ARRANGEMENTS OF OVERHEAD POWER LINE PHASE CONDUCTORS ACHIEVED BY AN DIFFERENTIAL EVOLUTION METHOD

Abstract— This paper presents a computational tool intended to calculate and minimize the electric fields at ground level of High Surge Impedance Loading transmission lines. This type of transmission line achieves higher power transmission rates by utilizing optimized configuration for the phase conductors. This method is advantageous over other actions taken by the utility company such as increasing the maximum operation temperature of the line, increasing the size of the conductors or the utilization of multiple conductors per phase. In the present work, a Differential Evolution Method is applied to find an optimized transmission lines with non conventional configuration for the phase conductors with reduced electric field profiles at ground level. The surge impedance loading of the transmission lines before and after the optimization process are calculated.

Keywords— Transmission lines, optimization, differential evolution method; high surge impedance loading.

Resumo— Este trabalho apresenta uma ferramenta computacional desenvolvida para calcular e minimizar os campos elétricos ao nível do solo de linhas de transmissão aéreas de potência natural elevada. Este tipo de linha de transmissão apresenta uma capacidade de transmissão de energia mais elevada do que as convencionais, utilizando uma configuração otimizada para os condutores de cada uma das fases. Esse método é vantajoso em relação a outras ações tomadas pelas concessionárias, como o aumento da temperatura máxima de operação da linha, o aumento da seção dos condutores ou a utilização de múltiplos condutores por fase. No presente trabalho, um Método de Evolução Diferencial é aplicado para encontrar linhas de transmissão otimizadas com configuração não convencional para os condutores de cada fase com perfis de campo elétrico reduzidos no nível do solo. A impedância característica e a potência natural das linhas de transmissão antes e depois do processo de otimização são obtidas.

Palavras-chave— Linhas de transmissão, otimização, método de evolução diferencial; potência natural elevada.

1 Introduction

Brazil is a country of great territorial extension. The large extent of its territory denotes the need of very long transmission lines (TL) which are very expensive. The increasing demand for electrical energy makes mandatory the implementation of new efficient methods of power transmission, in order to postpone the construction of new lines. Therefore, it is necessary to develop new studies aimed to increase the transmission line capacity (Melo,1999).

This increase in the TL capacity can be achieved through some techniques such as: increasing the diameter of the phase conductors, the thermal limit of the line, the operating voltage or the number of conductor per phase. The high surge impedance loading transmission lines (HSIL) is one non-conventional alternative that is highly viable (Aleksandrov,1999).

The HSIL technology comprises the rearrangement or the increase of the conductor's number per phase in order to equalize the electric field between them. The HSIL implementation has as fundamentals the understanding of the behavior of the electric field associated with each conductor and how the physical and geometrical parameters of the transmission line affect the field distribution (Nefzger,2003).

This work aims to develop a computational tool to calculate and minimize the levels of electric fields at ground level. This tool can obtained the surge impedance loading (SIL) of the transmission line configuration before and after the optimization process. An electromagnetic model of transmission line under study is developed and the electric field intensity of the system is calculated using the images method and the optimization is performed by a Differential Evolution method (Paul, 1997).

2 Modeling of Transmission Lines

The conductors of the transmission line are modeled as being parallel cylindrical straight conductors to the ground. Their length is assumed to be sufficiently long so that one may disregard the effects of the extremities and of the radius r.

The effect of soil in the determination of the electric field at ground level is taken into account by means of the Method of Images (Glover, 1994). The soil is considered as a perfect electric conductor. Then, based on the geometrical characteristics of transmission line and the voltage phasors of each phase, it is possible to obtain the electric charge of each phase using the Maxwell coefficients matrix (EPRI, 1987):

$$\begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} = \begin{pmatrix} P_{aa} & P_{ab} & P_{ac} \\ P_{ba} & P_{bb} & P_{bc} \\ P_{ca} & P_{cb} & P_{cc} \end{pmatrix}^{-1} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \tag{1}$$

In (1) q_a, q_b and q_c are the density of electric charges phasors of each phase, V_{an}, V_{bn} and V_{cn} are the voltage phasors applied in each phase. The elements of the Maxwell potential coefficients matrix are given by (EPRI, 1987):

$$P_{km} = \frac{1}{2\pi\varepsilon_0} \ln\left(\frac{H_{km}}{D_{km}}\right) \tag{2}$$

In (2), in case of $k = m$, H_{km} is the distance between each conductor and its image and D_{km} is the radius of the conductor; in case of $k \neq m$, H_{km} is the distance between the image conductor k and m and D_{km} is the distance between the conductors k

and *m*. The constant ε_0 is the electric permittivity of vacuum (EPRI, 1987).

Once the electric charge of each phase is determined, the electric field at the ground level can be determined by applying the Gauss's law (Glover, 1994):

$$\vec{E}\,(x,y) = E_x\hat{a}_x + E_y\,\hat{a}_y \tag{3}$$

Where E_x and E_y are given by:

$$E_x(\mathrm{x,y}) = \sum_{i=1}^{N} \frac{q_i}{2\pi\varepsilon_0}\left[\frac{(x_n - x_i)}{(x_n - x_i)^2 + (y_n - y_i)^2} - \frac{(x_n - x_i)}{(x_n - x_i)^2 + (y_n + y_i)^2}\right]$$

$$E_y(x,y) = \sum_{i=1}^{N} \frac{q_i}{2\pi\varepsilon_0}\left[\frac{(y_n - y_i)}{(x_n - x_i)^2 + (y_n - y_i)^2} - \frac{(y_n - y_i)}{(x_n - x_i)^2 + (y_n + y_i)^2}\right]$$

The electric field at ground level on x and y directions can be obtained by means of (3). Where, q_i is the density of electric charge of the *ith* conductor; x_i and y_i, x_n and y_n, 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 electric field calculation depends on the conductor's positions and the charge of the each conductor; then, it is possible to get optimal positions by means of an optimization process.

3 Surge Impedance Loading of Transmission Lines

A TL with enhanced capacity of energy transportation can be achieved by the improved of Surge Impedance Loading (SIL). The SIL is the MW loading of extra high voltage transmission lines (EHV) at which natural reactive power balance occurs. Reactive power is produced by the line depending on its capacitance and voltage level and consumed in the line to support magnetic field. Balance of both consumption and production of reactive power by line at particular level results into flat voltage profile along the line and keeps the angular and voltage stability within limits (Nefzger,2003).

The Surge Impedance is mathematically expressed as reactive power produced being equal the reactive power consumed. This relationship can be expressed as (Nefzger,2003):

$$V_{ff}^{\;2}\omega C = I^2\omega L \tag{4}$$

$$Z_c = \frac{V_{ff}}{I} = \sqrt{\frac{L}{C}} \tag{5}$$

In (4), V_{ff} is the voltage between two phases, *I* the line current [A], *L* the line inductance by meter [H/m], *C* the line capacitance by meter [C/m] and Z_c the Surge Impedance [Ohms]. The SIL can be expressed as (Glover, 1994):

$$SIL = \frac{V_{ff}^{\;2}}{Z_c} = \frac{V_{ff}^{\;2}}{\sqrt{L/C}} \tag{6}$$

From (6) it is seen to increase the Surge Impedance Loading level, line inductance (L) is to be reduced and/or capacitance(C) is to be increased. The capacitance and the inductance of the transmission lines depends of the configuration of the conductors. The High Surge Impedance Loading Transmission Lines adopted reduced distance between phases and improved distance among the subconductors.

Others procedures adopted are the augmented number of the conductors by phase and the non conventional configuration in each phase (Melo, 1999). The best configuration of the conductors suggests in this work are based on minimized electrical field levels at ground level achieved by the Differential Evolution method implemented during the optimization process. This optimized configuration delivery new level of surge impedance loading of than original configurations.

The configuration suggested by the optimization process must be analyzed by their technical feasibility of construction, through studies of mechanical stress, costs, wind efforts among others (Regis, 2009).

4 Optimization Process

In order to optimize the aforementioned TL model, methods based on the stochastic family have been used (Storn, 1997), (Lin,2010), (Arruda, 2015).

In the Differential Evolution method, the initial population is randomly created in the feasible region and then three operations (mutation, crossover and selection) are sequentially performed on each individual until a stopping criterion is satisfied (Storn, 1997).

In this optimization process, difference vectors are obtained from pairs of vectors of the own population. Two individuals are randomly selected in the current population and the difference vector is computed between these individuals (Arruda, 2015).

A mutated solution is created adding the difference vector to a third individual also obtained randomly in the current population given by (Storn, 1997):

$$v_{i,g+1} = x_{r_1,g} + F(x_{r_2,g} - x_{r_3,g}) \tag{7}$$

In (7) for individual i at generation g, a mutant vector is generated, $v_{i,g+1}$ where r_1,r_2 and r_3 are different individuals randomly selected from the whole population; $x_{r_1,g}$ is the base vector; $(x_{r_2,g} - x_{r_3,g})$ is difference vector and F is the scaling factor wich controls the amplitude of difference vector. This mutated individual is resulted of perturbation caused by the difference vector (Lin,2010).

The crossover operation, to generate a trial solution $u_{i,g+1}$, is performed by mixing variables from the mutated solution and the correspondent solution in population (Storn, 1997):

$$u_{i,g+1}^{j} = \begin{cases} v_{i,g+1}^{j} & \text{if (rand} \leq \text{CR)} \\ x_{i,g}^{j} & \text{otherwise} \end{cases} \tag{8}$$

In (8) rand is uniformly drawn from [0,1]; CR is crossover probability; $v_{i,g+1}^{j}$ is mutant vector and $x_{i,g}^{j}$ is the target vector (Lin,2010).

The objective functions of the original individual and the trial individual are compared and the individual with lower objective function is selected for the next generation. During the optimization process, the scale factor applied in the difference vector is reduced in the last generations of the individuals. The complete algorithm to implement this method can be obtained from (Storn, 1997).

In this work, each individual is a possible configuration of transmission line conductors. Each individual is the set of *x* and *y* positions of the each conductor in a specific configuration. In the optimization process, the probability to select variables from the mutated or original individual is variable. In this optimization methodology the mutant probability is higher in the first generations and low in the last generations.

The obtained electric field's intensity given by (2) is added to the entire right-of-way width of the transmission line and originates the objective function at *x* direction:

$$\left|\vec{E}\,(x,y)\right|^2 = \left(\sum_{i=1}^{N}\left(\frac{\begin{pmatrix}\mathrm{Re}(q_i)+\\ \mathrm{Im}(q_i)\end{pmatrix}}{2\pi\varepsilon_{0q}}\right)\left[\frac{(x_n-x_i)}{(x_n-x_i)^2+(y_n-y_i)^2} - \frac{(x_n-x_i)}{(x_n-x_i)^2+(y_n+y_i)^2}\right]\right)^2 \tag{9}$$

In (9), *Re(q*$_i$*)* and *Im(q*$_i$*)*, are the real and imaginary parts of the electric charges. x_n and y_n are the coordinates of the observation points; while x_i and y_i are the coordinates of the source points.

In the optimization process, the conductor's height can vary from a minimum value due to security concerns up to a maximum value which is set as one meter above and below the initial positions. Figures 1-a and 1-b show two diagrams illustrating the restrictions adopted in the optimization process.

Figure 1-a specify D_{min} which determines the minimum distance between different phases and Figure 1-b define d_{min}, which determines the minimum distance between conductors of a given phase.

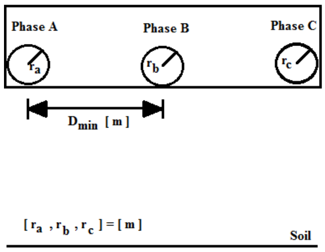

Figure 1-a Minimum Distance Between Different Phases (Dmin) and Area of Variation of Positions of Conductors

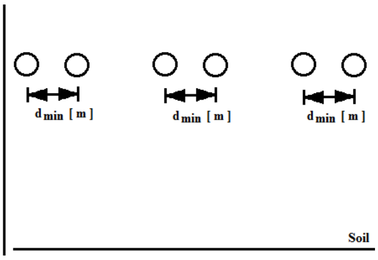

Figure 1-b Minimum Distance Between Conductors of the same Phase (dmin)

In order to simplify the optimization process, the shield wires are disregarded, since their effect in the electric field evaluation at ground level is negligible (Nayak, 2006).

Brazilian law determines that when the LT is subjected to maximum operating voltage, the electric field at one meter of the ground level in the right of way width must be less than 4170 V / m (Brasil, 2009). The optimization process is applied in three different cases.

5 Results

In order to check the applicability of the Differential Evolution Method in transmission lines electric field profile problems, three cases are analyzed.

Case I corresponds to a 500-kV TL horizontal configuration with 4 conductors by phase (Regis, 2009). In this case heights of different phases are the same.

Case II corresponds to a 500-kV TL delta configuration with 4 conductors by phase (Machado, 2007).

Case III corresponds to a 500-kV TL configuration with 3 conductors by phase (CEMIG,1988).

The constraints of the optimization are presented in Table I, where D_{min} is the distance between different phases, d_{min} is the minimum distance between conductors of each phase, X_e and X_d are the horizontal limits, and H_{min} and H_{max} are the vertical limits.

TABLE I. CONSTRAINTS OF OPTIMIZATION PROCESS

Case	Dmin [m]	dmin [m]	Xe [m]	Xd [m]	Hmin [m]	Hmax [m]
I	6.00	0.35	-7.95	7.95	15.50	19.45
II	6.00	0.35	-7.95	7.95	16.50 24.00 16.50	19.45 26.95 19.45
III	9.00	0.45	-12.23	12.23	10.38	16.38

The profile of the original and optimized electric field for the TL with four conductors by phase can be observed in Figure 2. The numbers of individuals and generations in the Case I are 400 and 201, respectively.

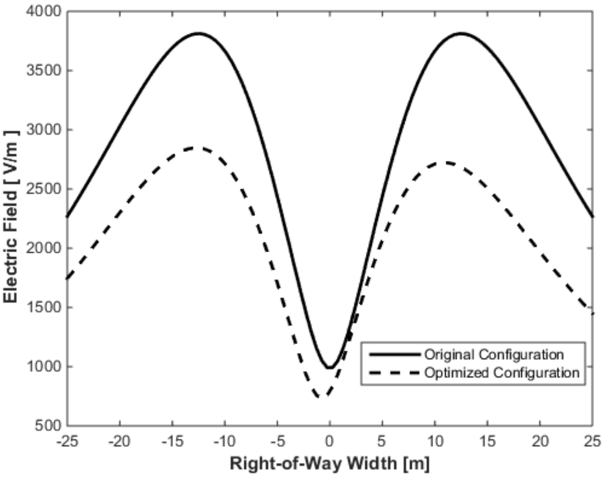

Figure 2. Original and Optimized Profiles of Electric Fields Case I

On can observes from the Figure 2 that application of a Differential Evolution Algorithm gives a new configuration with significant reduction on the electrical field at ground level along the right-of-way width of TL. The maximum value of the electric field of the original configuration is 3809 V/m while in the optimized one is 2841 V/m.

The limit of electric field intensity determined by Brazilian law in the entire right-of-way width of the transmission line Case I is respect (Brasil, 2009). The original and optimized configuration conductors can be observed in the Figure 3.

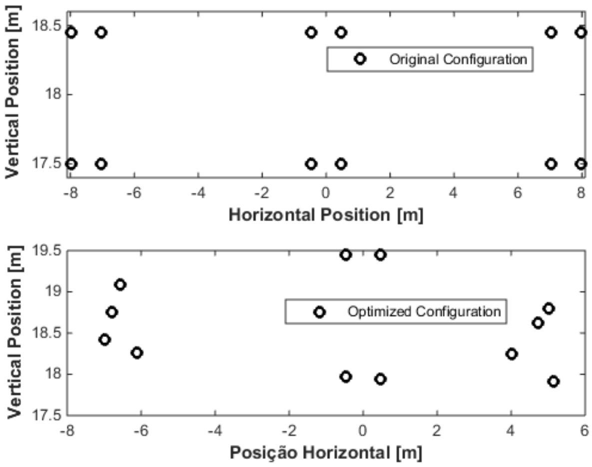

Figure. 3 Original and Optimized Positions of Conductors Case I

The configuration suggested by the optimization method is non-conventional and don’t have a symmetrical aspect. All positions suggested by the optimization process are supported by the current right-of-way width of the transmission line. All constraints are satisfied in this case.

The original and optimized configuration of the transmission lines for Case II can be observed in the Figure 4.

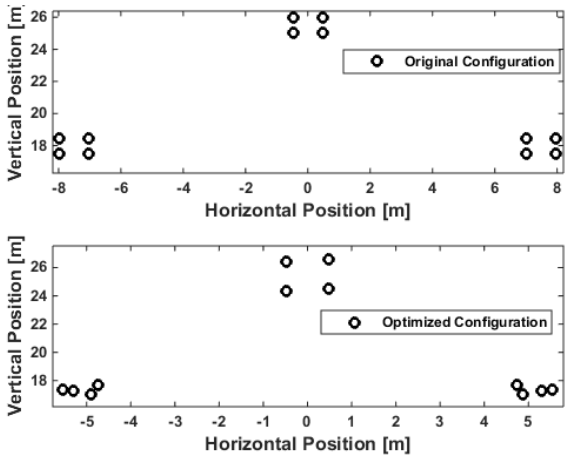

Figure. 4 Original and Optimized Positions of Conductors Case II

In this Case II, the suggested configuration is symetrical and the profile of the electric field is reduced at ground level along the right-of-way width of TL. The numbers of individuals and generations in the Case II are 400 and 301, respectively.

The profile of the original, and optimized electric field for the TL delta with four conductors by phase can be observed in Figure 5.

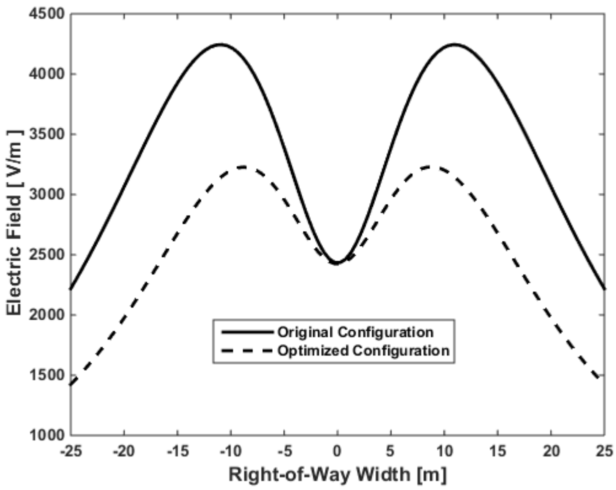

Figure 5. Original and Optimized Profiles of Electric Fields Case II

On can observes in the Figure 5 that the maximum value of the electric field of the original configuration is 4244 V/m while in the optimized one is 3222 V/m. It´s reduction of electric field at ground level are observed over the entire right-t-way width of transmission line.

The maximum electric field level established by Brazilian law is not exceed into and in the limits of the right-of-way width in transmission line Case II.

Three conductors by phase, is the configuration adopted in the Case III. The geometrical position of each conductor in the original and optimized configuration can be observed in the Figure 6.

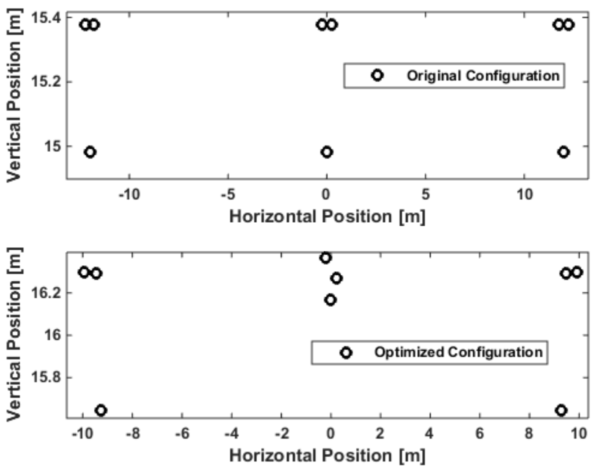

Figure. 6 Original and Optimized Positions of Conductors Case III

In the Case III the optimized configuration is not conventional but have a symetrical aspect. The optimization process change the arrangment of the middle phase and the others phases. The numbers of individuals and generations in the Case III are 600 and 301, respectively. The profile of the original, and optimized electric field for the TL with three conductors by phase can be observed in Figure 7.

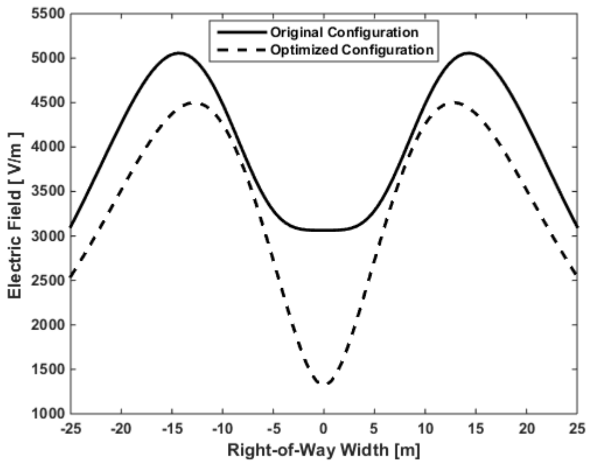

Figure. 7 Original and Optimized Profiles of Electric Fields Case III

On can observes in the Figure 7 that the maximum value of the electric field at ground level of the original configuration is 5056 V/m while in the optimized one is 4491 V/m.

In the Case III, the limits of electric field at ground level into the right-of-way width is exceed. In the limits of the right-of-way width the maximum electric field level is not exceed, in agree with the Brazilian law.

The Surge Impedance (Zc) and the Surge Impedance Loading (SIL) of the original and optimized configuration of the transmission lines are analyzed by each case.

The Case I, the Surge Impedance and the Surge Impedance Loading are presented in Table II.

TABLE II. Case I - Surge Impedance Loading (SIL) and Surge Impedance (Zc)

Case I Horizontal 500 kV -Four Conductors by Phase	Original Configuration	Optimized Configuration
Zc [Ohms]	194.84	185.02
SIL [MW]	1283.10	1351.10
Increase in SIL [%]	5.33	

In the Case I, the SIL of the TL is increased in 5.33 % with little modifications on the positions of the conductors suggested by optimized method. The results obtained for the Case II can be observed in Table III.

TABLE III. Case II - Surge Impedance Loading (SIL) and Surge Impedance (Zc)

Case II Delta 500 kV - Four Conductors by Phase	Original Configuration	Optimized Configuration
Zc [Ohms]	208.47	207.73
SIL [MW]	1199.20	1203.40
Increase in SIL [%]	0.0035	

In the Case II, the increased of the SIL observed is lower than Case I. The improve of the transmission line energy capacity is 0.0035 %. In this case, the initial configuration is result the idea of expanded bundle and compacted phases. The optimization process reduces electric field levels at ground level and does not achieve significant improvement in transmission capacity. The results obtained for the Case III can be observed in Table IV.

TABLE IV. Case III - Surge Impedance Loading (SIL) and Surge Impedance (Zc)

Case III LT 500 kV – Three Conductors by Phase	Original Configuration	Optimized Configuration
Zc [Ohms]	276.77	256.58
SIL [MW]	903.27	974.32
Increase in SIL [%]	7.87	

In the Case III, the SIL of the TL is increased in 7.87 % with little modifications on the positions of the conductors suggested by optimization method. This optimized configuration is supported by the actual right-of-way width of the transmission line analysed.

6 Conclusions

The obtained results show that optimized configurations trend decrease of the distances between different phases and to increase of the distances between the subconductors of a given phase. Such modifications are the basic actions to be taken in the transmission lines with high surge impedance loading.

These results show that the Differential Evolution Algorithm can be potentially applied to more complex cases, for example, transmission lines with more than four conductors by phase in order to mitigate the electric field at the ground level and to increase the SIL of them.

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