallel exposure of the metallic pipeline and power line is 4 km, thickness of the insulating covering of the pipeline is considered to be 0.004 m, the relative permittivity of the insulating covering is equal to 5.

5. RESULTS AND ANALYSIS

To choose the better parameters for the PSO algorithm, we have carried out many experiments randomly, the parameters which made the fitness value be the smallest are chosen to use in this paper, the optimum parameters used in the numerical calculation are shown in Table 1.

Table 1. Charge simulation method and PSO Parameters

method	Parameters
PSO	number of optimization variables (6 variables) N=20, C_1=C_2=2, w_{max}=1.40, w_{min}=0.20, k_{max}=250.
CSM	range of fictitious charges :2–30 range for R(phase) : 0.01–0.084 range for R(wire) :0.001–0.0068 range for R(pipe) :0.1–0.27

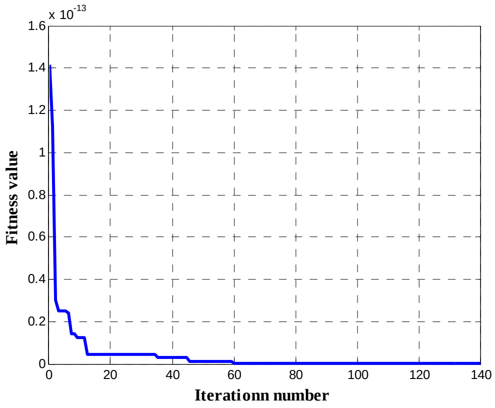


Figure 5. Evolving process of PSO algorithm with optimum parameters

The fitness value namely (Fg) given in equation (7) varies with the iteration number as shown in Figure 5. The application results in values that finally converge to the optimum values are detailed in the Table 2.

Table 2. The optimum values of the CSM

conductor	Fictitious charges number	Fictitious radius [m]	Fg
Phase conductor	3	0.0716	1.4422e-016
Ground wire	7	0.0026	
Pipeline	14	0.2493	

The simulation results are shown in Figures 6 and 7, where it becomes obvious that the algorithm converges rapidly to these values. The CSM and PSO model were constructed in MATLAB 7.8 (R009a).

Figure 8 shows the computed electric field profiles at 1m above ground level, without and with the presence of a metal pipeline. We can see from the graph that the electric field increases from the center point of the line and it reaches its maximum value at a transverse distance equal to 13 m from this point. Further, from the conductors, the electric field strength decreases rapidly with distance. The presence of the pipeline has a significant effect on the value of the electric field at the position where the pipeline is located. This figure shows how a pipeline perturbs the electric field beneath a power line. The field is reduced at the top of the pipeline, but increased around its sides.

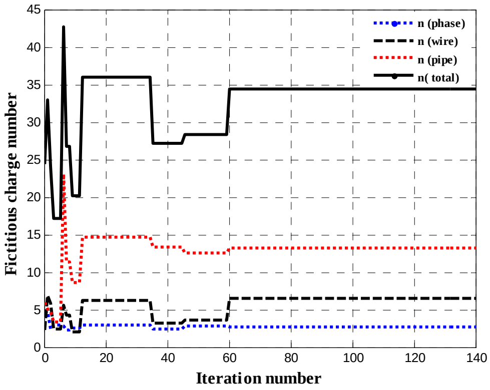


Figure 6. Convergence of the optimum values of fictitious charges number (nc, ng,np)

The perturbed electric field on the pipeline located at different distances from the transmission line is shown in Figure 9. It can be seen that the maximum electric field is nearly under the side conductors for a separation distance equal to 13 m. The electric field under the middle conductor is less than the side conductors. The electric field decreases rapidly with the distance.

Induced voltages on the pipeline located at different distances from the midpoint of the line have been calculated and the result is given in Figure 10.

The lateral distribution of the Induced voltage is broadly similar to that of the electric field shown in Figure 9. For this example, the Induced voltage on the pipeline due to the voltage 400 KV on the power line is equal to 1.91 KV. We can also observe that the induced voltage becomes almost negligible at a critical distance. It is suggested that the pipeline could be located close to the critical distance so that the induced voltage would be close to zero.

The body current of influence in a person touching the pipeline located at different distances from the midpoint of the line is shown in Figure 11. We noticed from the result if the induced voltage becomes very intense in the pipeline, so the induced current also increases. The current on the pipeline by the capacitive coupling is 71.16 (mA) , this value is much higher than the permissible safety value which can flow through the body of a person in contact with the pipeline under steady state conditions which is 10 (mA) for adult males.

Therefore, the pipeline must be grounded through adequate strength typically of the order of a few hundred ohms. According to the American standard IEEE 80:2000, the overall resistance of the human body is usually taken equal to 1000 Ω [21], in this example the pipeline would generally be earthed through an resistance equal to:

$$R_g \prec \left(1000/\left(71.16/10\right)-1\right)=163.5\ \ \Omega$$

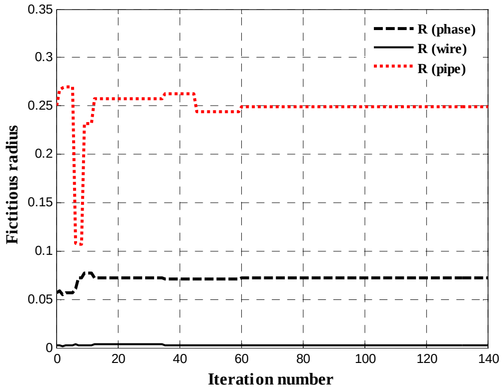


Figure 7. Convergence of the optimum values of fictitious radius (rc, rg,rp)

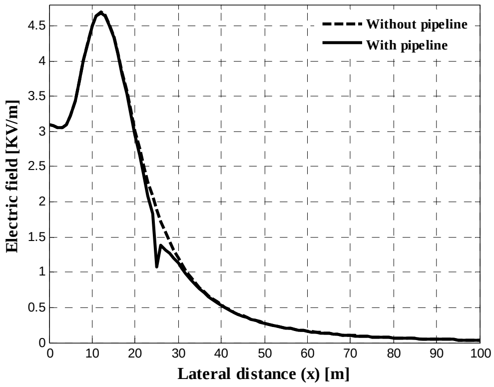


Figure 8. Electric Field profile at 1 m above the ground with and without the pipeline

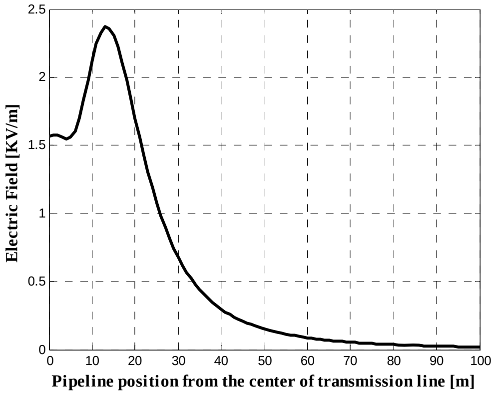


Figure 9. Perturbed Electric Field on the pipeline

Resistance of grounding (Earthing) the pipeline as a function of the horizontal proximity distance of pipeline is shown in Figure 12.

For safety problems during pipeline construction, the important parameter is the current passing through the human body in case of a direct contact with the pipeline, the admissible body current in steady-state operation as defined by the national regulations. In order to ensure there is no risk of electric shock, a safe separation distance between the pipeline and the power line is required, the minimum distance recommended by IPS standard [24], for a transmission line of 400 kV single circuits; this distance is equal to 60 Meter.

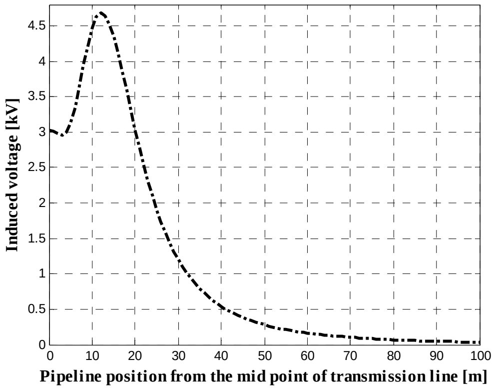


Figure 10. Induced voltage on an insulated pipeline

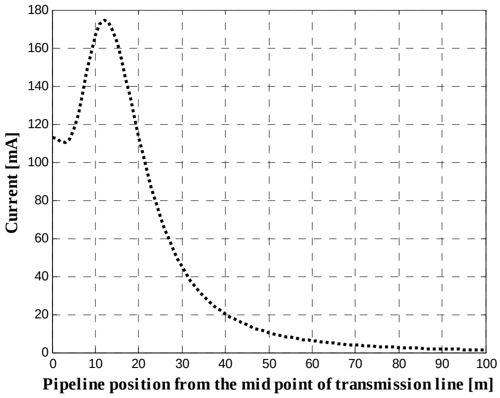


Figure 11. Current in the body during a contact with the pipeline

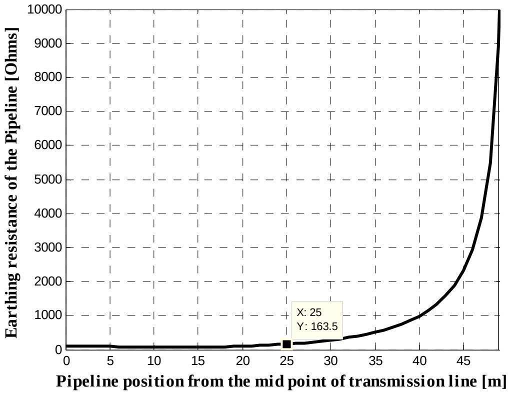


Figure 12. Calculation of the earthling resistance

Figure 13 shows the simulation results obtained for the values of minimum distances from this approach, minimum values of distance indicated in this figure tend to range from 45 to 65 Meter; the minimum distance recommended by this standard is located in this range.

To validate the modelling in this study, the simulation results are compared with experimental results published by the International CIGRE Working Group 36.02 [6]. We have shown in Figure 14, a best agreement between the results obtained by CSM-PSO model and the CIGRE Group.

We can therefore conclude that the proposed model has been successfully used to simulate and model both the conductors of the transmission lines and the pipelines, also as to evaluate the calculation of the electric field, the capacitive coupling between the electrical power lines and pipelines sharing the same corridor.

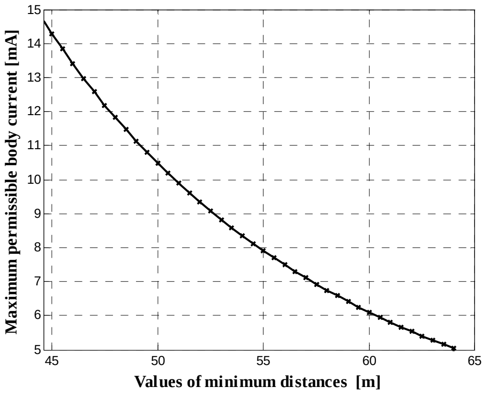
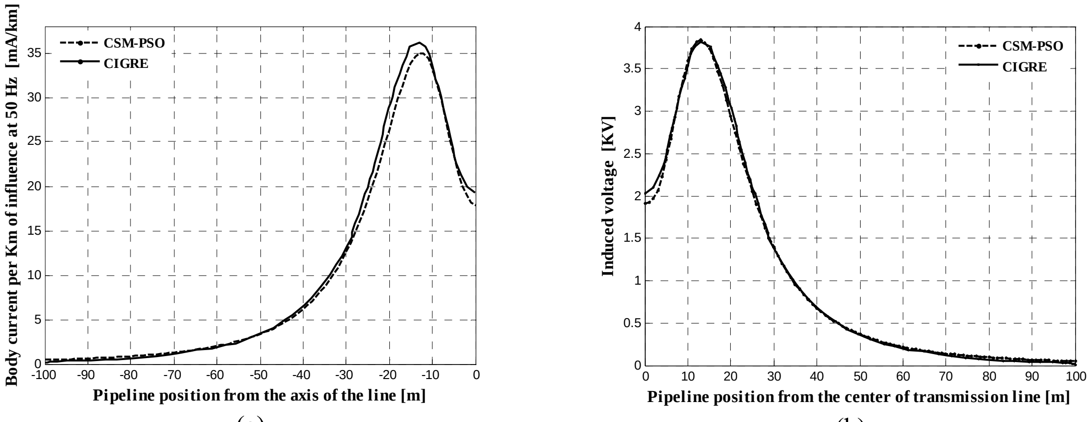


Figure 13. Minimum horizontal spacing between pipeline and parallel overhead power line



(a) (b)

Figure 14. Comparison of the results between the CSM-PSO model and the CIGRE method Ref. [6]
a: Body current per km a person touching the pipeline, b: Induced voltage on the pipeline

6. CONCLUSION

In this paper, a PSO technique is used to determine the appropriate arrangement of fictitious charges in charge simulation method (CSM), thus the CSM-PSO model is proposed to estimate the capacitive coupling on aerial metallic pipelines operating near power lines.

From the calculation results, we noticed that the profile of the field electric with the presence of the pipeline has been modified compared to the original figure. It is clear that the presence of the pipeline in the vicinity of power line causes the distortion of the electric field on the pipeline surface due to electric charges accumulated in the pipeline.

The induced voltages due to capacitive coupling on aerial metallic pipelines have been computed using the CSM-PSO model. It is seen that the induced voltage is proportional to the electrical field. Induced voltage on the pipeline becomes almost negligible at a critical lateral distance from the center of the power line. It is recommended that the pipeline should be positioned as far away from the power line as possible to reduce the induced voltage. The current flowing in the case of direct contact with the pipeline exceeds the permissible safety limit. They can cause risk of electric shock to people or working personnel touching the pipeline. This risk can be reduced by earthing the pipeline through a suitable resistance. The results obtained by the proposed model were compared with the results obtained by the literature. The results show a good agreement.

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