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Passive mitigation for magnetic coupling between HV power line and aerial pipeline using PSO algorithms optimization

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ABSTRACT

This paper proposes a methodology based on Faraday's electromagnetic induction law (EMF) for evaluating the induced voltage produced by high voltage power line on an aerial metallic pipeline located parallel in its immediate vicinity under normal operating condition. It also describes the procedure of the induced voltage mitigation using the passive loop technique combined with the particle swarm optimization algorithm (PSO). The presence of a pipeline in the vicinity of an overhead power line strongly disturbs the mapping of the magnetic induction produced by this power line. The mitigation efficiency is significantly improved by optimizing the position of the loop conductors, by increasing the number of loops and the use of a shielding magnetic material of high relative permeability. The obtained simulation result is compared with that obtained by the Carson's formulas. A good agreement was obtained.

1. Introduction

The continued increase in electricity consumption in developing regions of the world has created significant demand for energy resources. The development of the installations for the transport of energy sources (oil, gas) with electric power transmission networks at very high voltage levels are accelerating to satisfy electrical needs of the world's population. These two types of transport use long distances to fulfill their functions. Thus, the sharing of a common right-of-way between the two transporters operating along their routes is inevitable. In fact, the overhead AC high voltage power transmission lines (HVTLs) generate high levels of extremely low frequency electric and magnetic fields. These generated fields can induce currents inside the human body and metallic objects located in the vicinity of these HV transmission lines. Therefore, it is necessary to assess and analyze the interference levels between these transmission lines and the metallic pipelines placed inside the right-of-way.

Generally there are three coupling modes of interference to be considered, the capacitive coupling; inductive coupling and conductive coupling, which produce an induced voltage in the metallic pipelines, the inductive effect is the most important from among those three couplings [1–3].

In the last years, several important studies on electromagnetic interferences have been conducted [4–14], based on the recommendations reported by these research studies, a number of reports, standards and guides have been established, to define the safety limits values of voltages and currents under normal operating conditions and fault conditions [15–19].

In this study, the magnetic coupling (inductive coupling) between the HV power lines and aerial metallic pipelines under normal network operating conditions is processed by means of a quasi-static numerical modeling. The purpose of this paper is to quantify the safety aspects of the operator and the personnel coming into contact with the pipeline, as well as an optimum location for the passive mitigation has been suggested where the induced voltage safety limits recommended by the standards [15–17] are exceeded. Also, an appropriate location for the pipeline which gives a better reduction of the induced voltage on the pipeline can be chosen using the Particle Swarm Optimization (PSO) algorithm.

In recent years, Particle Swarm Optimization (PSO) has been successfully and widely applied in various areas of electric power and high voltage engineering. PSO is a stochastic population based optimization approach that may be used to find optimal solutions to numerical and qualitative problems. This technique was developed by Kennedy and Eberhart in 1995 and is inspired by the social behavior of insects and animals searching for food [20–22].

The present paper is structured as follows. Section 2 gives a brief presentation of the magnetic coupling between the AC transmission

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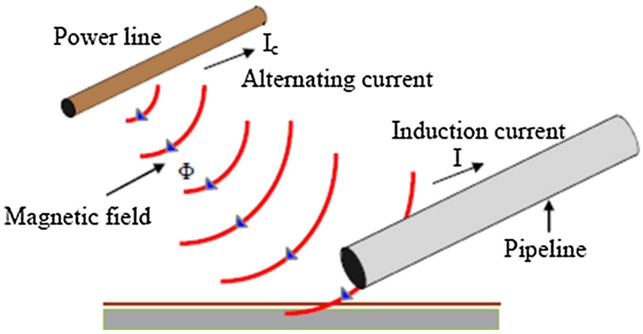

Fig. 1. Magnetic coupling between aerial pipeline and HV power line.

lines and the aerial parallel pipeline. The calculation methods used for the evaluation of magnetic coupling and optimized mitigation are presented in Sections 3 and 4. Finally, Section 5 describes the Carson's method that validated the simulation results.

2. Magnetic coupling from power lines to pipelines

The magnetic coupling is the result of the magnetic field generated by the power lines, as shown in 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 force causes currents circulation in the pipeline and voltages between the pipeline and the surrounding earth [16,19,23].

3. Magnetic coupling evaluation

3.1. Magnetic flux density calculation

The intensity of the magnetic induction $\overrightarrow{B}$ due to the currents I_i flowing in supposed infinitely long horizontal conductors is obtained by the direct application of the Ampere's law and superposition principle of the partial results. The image theory of the conductors can be applied taking into account the penetration depth De; indeed, the images of the conductors are located at a depth in the ground, much greater than the height of the conductors above ground. The effect of currents induced in the de-energized conductors (earth wires and pipeline) must also be taken into account in this calculation.

In this analysis of magnetic coupling and mitigation between the high-voltage power line and the aerial pipeline, the following simplifying assumptions were applied [24]:

- The conductors are horizontals and parallel to a flat ground on an infinite distance;
- The average height of the conductor is taken into consideration as the tower height minus 2/3 of the sag;
- The influence of the towers and metallic objects encountered which act as screens is neglected;
- The effect of varying environmental conditions on soil resistivity is neglected;
- The length of the loop is at least 15 times longer than their width.

By neglecting the displacement current density in Ampere's law, the horizontal and vertical components of the magnetic induction intensity phasors ($\overline{B}_h$ and $\overline{B}_v$) due to all the power line conductors located at coordinates (x_i, y_i) above a homogeneous earth at the desired point p (x,y) can be calculated as follows [25–30]:

$$\overline{B}_h = -\frac{\mu_0}{2.\pi}\sum_{i=1}^{n}\overline{I}_i\left[\frac{y-y_i}{{r_{pi}}^2} - \frac{y+y_i+D_e}{{r'_{pi}}^2}\right]$$
$$\overline{B}_v = \frac{\mu_0}{2.\pi}\sum_{i=1}^{n}\overline{I}_i\left[\frac{x-x_i}{{r_{pi}}^2} - \frac{x-x_i}{{r'_{pi}}^2}\right] \tag{1}$$

where, $\overline{I}_i$ are the currents phasors flowing through the conductors; μ_o represents the permeability of free space; n is the total number of conductors; r_{pi} is the distance between each conductor and desired point p; r'_{pi} is the distance between each image conductor and desired point p; D_e is the complex penetration depth and is given by [25,26,31]:

$$D_e = \sqrt{2}.\delta.e^{-j\pi/4}\ ,\ \delta = 503\sqrt{\frac{\rho_s}{f}} \tag{2}$$

where, δ is the skin depth of the ground; ρ_s is the earth resistivity expressed as (Ω m); f is the frequency of the current in (Hz); j is the imaginary number.

The rms value of resultant magnetic induction at the desired point p can be calculated as:

$$B_t = \sqrt{|\overline{B}_h|^2 + |\overline{B}_v|^2} \tag{3}$$

The induced currents circulating in the de-energized conductors (earth wire and pipeline) can be found by solving the following equation using the Gauss method [32,33]:

$$[I_g] = -[Z_g^{-1}].[Z_{gc}].[I_c] \tag{4}$$

where, Z_{gc} is the matrix of mutual impedances between the de-energized conductors and phase conductors; Z_g is the self-impedances matrix of the de-energized conductors; I_c is the matrix of currents passing through the phase conductors.

In low frequencies, the self and mutual impedances with earth return of the conductors are obtained according to Carson-Clem's formulae [34,35]:

$$Z_{ii} = R_i + \pi^2.f.10^{-4} + j.\omega.2.10^{-4}\left[\ln\left(\frac{D_e}{R_{GM}}\right)\right]\left[\frac{\Omega}{\text{km}}\right] \tag{5}$$

$$Z_{ij} = \pi^2.f.10^{-4} + j.\omega.2.10^{-4}\left[\ln\left(\frac{D_e}{d_{ij}}\right)\right]\left[\frac{\Omega}{\text{km}}\right] \tag{6}$$

where, R_i is the DC resistance per unit length of conductor in (Ω/km), R_{GM} is the geometric mean radius of the conductor in (m); d_{ij} is the distance between the conductor i and the conductor j.

These Carson-Clem's simplified expressions are generally sufficiently accurate when the mutual distance d_{ij} between conductors i and j is less than 15% of the equivalent earth return distance D_e [35].

3.2. Induced voltage calculation using Faraday's law of induction

The basic principle of the induced voltage due to high voltage power lines on a nearby conductor or a pipeline, which forms a closed loop, is the Faraday's law of induction. This law explains that a variable magnetic field over time can induce an electromotive force on the pipeline. The total magnetic flux due to the sinusoidal variation of all currents flowing in conductors of the overhead power line through the pipeline can be calculated from the formula given below [25,27,36,37].

$$\phi_p = L_p\int_{r_1}^{r_2}\overrightarrow{B_h}.d\overrightarrow{r} \tag{7}$$

where, Lp is the length of pipeline, B_h is the magnetic induction component perpendicular to the plane that contains the pipeline conductor.

Generally the pipeline is represented as a long lossy transmission conductor, with a return path through the earth, which constitutes a loop located at the coordinates (x_{p1}, y_{p1}) and (x_{p2}, y_{p2}), as shown in Fig. 2, applying the coordinates of the line conductors and the pipeline [25,27,36,37].