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Role of upward leaders in modifying the induced currents in solitary down-conductors during a nearby lightning strike to ground

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ABSTRACT

Electromagnetic field produced by a lightning strike to ground causes significant induction to tall objects in the vicinity. The frequency of occurrence of such nearby ground strikes can be higher than the number of direct strikes. Therefore, a complete knowledge on these induced currents is of practical relevance. However, limited efforts towards the characterisation of such induced currents in tall down-conductors could be seen in the literature. Due to the intensification of the background field caused by the descending stepped leader, tall towers/down-conductors can launch upward leaders of significant length. The nonlinearity in the conductance of upward leader and the surrounding corona sheath can alter the characteristics of the induced currents. Preliminary aspects of this phenomenon have been studied by the author previously and the present work aims to perform a detailed investigation on the role of upward leaders in modifying the characteristics of the induced currents. A consistent model for the upward leader, which covers all the essential electrical aspects of the phenomena, is employed. A first order arc model for representing the conductance of upward leader and a field dependant quadratic conductivity model for the corona sheath is employed. The initial gradient in the upward leader and the field produced by the return stroke forms the excitation. The dynamic electromagnetic response is determined by solving the wave equation using thin-wire time-domain formulation. Simulations are carried out initially to ascertain the role of individual parameters, including the length of the upward leader. Based on the simulation results, it is shown that the upward leader enhances the induced current, and when significant in length, can alter the waveshape of induced current from bipolar oscillatory to unipolar. The duration of the induced current is governed by the length of upward leader, which in turn is dependant on the return stroke current and the effective length of the down-conductor. If the current during the upward leader developmental phase is considered along with that after the stroke termination to ground, it would present a bipolar current pulse.

1. Introduction

The lightning current statistics presently employed in the engineering designs are mostly derived from the measured data on tall instrumented towers. Also, such measurements continue to form the major source of data for the characterisation of the phenomena. In view of these, there are several efforts around the globe to record the lightning currents on tall towers. Major ones have been reviewed by Heidler et al. (2008) and Rakov (2012).

Lightning strike to tall towers has also drawn attention from a different context. Threat due to a direct hit to communication and instrumented towers is well-known and hence suitable protective measures are suggested in the literature (ITU-T Rec.K.56, 2003; Lo Piparo, 2010; Barbosa et al., 2007). On the other hand, the response of towers to the electromagnetic field produced by a nearby lightning strike to ground has not received adequate attention. The field produced by a nearby strike illuminates the tower/down-conductor leading to induced currents. As compared to the case of a direct strike, the induced currents will be lower in magnitude; however, their frequency of occurrence will be much higher. They can be a source of electromagnetic noise for the sensitive electronic systems mounted on the tower. Further, they are contained in the data obtained from instrumented towers for lightning current measurements. Therefore, a clear knowledge on them will be of practical relevance. These induced currents can be significantly modified by the presence of upward leaders, which are easily produced at the top of tall towers and can assume significant spatial extensions as well (Cooray and Becerra, 2010). A survey on the related literature will be carried out next.

For systems with relatively low basic insulation levels like electric distribution and telecommunication lines, even the indirect effects of lightning assumes importance. A nearby strike to ground or objects on the ground, as well as, the cloud discharges

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can induce voltage surges in these lines (Silfverskiold et al., 1999; Piantini, 2010; Nucci and Rachidi, 2010). Among these, a nearby cloud-to-ground lightning has been investigated in a vast amount of literature spanning theoretical evaluation, experimental validation and field observations. For brevity only a selected references will be quoted here.

The theoretical approach, which is dealt in most of the works, involves modelling of the return stroke for the field it produces, modelling for coupling to the system and simulation for the response of the system. A review of the return stroke models including that for the lightning electromagnetic fields have been carried out by Rakov (Rakov and Uman, 2003) and Cooray (Cooray, 2003). Various models for the evaluation of coupling of lightning electromagnetic fields to the overhead lines have been reviewed by Rachidi (Rachidi, 2012). Experimental validations for the coupling models have been provided with reduced scale models (Ishii et al., 1999; Piantini et al., 2007). Some experimental investigation with test lines have also been reported (Master et al., 1984; Silfverskiold et al., 1999). An assessment of the lightning performance of overhead distribution lines using an improved method and its comparison with the IEEE std. 1410 method has been reported (Borghetti et al., 2004).

Similarly, induction to the buried cables has been investigated and a suitable validation is provided through the triggered lightning experiments (Petrache et al., 2005; Paolone et al., 2005). The induction to the electric network of a building and that to the protection system has been dealt with by, e.g., Kato et al. (2001) and Miyazaki and Ishii (2005). However, an in-depth study on the currents induced in tall and solitary down conductors/towers has not been carried out.

Some preliminary studies on the characteristics of induced currents in down-conductors were reported in an earlier work (Kumar et al., 2006), considering only those cases that do not involve significant upward leader activity. The Numerical Electromagnetic Code (NEC-2d) (Burke and Poggio, 1980) was employed for the simulation of the return stroke field and the induced currents. A lumped source model was used to drive the channel current and the required time-domain transformation from the frequency domain results yielded by NEC based simulation was carried out using Fourier techniques (in Matlab). However, tall down conductors/towers can launch upward leaders of significant length (Cooray and Becerra, 2010; Cooray et al., 2014) and therefore it is necessary to consider their effects as well, while determining induced currents.

To investigate the characteristics of current induced in buried loop and a grounded vertical conductor of 7 m length, triggered lightning experiments have been conducted by Schoene et al. (2008). The main findings of this work are: (i) Strong correlation exists between the peak value of return stroke currents and the peak values of respective induced currents and (ii) Multiple current pulses observed are due to the multiple attempts made by an upward leader to establish contact with the downward propagating leader. However, the results of this experiment cannot be extended to the general range of down conductors and stroke currents found in practise.

Currents in two unconnected upward leaders from a 60 m tall tower of Morro do Cachimbo Station in Brazil are presented by Visacro et al. (2010). In this interesting measurement, currents in the tower before and after stroke termination have been recorded. Immediately after the stroke termination (elsewhere), the leader current changed its polarity and exhibited a small unipolar oscillation. A further reference to this work will be carried out later.

In the authors' previous work, an attempt was made to ascertain the possible role of upward connecting leaders on the current induced in tall solitary down-conductors (Kumar and Sruthi, 2014). The simulation results presented showed two distinct influences of the upward leaders, namely, the magnitude of the induced current is enhanced and the oscillatory nature of the current is totally eliminated immediately after the initial portion. However, it was not clear whether these salient features are specific only to higher upward leader lengths, tower heights in a particular range, the parameters used in the current evolution models employed, etc. The present work intends to address all these issues to establish the extent of role of each of these parameters on currents induced in solitary down-conductors/towers. As indicated earlier, the currents induced after the termination of the stroke to ground elsewhere is the quantity of interest. In other words, current in the down conductor during the upward leader growth phase, which involves current due to spatial extension of the upward leader and that due to electromagnetic field produced by the steps in the downward leader, is not dealt with here. The intended study will be carried out using numerical simulation.

2. Present work

In this section, various modelling approaches employed in the study will be discussed.

2.1. Upward leader

For the intended work, it is necessary to find the final loci of the unconnected upward leader along with its line charge distribution. It will be dealt in this section. Prior to the stroke termination on the ground, owing to a rather slow variation in the electric field near ground and grounded objects, it is customary to invoke quasistatic fields. Hence, for evaluating the field prior to the inception of the upward leader, as well as, for evaluating the radial extension of the upward leader, the required calculations are carried out under quasistatic regime. The charge simulation method (Malik, 1989) is employed considering line-charges for the cylindrical portion and point-charges for the hemispherical head of the down-conductor. The error in the numerically simulated potential is kept below 0.1%. The ambient field required for the inception of continuous upward leaders from the down conductor is obtained from Becerra and Cooray (2006a, 2006b).

The main leader propagates vertically down without being affected by the local field modification caused by the tower/down conductor and the upward leader. On the other hand, the elongation of the upward leader at every instant is in a direction to seek the downward leader tip. This assumption is routinely employed in the classical literature (as discussed in Cooray and Becerra, 2010). In numerical simulations, the extension of the upward leader is assumed to be in fixed steps of 1–3 m, and along the line joining the tip of the two leaders. The velocity ratio between the downward and the upward is varied between 1:1 and 4:1. Slower velocities for the upward leader are employed only to get shorter leader lengths. It may be noted here that only unsuccessful upward leaders are relevant to the present work and therefore upward leaders which fail to connect with downward leader are only considered.

The charges on the cloud and that on the descending leader produce ambient or background electric field above the ground. Charges will be deposited on the tower/down-conductor so as to cancel this background field in their volume, thereby rendering the potential to be zero. Based on experimental observations, the upward leader is generally considered as an electric arc and is similar to the main leader. In view of this, the internal axial gradient can be estimated to be in the same range of 3–6 kV/m (Berger, 1977). There will be a corona sheath surrounding the core of the upward leader and the extension of the radial corona sheath is fixed (iteratively) such that the field on its surface is just equal to