MAGNETIC FIELDS MINIMIZATION OF TRANSMISSION LINES BY DIFFERENTIAL EVOLUTION METHOD

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Abstract— The transmission lines are equipment that emit high-intensity magnetic field due to their high currents. Such magnetic fields can be harmful to health and cause interference in electronic devices. This paper presents a methodology to minimize the magnetic field emitted by transmission lines at ground level. For this, the magnetic field is calculated based on the electromagnetic analytical model and optimized by a stochastic method known as Differential Evolution (DE). The penalty method is considered for the treatment of problem constraints. To show the DE robustness, the results are compared with a well-established optimization method, the Genetic Algorithm (GA).

Keywords— Magnetic field, Transmission lines, Optimization, Differential Evolution.

Resumo— As linhas de transmissão são equipamentos que emitem campo magnético de alta intensidade devido à sua alta corrente. Tais campos magnéticos podem ser prejudiciais para a saúde e causar interferência em equipamentos eletrônicos. Este artigo apresenta uma metodologia para minimizar o campo magnético emitido pelas linhas de transmissão ao nível do solo. Para isso, o campo magnético é calculado com base no modelo analítico eletromagnético e otimizado por um método estocástico conhecido como Evolução Diferencial (ED). O método de penalidade é considerado para o tratamento de restrições do problema em questão. Para mostrar a robustez do ED, os resultados são comparados com um método de otimização consagrado, o Algoritmo Genético (AG).

Palavras-chave— Campo magnético, Linhas de transmissão, Otimização, Evolução Diferencial.

1 Introduction

Overhead transmission lines (TLs) are crucial equipment on today's electric power system. They are responsible for transmitting the generated electric energy to the consumer centers. Countries such as Brazil, which has a great territorial extension and a great distant hydraulic bases between them, are highly dependent on TLs. Furthermore, due to the population growth and rising demand for energy, the necessity of new TLs have increased considerably in recent years (Campos, 2010; Mustafa et al., 2017).

Due to environmental, economic and geographic problems, some TLs are built close to urban centers and industries. This fact causes some concerns about the magnetic field levels emitted by the operation of the electrical power system equipment. The health effects related to exposure to magnetic fields are widely questioned. In addition, such fields may cause electromagnetic interference in elements close to TLs (Sawma et al., 2010; Yu et al., 2016).

Therefore, regulatory agencies of each country have developed regulations to standardize the maximum limits exposure of magnetic fields in the TLs bandpass. The World Health Organization (WHO) recommends the limits set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). For the general public, the maximum exposure limit is 200 μT (ICNIRP, 2010).

Hence, studies regarding the optimization techniques for transmission lines becomes attractive. In Vyas and Jamnani (2016), the optimization is applied by changing design parameters of the line configurations and best design involving minimum cost and giving best performance in terms of electric and magnetic fields, utilizing the concept of compact tower design. However, the authors do not use any optimization method. In Arruda et al. (2015), it is applied the Particle Swarm Optimization metaheuristic with multi-ring topology to obtain the cable-ground height, the distance between phases, the equivalent diameter of conductors, the currents and voltages, through a cross-section of a transmission line, using the reference values of the electric and magnetic fields.

Studies carry out by Paganotti et al. (2015; 2017) present a computational tool intended to calculate and minimize the electric fields at ground level of high surge impedance loading transmission lines. In first study, an enhanced deep-cut ellipsoidal method is applied and the second one, the Differential Evolution Method is applied, both to find a non conventional optimized configuration for the phase conductors with reduced electric field profiles at ground level.

Thus, the aim of this paper is to develop a computational tool to evaluate the magnetic fields at ground levels using the method of the complex ground return plane and minimize the magnetic field, little investigated in literature, using the Differential Evolution method.

2 Electromagnetic Modeling

The TL under study is modeled considering the following assumptions: three-phase, symmetrical and balanced. In magnetic field calculation at ground level, the conductors are modeled as infinite lines traveled by an infinitely long filamentary current, parallel to the ground. The domains that involve the problem, the air and the ground are considered semi-infinite, linear, homogeneous and isotropic. The TL's operating regime is quasi-static, i.e. 60 Hz, which allows independent modeling to calculate the magnetic field (Santos, 2017).

The magnetic field at the ground level can be determined by applying the Ampère's Law,

$$\vec{H} = \frac{I}{2\pi\rho}\hat{a_\phi} \tag{1}$$

In (1) I refers to the current flowing through the conductor, ρ is the vertical distance between the point of the field source and the observation point and $\hat{a_\phi}$ is the cross product between the current vector $\hat{a_L}$ and the position vector $\hat{a_\rho}$ (Sadiku, 2014). The ground effect is entered into the calculations by the method of the complex ground return plane. Such a method establishes that the current I which runs through the conductor returns through the ground by means of a conductor image located directly below the real conductor at a complex penetration p, calculated in (2) (Deri et al., 1981).

$$p = \frac{1}{\sqrt{j\omega\mu_0\sigma_S}} = \sqrt{\frac{\rho_S}{j\omega\mu_0}} \tag{2}$$

Where ω is the angular frequency in rad/s, μ_0 is the magnetic permeability of vacuum equal to $4\pi \times 10^{-7} H/m$, σ_S is the ground conductivity in S/m and, ρ_S is the ground resistivity in $\Omega.m$. Figure 1 illustrates the Method of the complex ground return plane for a single-phase system, which by applying the method, the air and ground in the left side of the Figure 1 are considered to be a single medium as shown on the figure right side. (Deri et al., 1981).

The total magnetic field corresponds to the superposition of fields generated by real conductors and image conductors for each cartesian coordinate, resulting in (3) (Santos, 2017).

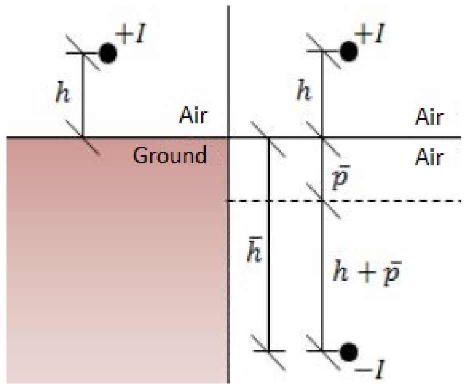

Figure 1: Method of the Complex Ground Return Plane for a single-phase system (Santos, 2017).

$$\vec{H} = (H_{xRe} + jH_{xIm})\vec{a_x} + (H_{yRe} + jH_{yIm})\vec{a_y} \tag{3}$$

Which the sub-index Re and Im represent H real part and H imaginary part, respectively. H_x and H_y are given by (4) and (5) (Santos, 2017).

$$H_x = \sum_{i=1}^{N} \frac{I_i\angle\theta_i}{2\pi}\left[\frac{-(y-y_i)}{(x-x_i)^2+(y-y_i)^2}\cdots + \frac{-(y+2p+y_i)}{(x-x_i)^2+(y-y_i)^2}\right] \tag{4}$$

$$H_y = \sum_{i=1}^{N} \frac{I_i\angle\theta_i}{2\pi}\left[\frac{-(y-y_i)}{(x-x_i)^2+(y-y_i)^2}\cdots + \frac{(x-x_i)}{(x-x_i)^2+(y+2p+y_i)^2}\right] \tag{5}$$

In (4) and (5) x_i and y_i, x and y, are respectively, the horizontal and vertical positions of the source conductors and the point of field evaluation; and N is the number of the conductors. Note that, the magnetic field calculation depends on the conductor's positions and the current of each conductor.

To obtain the magnetic flux density through (3) it is necessary to apply the constitutive relation, showed in (6) (Sadiku, 2014).

$$\vec{B} = \mu_0\vec{H} \tag{6}$$

Moreover, it is necessary to define an electromagnetic model to determine the currents in each cable of the TL. However, these currents vary according to its load curve. Due to the difficulty in determining the instantaneous current values, it is considered the nominal operating current (Santos, 2017).

In this way, the objective is to find, during the optimization process, the best conductors positions x and y that minimize the magnetic field at ground level, using the Differential Evolution method.

3 Optimization

3.1 Optimization Problem

A monobjective optimization problem can be formulated by finding a vector of n design variables $X = [x_1, x_2, ..., x_n]^T$ that optimizes an objective function, $f(X)$, and satisfies the constraints of equality, $h_l(X)$; inequality $g_j(X)$; and sides (lower, x_i^L, and upper, x_i^U, bounds). X refers to vector of real variables and T represents the transposition of the vector. The problem can be written according to (7) and (8) (Oliveira and Saramago, 2005).

$$Minimize\ f(X) \tag{7}$$

$$Subject\ to \begin{cases} g_j(X) \leq 0,\ j = 1, ..., J. \\ h_l(X) = 0,\ l = 1, ..., L. \\ x_i^L \leq x_i \leq x_i^U,\ i = 1, ..., n. \end{cases} \tag{8}$$

In order to deal with problems with these constraints, it is crucial to insert some techniques into the optimization method. In the proposal problem, there are only inequality constraints and the penalty method is used. In this technique, constrained problems are transformed into unrestricted problems by adding a penalty function $P(X)$ to the original objective function to limit constraint violations. This new objective function, called pseudo objective, is penalized according to a penalty factor every time the DE algorithm encounters a solution that have infeasible constraints. Let define the pseudo objective function, B, given according to (9), and the penalty function P to (10). The scalar r_s is a multiplier that quantifies the magnitude of the penalty (Oliveira and Saramago, 2005).

$$B(X) = f(X) + r_s P(X) \tag{9}$$

$$P(X) = \left[\sum_{j=1}^{J} max(0, G_j(X))^2 \right] \tag{10}$$

3.2 Optimization Method: Differential Evolution

The Differential Evolution (DE) method is part of the stochastic methods. It was created by Storn and Price in 1997. In order to minimize the magnetic field previous model, the DE method has been used.

The DE algorithm is initiated by creating a initial randomly population, $x_{(i,G)}$, for individual i at generation G, and it must cover the entire search space. Generally, it is created by a uniform probability distribution, when there is no knowledge about the problem (Storn and Price, 1997).

The main differential evolution idea is to generate new individuals, $v_{(i,G+1)}$, adding the weighted difference, F, which controls the amplitude of between two random individuals of the population to a third individual, showed in (11). This operation is referenced by mutation. Figure 2 shows the process to generate a donor vector, adding a weight. (Storn and Price, 1997).

$$v_{i,G+1} = x_{r1,G} + F(x_{r2,G} - x_{r3,G}) \tag{11}$$

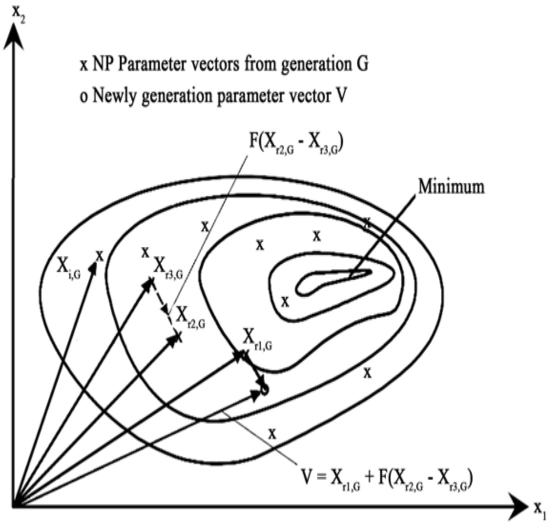

Figure 2: Two-dimensional objective function showing its contour lines and the process for generating $v_{i,G+1}$ (Storn and Price, 1997).

The index $r1$ is the base index and $r2$ and $r3$ are difference indexes that indicate different individuals randomly selected from the whole population $x_{(i,G)}$. This mutated individual is resulted of perturbation caused by the difference vector (Storn and Price, 1997).

The components of the individual donor are mixed with the components of a randomly chosen individual to result in (12), the target vector, $u_{(i,G+1)}$. The process of mixing parameters is referred to as crossover in the evolutionary algorithm community (Storn and Price, 1997).

$$u_{i,G+1} = \begin{cases} v_{i,G+1},\ if\ (rand \leq CR) \\ x_{i,G},\ otherwise \end{cases} \tag{12}$$

In (12) rand refers to the uniformly drawn from $[0, 1]$ and CR refers to the crossover probability. If the trial vector $u_{(i,G+1)}$ results in a smaller objective function value than the target vector $x_{(i,G)}$, then the trial vector replaces the target vector in the next generation. This last operation is called selection. The procedure is stopped when the algorithm reaches the maximum generations number (Storn and Price, 1997).

The computation processes of DE algorithm is illustrated by the flowchart in Figure 3.

Table 1: TL electrical and geometric characteristics (Santos, 2017)

Voltage	500 kV				
Power	725 MVA				
Frequency	60 Hz				
Soil Resistivity	1000				
Phases					
A		**B**		**C**	
x (m)	y (m)	x (m)	y (m)	x(m)	y (m)
-10.4785	16.5320	-0.2285	16.5320	10.0215	16.5320
-10.0215	16.5320	0.2285	16.5320	10.4785	16.5320
-10.2500	16.9280	0.0000	16.9280	10.2500	16.9280

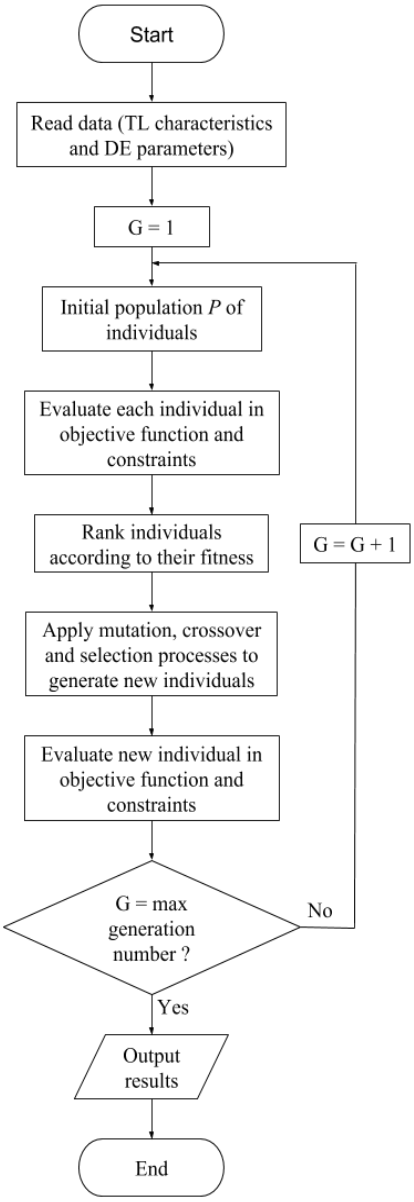

Figure 3: DE flowchart.

3.3 TLs Objective Function and Constraints

The optimization process decreases the magnetic field H that is the objective function indicates in (3). Also, the geometrical parameters are used as inequality constraints. The new TL configuration is defined by considering four geometric constraints: left and right lateral boundaries (LB), maximum and minimum vertical boundaries (VL), minimum distance between conductors of the same phase (d_{min}) and minimum distance between conductors of different phases (D_{min}). The inequalities of all geometric constraints considered in the optimized process are presented as follows in (13) to (16) (Santos et al., 2017):

$$\begin{aligned} LB_{left} - x_i \leq 0 \\ x_i - LB_{right} \leq 0 \end{aligned} \tag{13}$$

$$\begin{aligned} VL_{min} - y_i \leq 0 \\ y_i - VL_{max} \leq 0 \end{aligned} \tag{14}$$

$$\begin{aligned} -(y_i^{ph1} - y_k^{ph2})^2 - (x_i^{ph1} - x_k^{ph2})^2 ... \\ + d_{min}^2 \leq 0 \end{aligned} \tag{15}$$

$$\begin{aligned} -(y_i^{ph1} - y_k^{ph2})^2 - (x_i^{ph1} - x_k^{ph2})^2 ... \\ + D_{min}^2 \leq 0 \end{aligned} \tag{16}$$

4 Results

To evaluate the proposed methodology, the Differential Evolution method is applied to TL of São Gonçalo do Pará - Ouro Preto 2 of CEMIG[1]. Figure 4 shows the structure of the tower under study and Table 1 shows the TL electrical and geometric configurations.

The imposed geometric constraints are: $LB_{left} = -10.5258$, $LB_{right} = 10.5258$, $VL_{min} = y_i - 1$, $VL_{max} = y_i + 1$, $d_{min} = 0.4$ and $D_{max} = 8$. To deal with constraints, the penalty factor is $r_s = 100$. The parameters for classic DE simulation were adjusted to the following values: number of population (NP) = 10 individuals, $F = 0.8$ and $CR = 0.9$. The number of generations was

[1]CEMIG - Energy Company of Minas Gerais, Brazil.

Table 2: TL optimization results

Phases	Original TL		Opt. TL by GA		Opt. TL by DE	
	x (m)	y (m)	x (m)	y (m)	x (m)	y (m)
A	-10.4790	16.5320	-10.0328	17.2844	-9.3004	17.2106
	-10.2500	16.9280	-9.8936	17.8581	-8.7642	17.7028
	-10.0220	16.5320	-9.5842	17.5063	-8.5208	17.0630
B	-0.2285	16.5320	-0.3847	16.7691	-0.0964	17.3863
	0.0000	16.9280	-0.0833	17.2223	0.4144	17.0048
	0.2285	16.5320	0.2465	16.6097	-0.5029	16.8681
C	10.0220	16.5320	10.4785	17.4217	9.5509	16.5509
	10.2500	16.9280	9.8356	17.1394	9.0972	17.5475
	10.4790	16.5320	9.4866	17.5200	9.4933	17.4349

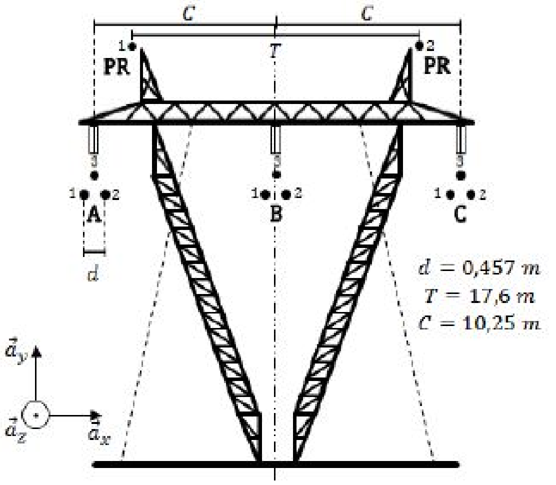

Figure 4: TL structure (Santos, 2017).

set at 100 for both the DE and GA for accurate comparison.

The GA is based not only on the theory of natural evolution of species but also on genetics. With each generation, the algorithms use the individuals of the current population to create the next population. This new population is created through the genetic operators (selection, recombination and elitism), obeying a pre-established proportion. Thus, GA parameters were adjusted to the following values: number of population $(NP) = 10$ individuals, the percentage of next-generation individuals from elitism is equal to 5%, the percentage of recombination per crossover equals to 80%.

The magnetic fields profiles for the original TL, optimized by GA and DE is showed in Figure 5.

The original TL maximum magnetic field is 15.67701 μT value that does not exceed the levels established by ICNIRP. The TL maximum field optimized by GA is 14.45922 μT and the optimized TL by DE is 13.91443 μT. Therefore, the DE method allows decrease the magnetic field at 11.2431% and the GA method decreases in 7.7680%. Figure 5 shows that the optimization of both GA and DE methods obtained good results. However, the DE method obtained a relatively better result than the GA approach.

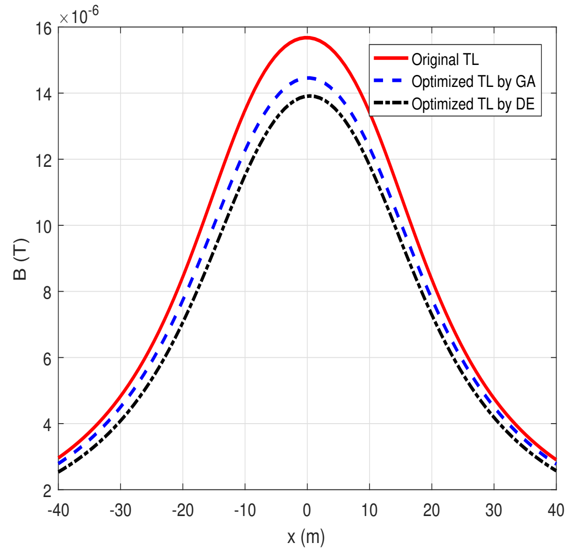

Figure 5: Profiles of original and optimized magnetic field at ground level.

The convergence curves of the Figure 6 shows that the DE converges in 65 generations and the GA in 26 generations. However, DE in its early generations already achieves better objective function value than GA.

Table 2 compares the conventional and optimized by GA and DE geometric parameters for the considered TL.

The original and the DE optimized configurations conductors can be observed in the Figure 7. It can be observed that the conductors have been compacted. This type of configuration is known as non-conventional because the conductors are not positioned symmetrically as in the original TL configuration.

Another fact to be observed in Table 2 after the optimization is that distance between the phases change and the height increases slightly, however respecting the constraints employed.

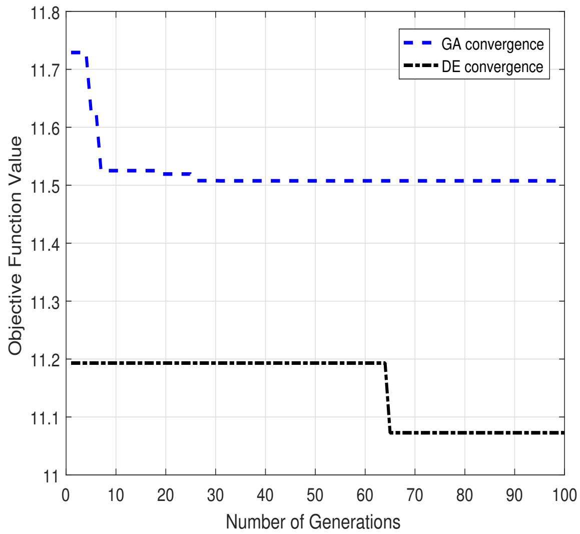

Figure 6: Profiles of original and optimized magnetic field at ground level.

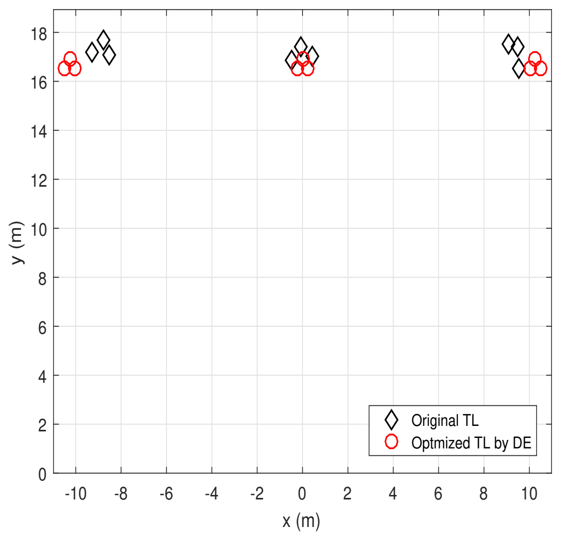

Figure 7: Original and optimized by DE transmission line positions cables.

5 Conclusion

In the last decades the electromagnetic fields produced by transmission lines have been studied because of the problems caused by such fields. In this way, several tools are being applied to mitigate fields at ground level.

As a result of this work, the optimization techniques are promising to minimize the magnetic fields emitted by TL at ground level. However, for this it was observed that optimized configurations trend decreases of the distances between different phases and to increase of the distances between the conductors and the ground.

The DE has shown an excellent approach in comparison to GA optimization method and can easily be applied to more complex transmission line problems such as multi-objective problems.

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