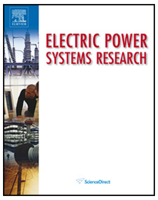
Electric Power Systems Research 143 (2017) 84–98

Contents lists available at ScienceDirect

Electric Power Systems Research

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



Influence of current reflections from the ground on corona sheath dynamics during the return stroke

Milica Tausanovic[a], Milan Ignjatovic[b], Jovan Cvetic[b,*], Fridolin Heidler[c], Malisa Alimpijevic[b], Dragan Pavlovic[b]

[a] *PD Elektrodistribucija Beograd d.o.o, Serbia*
[b] *School of Electrical Engineering Belgrade, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia*
[c] *University of the Federal Armed Forces, EIT 7, Munich, Germany*

ARTICLE INFO

Article history:
Received 19 September 2015
Received in revised form 5 March 2016
Accepted 13 October 2016

Keywords:
Ground reflections
Lightning corona sheath dynamics
Return stroke model

ABSTRACT

Appearance of an overcompensated positive electric field in most vertical field measurements performed very close to the channel core (0.1 m from it) is explained using the extended generalized traveling current source (extended GTCS) return stroke model with current reflections from the ground. As suggested by experiments in triggered lightning conditions or in measurements of simulated return strokes in the laboratory we assumed that the ground reflection coefficient depends on the current magnitude. New effects in the corona sheath due to the reflection of current pulses have been noted and taken into account. We separated the channel-base current into two components. The first current component is fast and with a greater peak value, while the second component is slower and with a lower peak. We analyzed two return strokes with simultaneously measured channel-base currents and close electric waveforms. In the first analyzed case, the first current component, with a peak value of over 15 kA, reflects from a perfect ground with the reflection coefficient that equals unity, while the second current component, with a peak value below 15 kA, reflects with the reflection coefficient lower than 1. In the second analyzed case, both current components reflect from the ground with the reflection coefficient <1. As a result, for the current component with the reflection coefficient lower than 1 an additional transient negative line charge density appears along the channel core at channel bottom, enhancing the negative radial electric field in the channel sheath. This field forces the overcompensated positive charges to move into the corona sheath, so as to satisfy the boundary condition between the channel core and the ground. Since the transient line charge density is proportional to the channel-base current, it disappears after the cessation of the return stroke, leaving accumulated positive charge in the corona sheath. The excess of positive charge generates the overcompensated positive electric field measured in most horizontal field measurements performed close to the channel core. A new charging function according to the extended GTCS model is calculated, as well as the value of the ground reflection coefficient for both analyzed strokes. The obtained results fit well with data reported in other independent studies performed in natural or laboratory conditions.

1. Introduction

Channel charge and its distribution along the channel prior to a return stroke have a crucial role in the generation of current at the channel base, as well as in the dynamics of the corona envelope during discharge. As a result, it determines the electric field near the channel core.

A rough estimation of the way in which dart leader charge is distributed along the channel can be obtained through a numerical procedure, using charge simulation methods, by treating the dart leader as a conducting channel connected to a spherical electrode with a radius of several kilometers, raised to the potential of a cloud, Larsson and Cooray [21]. Baum's model [1] of the dart leader charge distribution prior to the return stroke assumed that the corona envelope is in the shape of an inverted circular cone, a few tens of meters in size, at the bottom of the leader channel.

Contrary to Baum's conical model, electrostatic model of the dart leader (where it is modeled as a vertical conducting wire above ground, without the charge carrying corona envelope within a

---

[*] Corresponding author. Fax: +381 11 324 86 81.
E-mail address: cvetic_j@etf.rs (J. Cvetic).

http://dx.doi.org/10.1016/j.epsr.2016.10.035

Nomenclature

List of symbols

$E(t)$	Measured electric field
E_1, E_2	First and second electric field components, respectively, used as curve fits in the approximation of the measured electric field
E_m	Electric field magnitude
E_r^+	Breakdown electric field at the outer boundary of zone 1 in the corona sheath
E_r^-	Breakdown electric field at the outer boundary of zone 2 of the corona sheath
$E_{in\,R1}^+, E_{in\,R1}^-$	Electric field inside zone 1 due to positive and negative charges in zone 1, respectively
$E_{out\,R1}^+, E_{out\,R1}^-$	Electric field outside zone 1 due to positive and negative charges in zone1, respectively
$E_{R1,\,R2}^-$	Electric field inside zone 2 due to negative charge in zone 2
$E_{out\,R2}^-$	Electric field outside zone 2 due to negative charge in zone 2
E_{tr}	Electric field due to transition line charge along the channel core
f^+	Total channel charging function
f_0^+	Channel charging function without the influence of transition charge
f_{ad}^+	Channel charging function due to the influence of transition charge
$i_0(t)$	Channel-base current
i_{01}, i_{02}	First and second current components, respectively, used as curve fits in the approximation of the measured channel-base field
$i_{0/\mathrm{d}}, i_{0/\mathrm{u}}$	Downward and upward components of the current at the channel base, respectively
I_m	Channel-base current magnitude
k_1, k_2	Decay constants of the ground reflection coefficients, corresponding to first and second channel-base current components, respectively
$v* = vc/(v+c)$	Reduced return stroke speed, c is the speed of light
n_C	Current steepness factor
n_E	Electric field steepness factor
q_0^+	Absolute value of the initial line charge density along the channel
$q_{tr}(t)$	Transition line charge density
q_0^+	Absolute value of the initial line charge density in the channel at the height of the measurement
q_{tr}	Transition line charge density
R_1	Outer radius of zone 1
R_2	Outer radius of zone 2
R_c	Radius of the channel core
R_0	Radial distance from the channel core to the reference point on the ground
U_{C0}	Potential difference between the channel core and the reference point on the ground
$u = t - z/v$	Generalized time of discharge, t is the time from the onset of the return stroke, z is the altitude of the lightning channel, v is the return stroke speed
$\Gamma = i_{0/\mathrm{u}}/i_{0/\mathrm{d}}$	Ground reflection coefficient at the striking point
Γ_{01}, Γ_{02}	Initial values of ground reflection coefficients, corresponding to first and second channel-base current components, respectively
ρ_0^-	Initial (leader) negative space charge density of the corona sheath
ρ_1^-	Negative space charge density in zone 1 of the corona sheath
ρ_2^-	Negative space charge density in zone 2 of the corona sheath
ρ_1^+	Positive space charge density in zone 1 of the corona sheath
τ_{C1}, τ_{C2}	Time discharge constants, determining the leading and the trailing edge of the channel-base current, respectively
τ_d	Charge diffusion constant in zone 2
τ_{E1}, τ_{E2}	Discharge time constants, determining the leading and the trailing edge of the electric field, respectively

certain diameter) predicts that if the electric field below the cloud is uniform, charge density per unit length of the dart leader model should increase linearly downwards, except in the last few tens of meters near the ground. Due to the influence of the ground (its influence is modeled by an image charge of opposite sign), the charge in the last few tens of meters increases almost exponentially toward the ground, Cooray et al. [6].

Unfortunately, no measurements are yet available to pinpoint the distribution of the dart leader charge along the entire channel. Charge per unit length in the dart leader channel located near the ground can be estimated from electric field changes produced by dart leaders within about 200 m, Crawford et al. [7]. Results obtained in this manner indicate that the average charge per unit length close to the ground has a strong linear correlation to the peak current of the ensuing return stroke, Rakov [36].

From a theoretical perspective, the physical picture during the dart leader phase should be as follows: charge deposited on a thin lightning channel core (away from the leader tip) creates a radial electric field which exceeds the breakdown value and pushes the charge away from the core. As a result, the leader channel consists of a thin core, surrounded by a radially formed corona sheath expanding outward to the point where the radial electric field is lower than the breakdown value, Rakov and Uman [37]. Due to the great velocity of the dart leader, calculation of its line charge density based on the quasi-stationary approach does not provide correct results. However, radial charge density distribution inside the corona envelope of a dart leader prior to the return stroke still remains unknown. Generally, this distribution is assumed to be more or less similar to the radial charge distribution formed in a corona discharge for a coaxial geometry in laboratory, Cooray [5].

First measurements that provided reliable results regarding the charge per unit length in a dart leader close to the ground were performed by Miki et al. [29]. Based on those measurements, several corona sheath models have been developed. The model with constant space charge density, Maslowski and Rakov [26], Maslowski et al. [27] and the model with constant electric field, Cvetic et al. [9], yield similar results with respect to the dynamics of charge neutralization inside the corona sheath.

New results and details of measurements presented in Ref. [29] were later published by Maslowski et al. [28], providing new insights and explanations of the corona discharge during the return stroke stage. They also demonstrated the existence of a positive overcompensated electric field in more than two thirds of measured field waveforms. These field overshoots are interpreted in Ref. [28] as the expansion of zone 1 of the corona sheath, with net positive charge at the position of an electric field sensor. From the TL-type model's point of view, the return stroke process in a negative lightning can be seen as a positive outward radial current, injected from the core to the sheath. Since this current deposits