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Power and energy dissipation in negative lightning return strokes

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ABSTRACT

In this paper the temporal variation of the electric field along the negative return stroke channel is calculated and this information in turn is used to evaluate the power and energy dissipation in negative return strokes. Moreover, by plugging in the results obtained here with the spark equation of Braginski, the temporal and spatial variations of the return stroke speed, the radius and the resistance of the return stroke channel were investigated. The results of the study showed that for a typical subsequent return stroke current pulse having a peak current of 12 kA in the return stroke channel: (a) The peak power dissipation is about 4×10^9 W/m; (ii) the energy dissipation over the first 70 μs or so is about $(2–3) \times 10^3$ J/m; (iii) the maximum channel radius is about 1 cm; and (iv) the resistance of the channel is about 0.5 Ω/m. The study also revealed that the speed of the return stroke is governed not only by the peak current, but also by the risetime of the current. The study shows that the speed of the return stroke increases with increasing peak current but it decreases with increasing current risetime. The results obtained using available experimental data on first return strokes indicate that the risetime of the return stroke current increases with increasing peak current. It is shown that this tendency for the first return stroke current risetime to increase with return stroke peak current could completely mask the relationship between the first return stroke speed and return stroke peak current. It is suggested that the apparent absence of such a relationship in experimental data is caused by these variations.

1. Introduction

Lightning return strokes can be treated as self-propagating discharges carrying a high electric field at their tip. The intense electric fields at the return stroke tip lead to enhanced ionization and prepare the channel for the passage of the return stroke current. The enhanced ionization at the tip is evident from the optical radiation that travels upwards along with the tip of the return stroke. Knowledge of the magnitude and the spatial extent of the electric field may help in understanding the amount of power and energy dissipation in return strokes and in determining their connection to the return stroke current. Moreover, such knowledge provides information necessary in understanding the underlying physical mechanism of return strokes.

In the existing literature, scientists have reported different ways of estimating the energy dissipation in lightning flashes. In the first category the amount of energy dissipated in lightning flashes is calculated on the basis of electrostatic energy considerations (Wilson, 1920; Malan, 1963; Krider et al., 1968; Uman, 1969; Conner, 1967; Berger, 1977). The energy dissipation is calculated by assuming that a known amount of charge is transferred across a known potential difference during the lightning flash. The potential of the thundercloud with respect to the earth is estimated by using familiar electrostatics principles. In the second category the energy dissipation in lightning flashes is derived from the measured optical radiation (Guo and Krider, 1983; Macckerras, 1973; Turman, 1978; Krider et al., 1968; Conner, 1967; Barasch, 1970). In the analysis, experimentally obtained relationships

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between the electrical and optical energy in spark discharges were extrapolated to obtain the electrical energy dissipation in lightning flashes on the basis of the measured optical radiation. In the third category, the energy dissipation in lightning flashes is estimated by measuring the spectrum of thunder and relating it to the energy dissipation by applying the theory of shock waves (Zhivlyuk and Mandelshtam, 1961; Few, 1969). In the fourth category the shape and amplitude of the return stroke current are assumed, and the energy dissipated in the channel is calculated by analyzing the temporal development of the channel properties such as the channel temperature, channel radius and channel pressure as a function of time (Hill, 1971; Plooster, 1971a; Paxton et al., 1986). In a recent study Jayakumar et al. (2006) measured the energy dissipation in the channel by measuring the electric field in the vicinity of the triggered subsequent return stroke channel and assuming that the same electric field exists inside the channel.

In this paper, mathematical expressions for the longitudinal electric field along the axis of the negative return stroke as a function of peak current and return stroke speed are derived. In their turn, these expressions are utilized to study the return stroke parameters such as the power and energy dissipation, channel radius, channel resistance and the return stroke speed. To the best of our knowledge, this is the first time in the reviewed literature, other than the presentation of the preliminary results from this study at the International Conference on Lightning Protection by Cooray (2012), that temporal and spatial variation of the return stroke channel are combined with Maxwell's equations to obtain the temporal variation of the electric field along the channel and from that the power and energy dissipated along the channel.

2. Mathematical analysis

The electric field on the axis of the return stroke consists of two parts. The first part, denoted by E_{arc} in our analysis is the electric field that was present along the axis during the dart leader stage of the return stroke. The second part, denoted by $E_r(t,z)$ in our analysis, is the time-dependent electric field produced by the deposition of positive charge during the return stroke process (Kasemir, 1960; Mazur and Ruhnke, 1993; Cooray et al., 2007). Thus, the axial electric field at any point along the channel at time, t, is given by

$$E(t,z) = E_r(t,z) + E_{arc} \tag{1}$$

In the analysis, it is assumed that the arc field of the leader channel is similar to the electric field supported by an atmospheric arc. Experiments conducted by King (1961) show that the electric field of arcs in atmospheric air stabilizes around 1000 V/m as the current increases. From experiments conducted with 7 cm long arcs, Bazelyan and Raizer (2000) found that the arc field is a function of the arc current and, with increasing current (in the range of kA), it stabilizes around 3000 V/m. In another experiment, conducted with 30 cm long sparks supporting currents in the range of kilo amperes, Montano et al. (2006) demonstrated that the electric field in the channel stabilizes around 2500 V/m. The step currents associated with stepped leaders and the currents associated with dart leaders may have values in the range of kA. Based on this data, the electric field in the leader channel may lie in the range between 1000 V/m and 3000 V/m. Thus, a value of $E_{arc} = 2500$ V/m seems a reasonable choice.

The mathematical procedure required to estimate the electric field produced by the charge neutralization process of the return stroke has already been described in Cooray (2012), and thus only a brief description is presented here. The temporal and spatial variation of the return stroke current are required to evaluate the electric field on the axis of the return stroke channel. These were obtained using a return stroke model similar to that introduced by Cooray and Rakov (2011). The model belongs to the current generation type engineering return stroke models (Cooray, 2010) in which it is assumed that each and every element of the leader channel acts as a current source. The current source associated with any given element of the leader channel is turned on by the arrival of the return stroke front at that element. Once turned on, the current source injects a current, called a corona current in the literature, into the hot core of the return stroke channel. In all of the current generation type return stroke models, it is assumed that the speed of propagation of the corona current along the return stroke channel to ground is equal to the speed of light in free space. This assumption is also made in the model of Cooray and Rakov (2011). The current at any given point on the return stroke channel is the sum of the corona currents flowing through that point. In the model introduced by Cooray and Rakov (2011), it was assumed that the corona current reaching the ground will be reflected at the ground end owing to the impedance mismatch between the return stroke channel and the perfectly conducting ground plane. In the version of the model considered here, the current reflection coefficient at ground level is assumed to be zero.

The input parameters of the model are the return stroke speed, the distribution of the charge neutralized by the return stroke and the discharge time constant of the corona current, which is assumed to decay exponentially with time. With these parameters as input, the model generates the temporal and spatial variation of the return stroke current. The risetime of the current depends on the value of the discharge time constant of the corona current selected in the model. This value was selected to match the desired risetime of the return stroke current. The distribution of the charge neutralized by the return stroke was obtained using the results presented by Cooray et al. (2007) as described by Cooray and Rakov (2011). The expression for the charge neutralized by the return stroke as a function of height is also given in Cooray (2012).

The electric field at the center of the return stroke channel is evaluated using the equations pertinent to the electromagnetic fields of accelerating charges as described by Cooray and Cooray (2010). Recently, the same equations have been used by Cooray and Cooray (2012) to evaluate the electromagnetic fields of electron avalanches. As described by Cooray (2012), the resulting expressions for the electromagnetic field consist of four terms. They are: (i) the static field generated by the accumulation of charge on the return stroke channel, (ii) the radiation field generated by charge acceleration during the initiation of the corona current, (iii) the radiation field generated during the deceleration of charges associated with the corona current when the downward moving corona current is terminated at ground end and (iv) the velocity field

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