Electric Power Systems Research 113 (2014) 30–40

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Vertical electric field inside the lightning channel and the channel-core conductivity during discharge – Comparison of different return stroke models

Dragan Pavlovic[a], Jovan Cvetic[a,*], Fridolin Heidler[b], Radivoje Djuric[a]

[a] School of Electrical Engineering Belgrade, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia
[b] University of the Federal Armed Forces, EIT 7, Munich, Germany

ARTICLE INFO

Article history:
Received 25 July 2013
Received in revised form
10 December 2013
Accepted 25 February 2014
Available online 30 April 2014

Keywords:
Lightning
Return stroke model
Channel core
Conductivity

ABSTRACT

The longitudinal electric field along the axis and the channel core conductivity of a straight, vertical lightning channel above ground has been calculated by using different return stroke models. The lightning channel is modeled by a negatively charged corona sheath that stretches around a thin, very conductive central core. It is commonly held that the majority of the leader charge is located within the corona sheath radius, which is of the order of meters, while the highly conductive channel core, with a diameter assessed at around 1 cm, in effect transports the whole of the axial current. An inhomogeneous channel line charge density generates as strong radial as well as vertical electric field inside the corona sheath. Transmission-line-type models and the generalized traveling current source model, representing the "engineering" return stroke models, are used for the calculation of the vertical field and the core conductivity in the channel. For the purpose of the present study only the influence of the charge in the corona sheath on the vertical electric field are taken into account while all other effects are neglected. For comparison purposes, the same channel-base current for all models is assumed. First, we calculated the vertical electric field along the axis on the channel. Knowing the axial current density profile along the channel determined by the particular return stroke model and the assumed channel core diameter, the core conductivity is calculated using simple scalar relationship. The conductivity is compared between the models and with the values found in the existing literature. It is concluded that all considered models give the maximum value of the core conductivity more or less in accordance with the predictions in the literature (of the order of 10^4 S/m). Some discrepancies (negative conductivity) are observed for two transmission-line-type models at the very bottom of the channel. They can be explained by the great amount of injected positive charge in zone 1 of the channel sheath and by the presence of the image charge, small changes in input parameters could diminished or avoid it. Due to the big charge accumulation near the ground the generalized traveling current source model gives greater discrepancies regarding negative conductivity at 25–35 m above ground. It is concluded that the removing of these discrepancies requires a more complex approach, the inclusion of the new physical mechanisms during the discharge (for example the magnetic field generated by the core current in the channel), that is a more accurate calculation of the channel discharge function. On the other hand our results are consistent with the 1 cm core diameter value found in the literature.

1. Introduction

Numerous return stroke models have been developed with the aim of enabling numerical calculation of the radiated lightning electromagnetic pulse and describing the physics of the gaseous-discharge processes in the lightning channel. The analysis given in this study is intended for the so-called "engineering" models. These models provide the answer to the question how the current varies along the channel. Due to the small number of channel and current parameters, the relation between the channel-base current and the current along the channel is relatively simple. The "engineering" return stroke models can be divided into two categories, the transmission-line-type Models (TLM, also called current propagation models) and traveling-current-source-type models (TCSM, also known as current generation models). In the first type of models the return stroke channel serves as a guiding structure for the

* Corresponding author. Tel.: +381 11 3370 156; fax: +381 11 324 86 81.
E-mail address: cvetic_j@etf.rs (J. Cvetic).

http://dx.doi.org/10.1016/j.epsr.2014.02.026
0378-7796/

propagation of the return stroke current wave which is injected at the channel base. The current wave travels upwards with a certain speed (usually assumed to be one third of the speed of light), while its amplitude may decrease with height depending on the model. Models of this type have been introduced by Uman and McLain [40] (original Transmission Line model – TL), Rakov and Dulzon [32], (modified transmission line model with linear current decay with height – MTLL), Nucci et al. [29] (modified transmission line model with exponential current decay with height – MTLE) and Rakov and Dulzon [33] (modified transmission line model with parabolic current decay with height – MTLP).

The TCSM represent the return stroke process as a current source that propagates upwards, injecting the current pulse on its way into the channel. In other words, the channel itself produces the current pulse as a product of neutralization of the corona sheath, positioned around the central core of the leader channel. The typical models of this category are: Bruce–Golde model (BG) [3], original traveling current source model (TCS) [16], Diendorfer–Uman model (DU) [14], and the modified DU model (MDU) [38].

In addition to these, the generalized lightning traveling current source return stroke model (GTCS) was established [9], as a generalization of all TCSM. The BG, the TCS, the DU and the MDU models all result from the GTCS, as its distinct sub-variants. Within the GTCS model, the channel-base current, the leader line charge distribution, and the return stroke speed are known (measured) functions. These functions determine the so-called channel discharge function [10].

Generally taken, electric field created by the charge located at the thin and lengthy conducting channel core is predominantly radially directed and surpasses the breakdown (critical) value. Repulsive electrostatic forces drive the charge out from the channel core, until the radial electric field drops below the breakdown value. Consequently, the leader channel comprises a thin core and a corona sheath which forms radially around it. 2 MV/m magnitude of the breakdown field at the boundary of the corona sheath was assumed by Baum and Baker [1], while Kodali et al. [20] adopted 1 MV/m.

It is commonly held [31,41] that the majority of the leader charge is located within the corona sheath radius, which is of the order of meters, while the highly conductive channel core, with a diameter assessed at around 1 cm, in effect transports the whole of the axial current.

Distributions of charge along the lightning channel for different "engineering" return stroke models are derived in details in [37]. The line charge density during the return stroke is expressed as the sum of two components, one component being associated with the return stroke charge transferred through a given channel section and the other component with the charge deposited by the return stroke on this channel section. Radiated electric and magnetic fields are also derived in [37] as a function of the line charge density. But in that study, the channel is represented by an infinitely thin conductive structure without taking into account the radial dimension of the corona sheath surrounding the channel. As a result, the derived expression for electric and magnetic fields are valid only far away from the channel and cannot be used at very close distances. On the other hand, the inhomogeneous channel line charge density profile calculated in [37] for all return stroke models, unequivocally indicates that there is a strong vertical electric field component in the corona sheath surrounding the thin channel core. We started with the line charge distributions calculated in [37] and [23] for different return stroke models applying it to two corona models presented in the paper. This enabled us to calculate the radial dimensions of the corona sheath and the vertical electric field inside it during the return stroke. Knowing the current distribution along the channel, the core conductivity is also calculated during the discharge.

Taking into account only radial electric field component in the corona sheath, the TLM [23–27], as well as the TCSM [12,13,21,36] are used to examine the dynamics of the corona sheath during the return stroke.

In the next section we shall briefly discussed the GTCS model since the TLM are well known from afore stated references.

2. Generalized traveling current source return stroke model

The GTCS model can be viewed as involving current sources distributed along the lightning channel that are progressively activated by the upward-moving return stroke wave-front. The current wave is generated from the leader charge deposited in the corona sheath. The upward velocity of the return stroke wave-front is an input parameter estimated usually from optical measurements [42,43]. The GTCS model enables the examination of the influence of different line charge distributions along the channel (charge per unit length of the channel) on the processes inside the corona sheath as well as on the radiated lightning electromagnetic pulse. The current at the channel-base $i_0(t)$ and the initial (negative) leader line charge density along the channel $q_{tot}^-(z)$ (prior to the return stroke stage) are considered as known. They are connected through the charge conservation law. The line charge distribution along the channel during the return stroke can be expressed as [36]

$$q_{tot}^-(z)\cdot f(u) = q_{tot}^-(z) + q_0^+(z)f^+(u), \quad u=\frac{t-z}{v}, \quad u\geq 0, \tag{1}$$

where f is the channel discharge function defined by the GTCS model [9], $q_0^+f^+(z)dz$ is the positive charge coming from the core and spreading uniformly in zone 1 during the return stroke stage, f^+ is the channel charging function (it charges zone 1 with positive charge), $q_0^+ = |q_{tot}^-|$ is the positive line charge density deposited during the return stroke stage within R_{out}^+, Fig. 1. The generalized time is denoted as $u = t - z/v$, where t is the absolute time (the time onset is usually the beginning of the return stroke), z is the height of the observed channel section, and v is the return stroke speed. The channel charging function f^+ can be defined as [36],

$$f^+ = 1 - f. \tag{2}$$

According to the features of the GTCS model, the function f^+ should satisfy the following conditions

$$\begin{aligned}&(a)\;\; f^+(u\leq 0)=0, \quad (b)\;\; 1>f^+(u>0)>0,\\ &(c)\;\; (df^+/du)_{u\geq 0}\geq 0, \quad (d)\;\; f^+(u\to\infty)=1.\end{aligned} \tag{3}$$

The downward moving current at the channel-base is the integral of all current pulses coming downward from differential segments over the activated part of the channel (Fig. 2),

$$i_{0/d}(t) = \int_0^{h_a} q_{tot}^-(z)\frac{\partial f(t-z/v*)}{\partial t\, dz}, \tag{4}$$

where $v* = vc/(v+c)$ is the so-called reduced return stroke speed [14,16]. Note that the direction of the current pulse is upwards. The downward moving component of the channel-base current function given by Eq. (4) is represented by a Volterra equation of the first kind. It is assumed that the upward return stroke speed (v) as well as the downward discharge current-wave speed (c) is constant. Similarly, the downward moving current $i_d(z,t)$ at some altitude z can be expressed as:

$$i_d(z,t) = \int_z^{h_{az}} q_{tot}^-(\xi)\frac{\partial f(t-\xi/v*+z/c)}{\partial t\, d\xi}, \tag{5}$$

where the "activated" channel altitude is defined by $h_{az} = v*(t + z/c)$.