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A high surge impedance loading technique approach for uprating transmission lines

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Abstract. This paper presents a study involving a viable unconventional transmission line (TL) uprating concept, named High Surge Impedance Loading (HSIL). This technique is based on the understanding of the variation of the electric field produced by the TL, regarding the geometric position of the conductors. It proposes the adoption of unconventional geometric bundles design, by reducing the distance between phases and increasing the distance between conductors of the same phase. An analytical model for transmission lines is developed for the soil effect determination on the estimate of electric field magnitude at ground level and at the conductors' surface of TLs. The model is submitted to a stochastic evolutionary optimization technique called Differential Evolution, aiming at maximizing the Surge Impedance Loading. However, many constraints as minimum distances among TL components and soil determined by NBR 5422 are considered, as well as the magnitude of the electric fields for human exposure of the general public at ground level, established by NBR 25415. Also, using altimetry data supplied by the Brazilian Geodetic System, maximum levels of the surface electric field are determined and compared with the values of the critical electric field, from which the Corona effect occurs. The results acquired from the developed computational tool suggested new bundle geometric configurations for an existing transmission line, with enhanced surge impedance loading and with electric fields at ground level and at conductors' surface below the thresholds values and defined by the norm.

Keywords: Transmission line, Uprating, High Surge Impedance Loading, Optimization, Differential Evolution.

1 Introduction

Transmission lines (TLs) are essential elements in the electric power system, enabling the interconnection between the generating centers and those of electric energy consumption. A country of continental dimensions, like Brazil, needs very extensive TLs, which can be costly and implies high environmental, social, and legal impacts. There are different electrical, magnetic, and mechanical concepts and phenomena associated with power transmission that can influence its safety and costs of design, operation, and maintenance [1]. Thus, it is relevant to develop studies proposing improvements in the transmission capacity of existing systems.

This upgrade in the TL efficiency can be achieved through some techniques, such as: enlarging the conductors' diameter, increasing the line thermal limit, boosting the operating voltage using compensators, and/or incrementing the number of conductors per phase [2]. Paganotti et al. [3], Duane et al. [2], Resende [4], and Sarmiento and Tavares [5] cite also a non-conventional alternative called High Surge Impedance Loading (HSIL), which can be highly viable and is adopted on this paper.

The HSIL technology consists of the rearrangement of the conductors' position in the TL to affect their impedance loading. The TL power transmission capacity is defined by the Surge Impedance Loading (SIL), calculated from electrical parameters, which are related to mechanical characteristics of the transmission tower, such as its geometric configuration [3].

The enhancement of SIL and a shorter right of way (ROW), resulted by HSIL, require also attention to the ocurrence of undesired phenomena, such as the Corona effect, which occurs when the electric field on the surface of conductors exceeds a critical value. There are also health and safety legal provisions that limit the parameters, such as the level of human exposure to electric fields and the minimum distances between TL components [1].

In this paper an implementation of a transmission line model is presented as a core for an optimization method application aiming to maximize the SIL of a TL. The influence of the conductors' position in the bundles and the electric fields and their profiles are addressed, limited by the legal provisions on human exposure to electric fields and the occurrence of the Corona effect on the surface of the cables. Therefore, it is noted that the uprating problem discusses a direct relationship between the mechanical design (geometric configuration) of the conductor bundles and the electrical parameters that affect the SIL.

This paper is organized as follows: Transmission line modeling is presented in section 2; section 3 introduces the optimization problem; results are presented and discussed in section 4; and section 5 gives the conclusion.

2 Transmission Line Modeling

2.1 Surge Impedance Loading

The power transmission capacity is highly influenced by the electrical parameters of TL, such as impedances and admittances. TL admittances can be represented by the capacitance. Such parameters consider the system in a steady and balanced regime, based on an ideal phase transposition [3, 5].

The SIL (MW) expresses the power transmitted by TL in the condition of balance between reactive power generated and consumed by the line [1, 3]. In this condition, the surge impedance Z_c (Ω) is defined from the equality $V_l^2 \omega C = I^2 \omega L$, as the ratio between the voltage line (between phases) V_l (V) and the line current I (A). L and C are the positive sequence inductance (H/m) and capacitance (C/m) of the TL per unit length, respectively. Then, the SIL is defined as [1]:

$$SIL = \frac{V_l^2}{Z_c} = \frac{V_l^2}{\sqrt{\frac{L}{C}}}. \tag{1}$$

The capacitance matrix is directly related to the LT's charge load and is calculated based on the method of images. The TL total impedance is composed of the internal and external effects of the current flow in the conductors and respective images. It is calculated by adding the external impedance matrix, considering the ground, to the real part of the internal impedance matrix [5].

The primitive capacitance and impedance matrices are subjected to a reduction process, using the Kron method, incorporating the effect of the conductor bundles and lightning rods as if the TL had only one conductor per phase [5]. Then, the system's conductors are ideally transposed to produce balanced matrices, in which a Fortescue transformation matrix is applied to obtain the sequence components of the TL [5].

It is noted that the capacitance and inductance of the TL are dependent on the bundle design. Increasing the SIL requires reducing Z_c, achieved modifying the original line capacitances and inductances. Seeking that, the HSIL technique is likely to expand the phase bundle and to reduce phase-to-phase distances [3].

2.2 Electric Field at Ground Level

According to the Electric Power Research Institute [1], electric fields in the vicinity of TLs can be calculated assuming that there are no free charges in space. The Earth is considered as a perfect electric conductor, with a null electric field inside, and therefore, the portion below the equipotential surface is replaced by air. It is assumed that the TLs have cylindrical straight conductors, parallel to the ground plane, and that the conductors' extension is so long as their extremities effects can be ignored. Stevenson [6] explains that the electric field for an observation point near a uniformly infinite charge line can be formulated based on the Gauss's Law.

The soil's effect is considered applying the method of images [1], where a TL equivalent model is adopted compounded by the physical conductors and their respective images in the soil plane.

Furthermore, based on the TL geometric configuration and the three-phase voltage phasors, the electric charge of each phase can be determined by Maxwell's coefficients calculation as [1]

$$[q] = [P]^{-1} [V], \tag{2}$$

where $[q]$ is the vector for the phase charge density (C/m) and $[V]$ is the complex phasor voltage vector (V). Maxwell's coefficients matrix $[P]$ (m/F) is defined as [1]

$$P_{ij} = \frac{1}{2\pi\epsilon_0} \cdot \ln \frac{H_{ij}}{D_{ij}}, \tag{3}$$

considering ϵ_0 as the electric vacuum permittivity ($8.854 \cdot 10^{-12}$ F/m). If $i = j$ then H_{ij} is the distance between the i-th conductor and its image, and D_{ij} is the external radio of the conductor. Otherwise, H_{ij} is taken as the Euclidean distance between the conductor i and the image of conductor j, and D_{ij} is the Euclidean distance between conductors i and j. Thus, it is stated that Maxwell's matrix is dependent on the conductors' position.

Thereby, Gauss's Law can be applied to determine the electric field vector $\vec{E}$ (V/m) at any point in the cross-sectional plane of a transmission line [1, 6]:

$$\vec{E} = \sum_{s=1}^{N} \frac{q_s}{2\pi\epsilon_0} \cdot \left[\frac{(x_p - x_s)\vec{a}_x + (y_p - y_s)\vec{a}_y}{(x_p - x_s)^2 + (y_p - y_s)^2} - \frac{(x_p - x_s)\vec{a}_x + (y_p - y_s)\vec{a}_y}{(x_p - x_s)^2 + (y_p + y_s)^2} \right]. \tag{4}$$

In eq. (4), a_x and a_y are the horizontal and the vertical component unitary vector, respectively and N is the number of conductors in the TL. For each s-th conductor, q_s is the corresponding phase charge density defined by eq. (2); x_s and y_s are the conductor's coordinate position. Analogously, x_p and y_p consist of the observation point coordinate. It follows that the electric filed determination is a function of TL's geometric parameters and the medium.

2.3 Electric Field at the Conductor Surface

Also known as surface gradient, the electric field at the conductor surface concerns the Corona effect [1]. This phenomenon occurs when the surface gradient overloads a critical value, causing the air ionization around the conductor and the air dielectric rupture. The air ceases to behave as an insulator, diverting a portion of the current transmitted by the system to circulate through the ambient. It outcomes such as audible and radio noises, ozone production, and also loss of power along with the energy transmission system [1].

The electric field at the conductor surface determination is calculated considering the TL maximum voltage operation and is established by the method of successive images, introduced by Sarma and Janischewskyj [7]. It consists of replacing the actual charge distribution on the conductor surfaces by a series of image line charges, and in calculating the field distribution due to the equivalent system of image charges.

The restriction is established ensuring the electric field at the conductor surface less or equal a critical value, modeled by the following expression [5, 8]:

$$E_c = 18.11 \cdot f_s \cdot \delta_{ik} \left(1 + \frac{0.54187}{\sqrt{r \cdot \delta_{ik}}} \right), \tag{5}$$

where r is the conductor radius (cm) and f_s is the surface coefficient, usually adopted as 0.82 [5]. δ_{ik} is the atmospheric pressure relative to the sea-level, which can be estimated based on the ambient temperature and the TL sea-level altitude. The altitude increases, the air density decreases, resulting in lower critical electric field values and, therefore, more restrictive constraints. Thus, conductors at higher geographical points are more vulnerable to the Corona effect [5].

3 Optimization Problem

The HSIL optimization problem has a non-linear and constrained modelling, which makes difficult for definition of derivatives functions and also neither classical nor heuristic optimization can ensure that global optimal solution will be found [5].

Aiming to optimize those aforementioned correlations between electrical and mechanical parameters, stochastic mono and multi objective strategies based in the Differential Evolution (DE) method have been applied. DE has presented good results for TLs' optimization [3–5] and has a less complex development when compared to other methods applyed to HSIL optimization in the literature [9, 10].

DE is a genetic, random, parallel search optimization algorithm, introduced by Storn and Price [11]. Each solution is represented by an individual. In the beginning, an initial population of individuals is randomly created in the feasible region. Then, they are submitted to sequentially operators: mutation, crossover, and selection. The optimization process occurs until a stopping criterion is satisfied (i.e.: some generations for the population) [3]. In this paper, each individual represents a solution, a possibility for the TL conductors positioning coordinates.

For each individual i from the generation g, the mutation operator creates a new mutant individual v based in three other randomly selected solutions (r_1, r_2, and r_3) from the current population. This is made by adding the difference vector between two individuals, multiplied by a scaling factor F, to a third individual [3, 4]. Storn and Price [11] proposed F to be used as 0.9.

$$v_{i,g+1} = x_{r_1,g} + F(x_{r_2,g} - x_{r_3,g}). \tag{6}$$

The crossover operator is applied for each dimension j of the individual i at generation g. A candidate individual u is created from a parameter exchange between the mutant vector v and the respective current individual i [3, 4].

$$u^j_{i,g+1} = \begin{cases} v^j_{i,g+1}, & if \quad (rand \leq CR) \ \ or \ \ (j = rand_j) \\ x^j_{i,g+1}, & \qquad otherwise \end{cases}. \tag{7}$$

In eq. (7), $rand$ is a random number between 0 and 1, and CR is the crossover probability, used as 0.7 [4]. $rand_j$ is a random number for one of the individual dimensions, which guarantees that at least one of the dimensions is going to be affected.

The selection operator consists in to decide on the best-scored solution for the next generation. To do so, the next generation individual is chosen between the candidate created towards the genetic operators and the current respective individual.

The optimization objective aims to maximize eq. (1). A fitness function calculates the score for an individual solution, specified by the SIL. However, this process is limited by project and norms restrictions. The geometric configurations proposed by the optimization must attend to the criterion for human exposure to electric fields and ensure that the electric field at the conductor's surface does not exceed the critical value, defined by eq. (5).

Intending more realistic data for the model, in this paper the TL's altitudes were obtained from the nearest geodetic stations from the highest altitude TL's electrical substation, provided by the Altimetric Network from the Brazilian Geodetic System, available at IBGE [12].

In Brazil, the federal legislation [13] and the NBR 25415 [14, 15] establish the reference levels for occupational and general public exposure to electric fields as 8.33 kV/m and 4.16 kV/m, respectively. The general public exposure level is defined at the limits of the TL right of way, despite the occupational exposure, which is applicable through all the ROW extension. Regardless of the 1 m height proposed by [1], this paper adopts the Brazilian measurement standard, defined at 1.5 m height [16].

Furthermore, there were considered in the optimization problem safety minimum distance requirements determined by the norm NBR 5422 [17], as the distances between the conductors and the soil; between the conductors and the lightning rods; and between the phases. There were also taken into account a minimum distance among the sub-conductors of each phase.

If any of those requirements were not attended by a solution, its score was highly and proportionally penalized. In practice, this disadvantage unqualifies the solution as one of the best in its generation but still allows it to participate in the evolutionary operators.

There were adopted 20 individuals per generation, as larger populations have not resulted in better solutions, and 100 generations, assuring good convergence. It was considered a geometric symmetric TL strategy about its longitudinal plane, assuring same sized cross arms with symmetric mechanical loads.

Generally, the solutions approach allows the conductors to move freely around the TL area, which can result in drastic changes in the bundle positions and/or design [2, 3]. It increases the chance to produce inconvenient TL geometric configurations, also considering its mechanical feasibility. To avoid this situation, this paper assumed a highly restricted optimization area for each conductor. Based in their original positions, the conductors were allowed to move limited by horizontal and vertical distances, in the rectangular directions.

Besides those arbitrary constraints, they were also narrowed by the minimum safety distances and by the horizontal extension occupied by the conductor from the original TL. These restrictions for the conductor movements are represented in Fig. 1.

Figure 1 illustrates a transversal view of a TL with 3 subconductors per phase, where each is depicted by a circumference in gray. For each conductor, δl_{min} and δl_{max} are the left and right horizontal maximum limits, and δh_{min} and δh_{max} are the top and bottom vertical maximum limits. Furthemore, H_{min} and H_{max} are the minimum

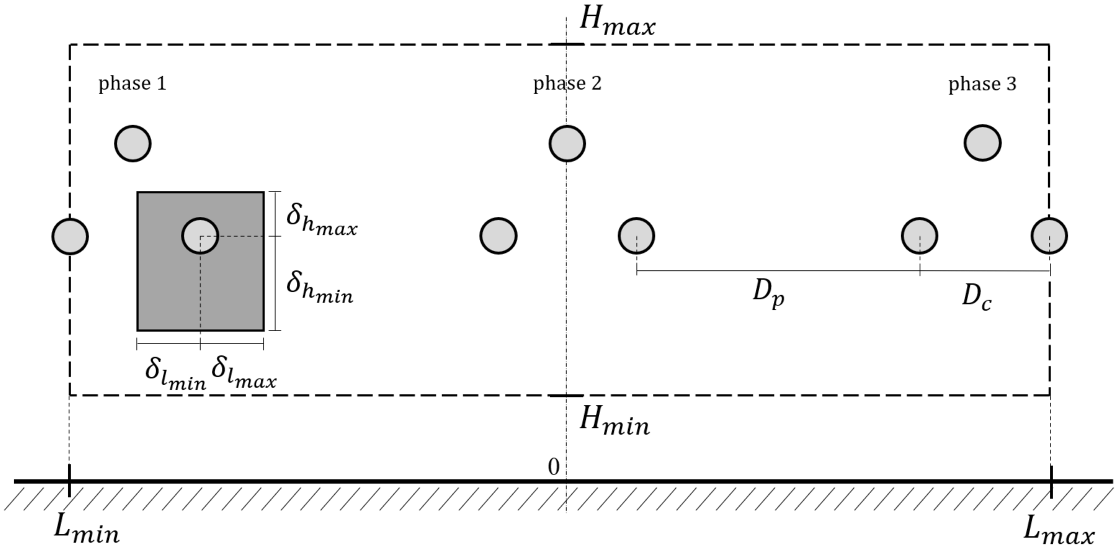

Figure 1. Constraints for the conductors' position optimization

and maximum safety heights imposed by norms, D_p is the minimum distance between phases, D_c is the minimum distance between phase sub-conductors, and L_{min} and L_{max} are the horizontal limits of the original TL.

All this approach tends to result in modest changes in the bundle design and, consequently, the main advantages of this strategy are the derived practical results. However, they still need to be analyzed considering the techincal feasibility regarding mechanical stress, costs and others.

4 Results

The effectiveness evaluation of the proposed approach was performed based on a real three-phase TL case [2], corresponding to a 500 kV TL (maximum operation with 525 kV), with 4 sub-conductors per phase and 682.54 m altitude. The conductors' cables model is the CAA Ruddy and the lightning rods' cables model is the AG 7/6" EHS. The optimization constraints are indicated in Tab. 1 [2].

Table 1. Optimization constraints

L_{min} (m)	L_{max} (m)	H_{min} (m)	H_{max} (m)	D_p (m)	D_c (m)	δl_{min} (m)	δl_{max} (m)	δh_{min} (m)	δh_{max} (m)
-7.98	7.98	9.03	25.23	5.00	0.90	0.50	0.50	1.00	0.50

A numeric comparision between the conductors' positon from the original and the optimized TL is presented in Tab. 2.

Table 2. Original and optimized conductors' positions

Position	Phase 1		Phase 2		Phase 3	
	Original	Optimized	Original	Optimized	Original	Optimized
Horizontal (m)	-7.980	-7.980	-0.475	-0.818	7.025	6.525
	-7.0.25	-6.525	0.475	0.818	7.980	7.980
	-7.025	-6.525	0.475	0.655	7.980	6.525
	-7.980	-7.980	-0.475	-0.655	7.025	7.980
Vertical (m)	18.450	18.950	25.950	24.950	18.450	18.722
	18.450	18.722	25.950	24.950	18.450	18.950
	17.500	16.500	25.000	24.005	17.500	16.500
	17.500	16.500	25.000	24.005	17.500	16.500

A graph juxtapositioning the conductors from both TLs is also available in Fig. 2.

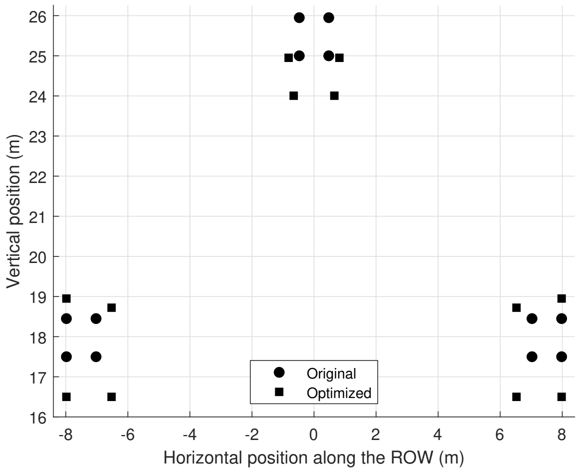

Figure 2. Original and optimized conductors' positions

It can be observed in Fig. 2 that the optimized configuration tended to expand the bundles and to decrease the distance between phases, even with the restricted constraints considered. Despite, the optimized bundle design alluded to its original geometric configuration and maintained its TL's area location, there was reached a considerable difference between the SIL from the original TL, as registered in Tab. 3, achieving 14.806% of uprating.

Table 3. Original and optimized SIL

	Original (MW)	Optimized (MW)	Increase (%)
SIL	1205.819	1384.350	14.806

A comparison between the profiles of the original and the optimized TL's electric field at ground level along the ROW is showed in Fig. 3.

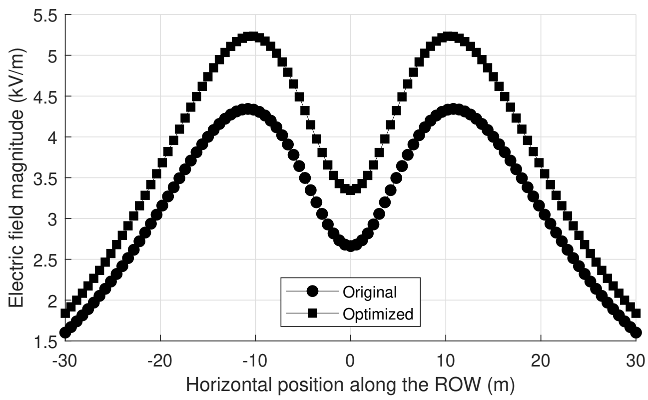

Figure 3. Original and optimized conductors' positions

It can be noted in Fig. 3 that the electric field at ground level for the original TL has a magnitude of 1.602 kV/m at the ROW's limits and peaks of 4.343 kV/m. For the optimized TL, those values changes to 1.839 kV/m and 5.234 kV/m, respectively. As the optimization problem did not include an electric field minimization, these results could be expected. Unconcerned about of these increases, the electric field at ground level still has a magnitude profile under the general public and occupational exposure levels.

For each conductor, there was also verified the attendance to the critical value for the maximum electric field at its surface. The calculated critical value was 19.378 kV/cm and it was validated for all the conductors that the maximum magnitude obtained was always less or equal the critical value. Thus, the Corona effect is not expected to occur in the optimized TL.

However, the suggested new bundle designs still need to be analyzed considering technical feasibilities, regarding of mechanical stress, costs, and others [4].

5 Conclusions

The results achieved by the optimization process are relevant once the uprating level presented a great increase in the power transmission capacity, even regarding many constraints. The suggested new conductor's geometric configuration is conservative in changes when compared to other projects. As this investigation purpose comes from uprating existing TLs, it becomes pertinent to narrow considerably the conductors' movements into the optimization process. Furthermore, the proposed solution also attends to minimum distance norms, human exposure level to electric fields, and avoid the occurrence of Corona effect. This approach can also be applied to other more complexes TL's geometries.

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