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Methodology for optimizing the capacity and costs of overhead transmission lines by modifying their bundle geometry

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ABSTRACT

The electrical power systems demand is continuously growing, in such a way that it is necessary to pursue methods to increase the overhead transmission line power capacity for single circuit lines. In this paper, it is proposed a methodology to increase the line energy transport capacity at lower costs. The enhancement is done by modifying the bundle geometry by using a heuristic optimization process divided into two steps. Firstly, a fixed bundle geometry is generated. Secondly, this form is modified seeking the optimization of line energy transmission capacities. During all process, electrical, mechanical and economical analyses are performed. As result, single circuit line geometries with almost 26% higher surge impedance loading than the original, significant costs reduction (50%), moderate bundles size (smaller than 2.5 m), similar electric fields within the conductors of the bundle, smaller right of way, and similar transient response were obtained. Thus, compared with regular single circuit transmission lines, these new transmission lines have a lower overall cost and environmental impact. Finally, a transient analysis of the proposed transmission line is presented.

1. Introduction

When power demand is greater than the existing transmission trunk capacity it is necessary to expand the transmission system. Typically, the adopted solution is to build more lines, to employ double circuit lines, or eventually to raise the operating voltage level. However, those solutions imply a greater amount of assets, towers, larger right of way (ROW), and therefore higher costs and environmental impacts. In this work new bundle geometries to increase the single circuit line's natural power capacity, or the surge impedance loading (SIL), at lower costs are presented. The values and characteristics of conventional single circuit Brazilian conventional lines for 500 and 750 kV and Chinese 1000 kV lines are presented in Table 1.

Lines with non-conventional bundle geometries are known as lines with high surge impedance loading (HSIL).

Percy H., in 1909 [1], verified that the use of more than one conductor per phase would increase the capacity of overhead transmission line since the line capacitance would increase while its inductance would be reduced. However, maintenance costs became higher, and for that reason the idea was abandoned for many years.

Later, in 1932 Dwight and Farmer [2] studied the difference of using one or two conductors in each phase. Parameters such as resistance, capacitance, reactance, corona effect and heating in the conductors were analyzed. In the same year Clarke [3] studied the performance of ideally transposed transmission lines operating at a fundamental frequency of 60 Hz, with bundle composed of two to five conductors.

Around the 1960s Abetti [4] and Sandell [5] presented a thorough revision about the use of bundles and its advantages, provoking the extensive adoption of bundles around the world. In America the typical separation distance is 0.457 m, while in Europe 0.4 m is used.

Several years later, researches on increasing the capacity of transmission lines using non-circular bundles for the first time in history were developed by the Russian researchers Alexandrov et al. [6]. HSIL lines were designed by increasing the number of conductors per phase. An important drawback was that with the larger number of conductors, the bundle sizes were extremely high. Alexandrov et al. continued their work [7] pursuing the power loss and line voltage drop reduction, proposing the distance reduction in-between phases, besides the use of bundling conductors. The proposed methodology was based on reaching the corona effect limit of the conductors. For this reason, the transmission line capacity increase should be subjected to the number of conductors and their superficial electric fields.

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Table 1
Characteristic of conventional lines for different voltage levels. The number of sub-conductors is n_{sc}.

Voltage [kV]	n_{sc}	Bundle [m]	P_n [MW]	Width [m]	Weight [ton]	Cost [MUSD/km]
500	4	0.457	1024	21.75	10.15	0.70
750	4	0.457	2123	31.75	17.47	1.04
1000	8	1.103	4552	33.49	41.92	2.10

Based on the concepts of non-conventional bundles presented by the Russian researchers, Portela and Salari Filho optimized the design of transmission lines seeking to maintain a balance in the current and charge distributions in each sub-conductor within a bundle, respecting electric field restrictions, and the maximum magnetic field [8].

Portela [9,10] throughout his publications established important facts such as the need for an interactive analysis through the sub-optimization of bundles, to eventually reach a global line optimization. Furthermore, in his research different bundle geometries were presented, such as elliptical and rectangular.

In Brazil some HSIL lines are under operation, with different bundle sizes for central and external phases in a single circuit line. These new 500 kV lines have a SIL of 1200 MW with 1.2 m external bundle sizes.

In 2013 Maciel [11] studied the topic from the point of view of classical optimization process by using the gradient method. Later in 2016 Acosta and Tavares, by using a self developed heuristic algorithm [12], produced new bundle shapes that resulted in greater SIL.

The present study makes an extension of the methodology presented in [12] by changing the objective function and the maximum bundle size allowed. In the aforementioned paper, the objective function focused only on SIL increase. However, our article focuses on two objective functions modeled as one: SIL increase and line cost reduction. In other words a multi-objective problem is modeled as a mono-objective problem. Because of the changes in the objective function and maximum bundle size, the configuration of the lines obtained are different, more compact, with lower cost and adequate for the industry than those presented in [12].

The procedure presented in [12] is detailed in order to show the equations necessary to reproduce the geometries used in the optimization section 1 and 2. Additionally, some transient analysis of a 500 kV conventional line and two optimized transmission lines with the same voltage level are presented. The geometries of the bundles are in concordance with international standards [13] and Brazilian standards [14]. They resulted in up to a 26% of SIL increase with a cost reduction of 50% compared with conventional transmission line, by using bundles with dimensions no larger than 2.5 m. The new tower width is smaller than the conventional one, which is an important advantage due to severe environmental restrictions in building new overhead lines worldwide. However, as the adopted solution is an heuristic algorithm, it is not possible to ensure that the optimized geometries are the best solution. Nevertheless, by the own nature of the problem, non-linear mixed integer problem, there is no methodology, algorithm or technique that can ensure to obtain the global optimal point.

2. Parameters of HSIL transmission lines

As summarized below, to calculate the electrical parameters of HSIL lines, basic formulas based on Maxwell equations were applied.

2.1. Power capacity or natural power

The natural power or SIL corresponds to the power that the line transmits in an equilibrium condition between the reactive power generated and absorbed by its shunt susceptance and series reactance, respectively. In this loading condition there is no need to provide reactive support to the line. The studied lines have a length of 350 km. An extensive study on this issue was presented by [15].

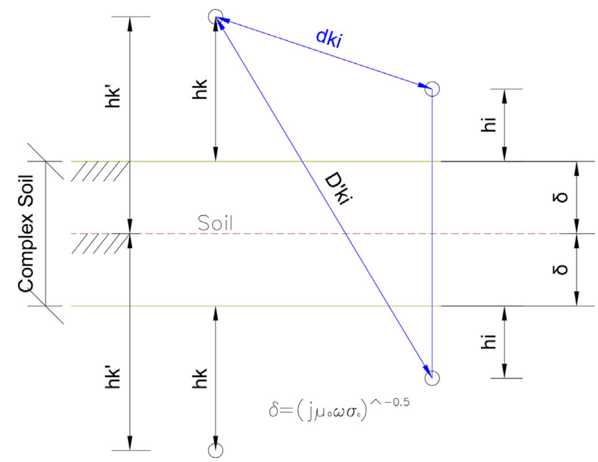

Fig. 1. Images method representation with complex soil.

To calculate the natural power (P_n), Eq. (1) is used. The natural power depends on the characteristic impedance ($\underline{z}_c$ Eq. (2)) and the line operation voltage (V_l), in kV.

$$P_n = SIL = \frac{V_l^2}{\underline{z}_c} \tag{1}$$

$$\underline{z}_c = \sqrt{\frac{\underline{z}_1}{\underline{y}_1}} \tag{2}$$

The line is supposed to be in steady-state operation at its rated frequency (60 Hz). Line parameters are calculated for this operating condition; as a consequence, only the positive sequence parameters, $\underline{z}_1$ and $\underline{y}_1$, are important for line optimization.

2.2. Longitudinal and transverse parameters

The line impedance and admittance per unit of length are calculated by using the image method (Fig. 1). In the case of the impedance, an extra complex depth $\underline{\delta}$ (Eq. (3)) [16] is considered to include the earth effect. As there is no return current in the soil, the depth $\underline{\delta}$ can be neglected in the admittance calculation. In order to compute each element of the impedance matrix equation (4) was applied, and for the admittance matrix equations (5) were used.

$$\underline{\delta} = \frac{1}{\sqrt{j\omega\mu_0\sigma_g}} \tag{3}$$

$$\underline{Z}_{e_{ii}} = \frac{j\omega\mu_0}{2\pi} Ln\left(\frac{2\underline{h}_{ci}}{R_i}\right) \quad \underline{Z}_{e_{ik}} = \frac{j\omega\mu_0}{2\pi} Ln\left(\frac{\underline{D}_{cik}}{d_{ik}}\right) \tag{4}$$

$$\underline{Y}_t = j2\pi\omega\varepsilon_0 \overline{[A]}^{-1} \quad A_{ii} = Ln\left(\frac{2h_i}{R_i}\right)$$
$$A_{ik} = Ln\left(\frac{D_{ik}}{d_{ik}}\right) \tag{5}$$

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