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Lightning grounding system of a tall-mast for human safety

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ABSTRACT

Numerical techniques enable realistic analysis of lightning currents effects on tall structures including actual installation conditions. Characteristics such as the frequency dependence of soil parameters, inductances and capacitances due to nearby metallic elements, and the actual geometry of the structure and its grounding system are commonly neglected or simplified in lightning grounding system design. In this paper, the impact of neglecting these characteristics on a tall-mast lightning grounding system design is discussed. The effects are determined using three risk assessment approaches based on energy calculation, voltage thresholds, and current integration, which allows comparing the performance of the grounding system under different conditions. Results obtained from numerical simulations and then verified by measurements show that a metallic protecting fence not connected to the earthing mesh produces lower human safety risks to lightning currents than when it is connected. This result is in opposition to common design practices and shows the need to assess each specific grounding design under true conditions to guarantee human safety requirements.

1. Introduction

The adequate design of lightning protection systems of tall structures is a basic requirement to guarantee the human safety and to avoid cultural, economic, or social losses. Protection systems should guarantee that voltages, currents, and energy induced by a lightning strike are lower than well-defined thresholds. Currently, computational tools can be used for this task; however, modeling induced voltages due to lightning currents injected into natural soil presents different challenges. On one hand, there is not a modeling technique that reproduces the impulsive response of the currents and materials, the ionization process, and non-linearity [1,2]. On the other hand, the available models and characterization techniques of the dynamic behavior of electromagnetic parameters of soils present inconsistencies [3]. Usual assumptions of frequency independent soil parameters are far from actual values for most soils and produce important deviations in the calculation of induced voltages [1,4].

For these reasons, the performance of earthing systems is commonly assessed using calculations and simulations based on a pure resistive ground behavior. When this happens, most simulations are performed with electrostatic simulations tools. This is mainly true due to the fact that substations grounding systems are almost always calculated for relatively low frequency fault currents. However, in some cases lightning currents, with high frequency components, could impact structures such as masts or protecting fences.

The effect of the frequency dependency of soil parameters on the ground potential rise (GPR) of grounding electrodes due to lightning currents has been analyzed by different authors using experimental results [1,5,6], numerical simulations [2,3] and electromagnetic models [7]. These studies revealed that neglecting the frequency dependence of the soil parameters produces an overestimation of the induced voltages. This overestimation is more pronounced in low conductivity soils, due to their strong frequency dependence; and in short impulses, such as associated with lightning subsequent return strokes, due to their higher frequency content. These effects become relevant for soil resistivity above 1000 Ωm [8].

Recently, numerical simulations have been used to study, in more detail, the effects produced by lightning strikes taking into account realistic earthing system characteristics [3,9]. In Ref. [9], the step and touch voltage distribution around a GSM base station are used to assess the earthing design using a full-wave electromagnetic simulation in time domain. Similar analyses have been performed for wind turbines [3,10]. These studies have shown that the inclusion in the simulation of details and nearby structures, usually neglected in grounding system analyses, produces signifi-

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Fig. 1. Installation of the 30 m high Corona current measuring mast in the campus of the Universidad Nacional de Colombia.

cant changes in its response to induced voltages due to lightning currents [11].

In the present work, the grounding system of the 30 m tall mast shown in Fig. 1 is analyzed using numerical simulations. This structure was installed in a quite deserted street at the Universidad Nacional de Colombia campus to investigate Corona currents in high masts. The mast base is isolated by a 2 m high square metallic fence, called here "*metallic enclosure*", separated 2 m from the mast centre. However, due to its location and to protect people walking or staying in the vicinity of the metallic enclosure, lightning induced over voltages around the structure are calculated. The effect of the metallic enclosure is investigated in order to evaluate a possible voltage induction due to inductive or capacitive effects, instead of the pure resistive ones.

This paper is organized as follows: In Section 2, the methodology used for the lightning protection system assessment is presented. Then, in Section 3, the numerical approach to calculate induced voltages due to lightning currents is validated. In Section 4, the earthing system design is described and numerical results are presented. Finally, Section 5 presents the conclusions.

2. Risk assessment methodology

The main purpose of the mast is to measure corona currents and local atmospheric conditions in its top. However, the mast is prone to be impacted by lightning and touch and step voltages could be expected in the metallic enclosure. Therefore, a special risk assessment was performed.

Risks caused by transient electric signals in human beings are still being studied [12]. Dangerous effects of currents on persons have being widely studied since the beginnings of the cities electrification. A reference study is the published by Dalziel in Ref. [13], where lethal levels for both AC electric currents and capacitor discharges are presented. In Ref. [13], Dalziel proposed the energy criterion to calculate the maximum current levels I and exposition times t before ventricular fibrillation occurs, by using the relation $K^2 = I^2 t$, where K is the energy constant that depends on the body weight. In Ref. [14], the study of physiological effects of electric currents is extended to DC and impulse shocks, while voltage, current, and energy thresholds are discussed. This study refers to 25 J and 10 J as lethal and dangerous energy levels, respectively; however, it also concludes that more research is required.

Here, the designed protection system is assessed by means of three parameters commonly used: the energy delivered to a person, the step voltage, and the severity parameter. To obtain these parameters, both step- and touch voltages generated by a lightning current injected in the earthing system are calculated using numerical simulations.

2.1. Numerical simulation

2.1.1. Simulation setup

The induced over voltages were calculated by simulating a direct lightning strike on the top of the mast. A numerical simulation in CST Microwave Studio using a transient solver was performed. The lightning current is represented by an ideal current source at the tower's top. To characterize a level III or IV scenario of the international standard IEC 62305-1, a 100 kA, 10/350 μs double exponential impulse current source was used to represent a first positive current impulse. In addition, to maximize inductive and capacitive effects in the induced voltages, a shorter waveform of 100 kA, 1/50 μs was considered. This waveform is based on the first negative lightning current impulse according to IEC 62305-1.

The simulation volume has a 30 m side length and is centered at the mast. To represent the fact that locally the currents spread in all directions into the soil, the simulation volume was set considerably larger than the simulated structure. While the side length of the grounding mesh is 5 m, the side length of the simulation volume is 30 m. In full-wave lightning phenomena simulations, the reported boundary conditions are the following: – Absorbing boundary conditions (ABC) in all the boundaries [15], – ABC with perfect electric conductor (PEC) ground [16], or – fully PEC [17]. ABC are used to truncate the computation domain by reducing the amplitude of the reflections of the electromagnetic waves impinging the simulation borders while PEC is used to provide a closed path for the lightning current [17]. In the performed simulation, absorbing wave boundary conditions were used on all the faces of the simulation volume as reported in [18]. In this simulation setup, it was verified that the effect of the reflected waves from the boundaries on the variables of interest is negligible since an error of 2.6% was obtained when results were compared with a simulation volume of a 40 m side length.

2.1.2. Soil parameter frequency dependency

Different models to calculate the frequency dependence of soil parameters are available. A comparison between some of these models is presented in Refs. [3,19]. Recently, a causal model with strong experimental support has been proposed to address this effect [6]. In this paper, the Messier model, which provides results in good agreement with experimental data for soils with moderate and low resistivity and which satisfies causality [3], is used.

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