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Transmission line vulnerability to lightning over areas of dense rainforests and large rivers in the Amazon region

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ABSTRACT

The vulnerability under lightning conditions of stretches of the 1500 km long electrical transmission line Tucurui–Oriximina–Manaus over dense Amazon forest canopy and river crossings is evaluated using a leader progression model (LPM) called *ModSalto*. We find vulnerability windows (low protection or unsafe) in all crossing stretches that use high towers to comply with environmental restrictions. The values of lightning flashover rates (LFR) reach 0.8277 flashover/year or an equivalent period of 14.49 months for stretches of river crossings, and 0.3403 flashover/year or an equivalent period of 35.26 months for stretches of forest canopy crossing. These numbers are above the computed equivalent ANEEL bidding figure of 0.15 flashover/year for that TL. This methodology uses a map of yearly lightning frequency produced with data from STARNET and SIPAM LLS and the level of lightning protection was evaluated with the electro-geometric model (EGM).

1. Introduction

The need for interconnection of isolated systems in northern Brazil, like those in Marajó island, Macapa, Manaus and Oriximina cities, has long pressured the Brazilian government's plans to build transmission lines to link these isolated systems to the bulk of the Brazilian interconnected electrical system.

After Tucurui, and now with the construction of Belo Monte dam, and the Rio Tapajos dam complex, the energy supply in the region has increased and with it the need to build long transmission lines. Currently, the emerging markets of the north region have begun to be supplied, a task that involves significant challenges, since stretches of these transmission lines have to cross wide rivers, some with maritime traffic and spans through dense forest canopy to comply with environmental rules.

While normally electrical transient simulations are achieved by software based on electromagnetic models, the Monte Carlo method and others, for determining the possibility of flashover and the maximum voltages appearing on important electric devices [1], one finds in literature works that make use of different models like the LPM type (Leader Progression Model) for evaluating lightning induced flashover in transmission lines [2–4], a simplified approach to model construction.

This paper assesses the vulnerability level of the Tucurui–Oriximina–Manaus 500 kV transmission line with a length of approximately 1500 km, under lightning conditions, calculating the protection levels and expected lightning flashover rates (LFR) (estimated overvoltage's due to lightning that may collapse the basic insulation level-BIL, or the insulator Critical Flashover Voltage – CFO), using an LPM model that we call *ModSalto*, abstracting the influence of discharges on the transmission line project and operation, by modeling the phenomenon of lightning attachment, when the discharge is irreversible, in the boundary between the atmosphere and the architecture of conductors, shield wires and support structures, for the analyzed transmission line.

The lightning flashover rate (LFR) in transmission lines will be assessed on behalf of lightning protection techniques and with the EGM model, complemented with the determination of *vulnerability windows*, i.e., a parameter corresponding to a segment of the structure height left unshielded by shield wires/EGM, as detailed in Figs. 5 and 6, that permits the evaluation of the probability of a insufficient protection upon a lightning event and estimation of the lightning flashover rate, simplifying the analysis and integrating it in the same security assessment methodology.

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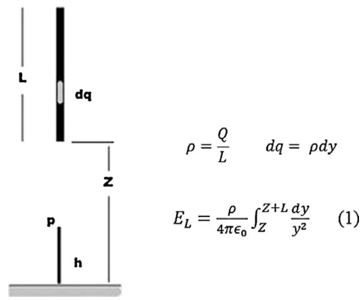

Fig. 1. Electric field E_L at P, caused by a downward leader of length L and linear charge distribution ρ.

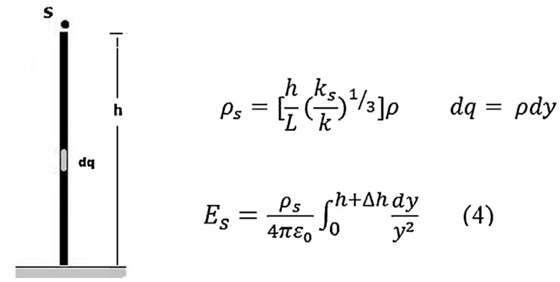

Fig. 2. Electric field E_s at S, caused by an upward leader.

As we are using lightning density to estimate an overvoltage in the transmission line, the so-called attractive area (or collection area) encompasses consideration of all prospective lightning hitting the structure directly but also in the immediate vicinity, so we are implicitly incorporating eventual contributions due to back flashover, the collapse of energized equipment and also indirect hitting in the calculated overall flashover rate. Segregation of the contributions due to phase hit (shielding failure), shield wire hit and structure hit (back flashover) is indeed possible with additional data and modeling, but we will be working this out in future developments.

As TL outage rate is directly proportional to lightning density, the lightning flashover rate calculated with the aid of this methodology is equated to a corresponding outage rate, considering that there is no explicit declaration of the use of improvement hardware like surge arresters, besides shield wires, in the transmission line being analyzed.

2. The attachment process

The attachment process has been studied with the aid of models, denominated leader initiation or progression (LPM), which include, among other calculations, the onset of streamers and their transformation into a connection leader, leading to subsequent attachment and stroke [5].

The objective of ModSalto is to model all phases of the leader's descent to the final attachment with streamers and/or connecting leaders, deriving parameters like the electric and magnetic field intensity at selected points, the leaders' path and velocities, with the aid of Lorentz's force, dealing with crossed fields due to cloud electrification (an electric field), and the earth magnetic field (hypothetically the force behind the tortuousness nature of stepped leaders). Additionally, the model calculates the final jump or the striking distance (d_s), the radius of attraction (R_a) of the structures and earth (d_{sg}).

The leader channel is modeled as a straight line segment perpendicular to the point of incidence and, by the fact that the charge distribution has a simple geometry, the electric field (E_L) due to the leader, established at the point of study is directly obtained by integration of the charge distribution along the straight leader channel model (Fig. 1). The charge distribution is consistent with lightning parameters obtained by Visacro [11] with values for the discharge of median 45 kA, a value that agrees with those verified by measurements of network type lightning by the Location System (LLS) of SIPAM (Amazon Protection System) [7].

To simulate the variability of charge distribution throughout the linearized leader channel, the variation factor proposed by Golde [8] was used:

$$\rho = \rho_0 e^{-z/la} \tag{2}$$

where $la = 1000$ is a propagation constant used in LLS systems. This formula is in agreement with the propagation/attenuation of electrical phenomena in the atmosphere, described by a Gamma distribution function.

The field at the height of the target grounded structure (lightning rod, sharp edges of structures, transmission line conductors and shield wire) due to the streamer buffer region and corona and its subsequent transformation into a connecting leader (or not) is modeled by integration of the image distribution of positive charges homonym to the negative charge in the channel of the downward leader, scaled by the ratio of the height of the target structure and the length of the stepped leader channel at specific altitudes in its descent path, as seen in Fig. 2. This charge distribution is corrected taking into account the strength of tips (the tendency of charges to accumulate in high curvature regions, so a natural field intensification factor) expressed by the relation

$$\frac{\rho_s}{\rho} = \left(\frac{k_s}{k}\right)^{1/3} \tag{3}$$

between the charge density and the radius of curvature at the tip of the structure (ρ_s and k_s) with their respective median values [9,10]. This technique is in contrast to the use of data obtained from discharge studies in high voltage laboratories, used for generating empirical formulas, and/or numerical models [2,3,11].

For the energized overhead conductors, the electric field is evaluated with the help of formulas derived from the Combined Charge Simulation Method (CSM) [12] depending upon the voltage in kV, remembering that this field changes polarity with the transmitting frequency of the transmission line.

3. Methodology

The methodology used in this paper applies the ModSalto to calculate the striking distance for the considered critical stretches of the 500 kV voltage Tucurui–Oriximina–Manaus transmission line; then these values are employed in an EGM model to calculate the protection levels in the sections studied. After implementation of EGM, vulnerability windows, a parameter corresponding to a segment line left unshielded by shield wires/EGM, that permit the evaluation of the probability of an insufficient protection upon a lightning event are determined with

$$P_f = \frac{J_v}{h} \tag{5}$$

where P_f is the probability of an insufficient protection, J_v the vulnerability windows and h is the height of the target structure.

Data from STARNET, a long distance LLS (no parameters estimation, beside location) and SIPAM's networks, a Vaisala LLS using LPATS IV sensors estimating all common parameters including stroke current (see Fig. 3 for location), are used to generate a density map corrected by a factor of 1.3 to account for multiple ending strokes, as recommended by CIGRE [13], on which is superimposed the path of the transmission line under study, obtaining the values