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A return stroke model based purely on the current dissipation concept

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ABSTRACT

A return stroke model based purely on the current dissipation concept is introduced. With three model parameters the model is capable of generating electric and magnetic fields that are in reasonable agreement with experimentally observed electromagnetic fields.

1. Introduction

Consider the injection of a current pulse into an ideal and uniform transmission line in air. If the amplitude of the current pulse is less than the critical current necessary for corona generation from the line, the current pulse propagates along the line without attenuation and dispersion and with a speed equal to the speed of light in free space. This basic idea, with several modifications either in the speed of propagation or the amount of current attenuation, is used as a basis in creating current propagation models (Cooray, 2010). In all the current propagation models the return stroke speed is assumed to be less than the speed of light and in several models the return stroke current amplitude is assumed to attenuate as it propagates along the return stroke channel (Uman and McLain, 1969; Nucci et al., 1988; Rakov and Dulzon, 1991). On the other hand when the current amplitude is larger than the threshold current necessary for corona generation from the transmission line, each element of the transmission line acts as a corona current source. Half of the corona current generated by the sources travels downwards and the other half travels upwards. The upward moving corona currents interact with the front of the injected current pulse in such a way that the speed of the net upward moving current (i.e. sum of the two upward moving current pulses) is reduced, and for a transmission line in air, to a value less than the speed of light in free space (Cooray and Theethayi, 2008). Thus in principle one would find three separate current waveforms along the return stroke channel. The first one is the upward moving injected current (Current Pulse 1). The second one is the current pulse generated by the sum of upward moving corona currents (Current Pulse 2). The third one is the current pulse generated by sum of downward moving corona currents (Current Pulse 3). The injected current transports positive charge upwards, the current pulse due to upward moving corona current transports negative charge upwards and the current pulse formed by the downward moving corona currents transport negative charge towards the ground. All the three current pulses propagate with speed of light along the return stroke channel. The net upward moving current is produced by the sum of Current Pulse 1 and Current Pulse 2. This concept with several modifications is used in constructing current generation (Heidler, 1985; Cooray, 1993; Diendorfer and Uman, 1990) and current dissipation models (Cooray, 2009). First let us consider the basic assumptions of current generation model. In current generation models the leader channel is treated as a charged transmission line and the return stroke current is generated by a wave of ground potential that travels along it from ground to cloud. The arrival of the wave front (i.e. return stroke front) at a given point on the leader channel changes its potential from cloud potential to ground potential causing the release of bound charge on the central core and the corona sheath giving rise to a corona current. Accordingly, each point on the leader channel can be treated as a current source which is turned on by the arrival of the return stroke front at that point. The corona current injected by these sources into the highly conducting return stroke channel core travels to ground with the speed of light. One can see directly that these models utilize the Current Pulse 3 described previously to represent the return stroke current. In these models the speed of propagation of the return stroke front is selected to be less than the speed of light.

In a recent publication Cooray (2009) showed that a combination of Current Pulse 1 and Current Pulse 2 can also be used to create return stroke models. He coined the term 'Current Dissipation Models' for the same. The basic concept as illustrated by

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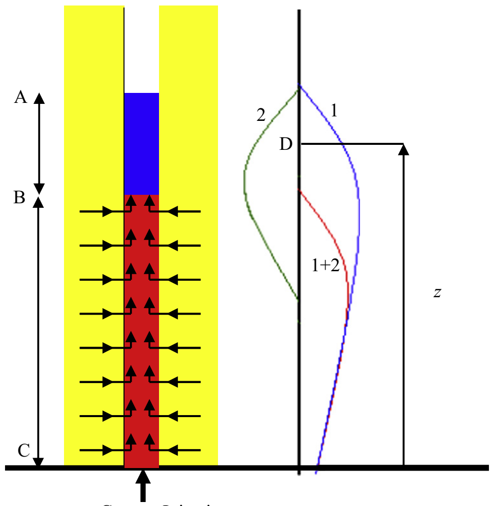

Fig. 1. Pictorial description of the processes associated with a current dissipation concept at a given time *t* as illustrated by Cooray (2009). The injected current (waveform 1 to the right) and the sum of corona currents (waveform 2 to the right) travel upwards with speed *c*. Point *A* is the front of these current waveforms. In the region *A*–*B* these two currents cancel each other making the current above point *B* equal to zero. The cancellation is not complete below point *B* and therefore the net current below point *B* is finite (waveform 1+2 to the right). Thus point *B* is the front of the net current (i.e. return stroke front) moving upwards. Distance *AC* is equal to *ct* and the distance *BC* is *vt* where *v* is the average speed of propagation of the net current front (i.e. return stroke front). Note that the current waveforms are not drawn to scale.

Cooray (2009) is depicted in Fig. 1. In that paper he only gave the basic principles that could be used to create a return stroke model. However, whether these principles could be used to create a viable return stroke model that can explain the observed features of return strokes was not explored in that paper. This is the task of the present paper.

The main assumptions of the current dissipation concept are the following: The return stroke is initiated by a current pulse injected into the leader channel from the grounded end. Following the correct physics of the problem the speed of propagation of this current pulse is assumed to be the speed of light in free space. The total current flowing upward is the sum of this current (i.e. Current Pulse 1) and the current generated by the corona (Current Pulse 2). Due to charge neutralization at the front of the injected current pulse by the corona current (i.e. Current Pulse 2) the net current propagates upwards with a speed slower than the speed of light. This net current front that propagates with a speed less than the speed of light is called here the return stroke front. At any given point on the return stroke channel the current is zero at times before the arrival of the return stroke front at that point and it starts to increase with the arrival of the return stroke front. The arrival of the return stroke front at a given channel element will turn on a corona current source that will inject a corona current into the central core. It is important to stress here that by the statement *the arrival of the return stroke front at a given channel element* it is meant the onset of the return stroke current in that channel element. In other words it represents the arrival of the net current at the point of interest. Once in the core this corona current will travel upward along the channel with the speed of light. In the case of negative return strokes the polarity of the corona current is such that it will deposit positive charge on the corona sheath and transport negative charge along the central core. According to this model the total current at a given point of the channel consists of two parts – upward moving current pulse injected at the channel base and the total contribution of the upward moving corona currents. The upward moving corona current being of opposite polarity leads to the dissipation of the current pulse injected at the channel base.

Cooray (2009) presented the basic concepts and the mathematics necessary to describe the return stroke current using current dissipation concept. Cooray and Rakov (2011) utilized the current dissipation concept to describe the reflected current waves from the ground end of the return stroke channel. However, no one has attempted yet to construct a return stroke model based on this concept that can be used in engineering studies. In this paper a return stroke model based on the current dissipation concept is introduced. Similar to other simple engineering models the new model contains three adjustable parameters.

2. Model parameters

The three model parameters are the channel base current, return stroke front speed and the decay time constant of the corona current. A corona decay time constant comes into the picture because, as in current generation models, the corona current generated by any channel element is represented by an exponential function that decays with time. The channel base current, which is the current pulse injected into the channel at the channel base, is represented by the typical subsequent return stroke current waveform introduced by Nucci et al. (1990). In the corona model corona current decay time constat, $\tau(z)$, is assumed to increase with height, z, according to the equation:

$$\tau(z) = kz \tag{1}$$

where k is a constant. In the model the value of k is selected in such a way that the decay time constant of the corona current increases by 10 μs for each kilometer; in other words, $k = 10^{-8}$ s/m. Once these two model parameters (i.e. the channel base current and the corona decay time constant) are given one has the possibility either to select the charge deposited by the return stroke on the leader channel or the return stroke speed, i.e. the speed of propagation of the return stroke front in the presence of corona, as the third input parameter. In the present model the return stroke speed was selected as the input parameter and it was held constant at 1.5×10^8 m/s as a function of height. This describes the three model parameters completely. With these model parameters the magnitude of the corona current and the net upward moving current at any height can be obtained using the procedure described in Cooray (2009). We will describe this procedure briefly in the next section.

3. Mathematical analysis

The corona current per unit length injected into the return stroke channel at any given point on the channel, $I_c(z, t)$, is given by

$$I_c(z, t) = I_0(z)e^{-t/\tau(z)} \tag{2}$$

In the above equation $I_0(z)$ is a parameter that is related to the charge dissipated by the corona current at location z. Let us denote by $\rho(z)$ the charge per unit length deposited by the return stroke at height z. In order to assure charge conservation, $\rho(z)$ and $I_o(z)$ should be related to each other through the following equation:

$$I_o(z) = \rho(z)/\,\tau(z) \tag{3}$$

This is the case because it is the corona current that deposit charge on the leader channel during the return stroke. Using the above relationship the corona current per unit length can be