Influence of Return Stroke Speed and Leader Line Charge Density on Lightning Corona Sheath Dynamics

***Grzegorz Maslowski*[1] *and Vladimir A. Rakov*[2]**

[1]Department of Electrical and Computer Engineering, Rzeszow University of Technology, Poland
maslowski@prz.edu.pl

[2]Department of Electrical and Computer Engineering, University of Florida, Gainesville, USA
rakov@ece.ufl.edu

Abstract

Positive transferred charge inside the lightning channel core during the return-stroke stage dominates the total charge when the speed of the return stroke current wave is relatively low and negative leader line charge density is less than typical values inferred from field measurements. As a result, the positive charge inside the channel during the return-stroke stage can be temporarily greater than the negative charge deposited by the preceding leader. This may explain significant positive overshoots in radial electric fields measured close to the lightning attachment point at ground.

1. Introduction

In the "engineering" lightning return stroke models, a spatial and temporal distribution of the current and charge density along the channel are specified based on measured channel-base current, the speed of the upward-propagating front, and the channel luminosity profile. It enables one to achieve an agreement between the model-predicted electromagnetic fields and those observed during natural and rocket-and-wire triggered lightning. Further, this class of models is divided into two main types. The first type represents the so-called Lumped Current Source (LCS) type models and the second includes the Distributed Current Sources (DCS) type models. In the LCS type models, a current pulse is originating at ground level by the lumped current source and propagating from ground to cloud along the transmission line created by the leader. In DCS type models, the leader channel is treated as a charged transmission line, and the longitudinal return stroke current is formed when the corona sheath progressively collapses into the highly conducting return stroke channel. It means that the return stroke current in DCS type models is caused by potential wave that travels along the channel from ground to cloud. Both types of models are very effective in engineering practice dealing with calculations of induced effects. In this paper, new insights into dynamics of the lightning channel corona sheath are presented using the LCS type models and corona current concept adopted previously in DCS type models by *Cooray* [1], and later in LCS type models by *Maslowski and Rakov* [2,3].

It is expected that the 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 [4]. The corona sheath expands outward from the channel core until the radial electric field is less than the breakdown value, assumed to be about 2 MV/m by *Baum and Baker* [5] and 1 MV/m by *Kodali et al.* [6]. It is generally thought that the bulk of the leader charge is stored in the corona sheath whose radius is of the order of meters, while the highly conductive channel core (probably less than 0.5 cm in radius) carries essentially all the longitudinal current. The return-stroke current wave traverses the leader-channel core and serves to bring it to ground potential. As a result, the leader charge stored in the corona sheath collapses into the channel core and is transferred to ground.

Wagner and Hileman [7] were the first to suggest that the return stroke current is generated by the neutralization of the corona sheath on the time scale of the order of microseconds. *Rao and Bhattacharaya* [8] suggested another scenario. They assumed that the charge deposited inside the corona sheath is neutralized in some milliseconds, and that the continuing current is generated by this process. *Lin et al.* [9] assumed that only part of the return stroke current is generated by the neutralization of the corona sheath. *Heckman and Williams* [10] concluded based on the electrostatics principles and laboratory studies of corona that the longitudinal current due to radial charge motion is, in all phases of the lightning discharge, considerably smaller than observed lightning currents. On the other hand, assuming longitudinal extension of the channel, they calculated currents which were of the same order of magnitude as observed currents. Finally, they stated that longitudinal currents during all stages of a lightning flash are governed by longitudinal extension of the channel.

978-1-4244-6051-9/11/$26.00

Arima et al. [11] and *Cabrera and Cooray* [12] performed laboratory experiments to study what happens during leader to return stroke transition in natural lightning discharges. They investigated the mechanism of the neutralization of space charge clouds created in the laboratory when the potential of the high-voltage electrode was suddenly brought to ground potential. The experiments showed that the neutralization of the space charge cloud takes place through the action of streamer discharges moving out from the high-voltage electrode with speeds of the order of 10^5 m/s. Later, *Cooray* [13, 14, 15] suggested that the return stroke current is generated by the neutralization of the corona sheath by positive streamers from the core of the lightning return stroke. He assumed that these streamers propagate into the corona sheath with speeds of the order of 10^5 m/s. Similar mechanism has been considered by *Gorin* [16], who studied corona processes during the return stroke stage of long laboratory sparks.

Expansion of the luminous region of the lightning return stroke channel has been investigated by *Takagi et al.* [17] using High-Speed Line-Scanning Camera with framing rates exceeding 7800 per second. It means that time interval between frames was 128 µs. The average expansion velocity of the natural lightning corona sheath was about 10^5 m/s, that is, it was similar to that measured by *Cabrera and Cooray* [12] during laboratory experiments. Therefore, one can assume the discharges causing the luminous expansion in negative lightning are positive streamer discharges, and this process can be responsible for draining the charge which is deposited in the corona sheath by the preceding leader.

Maslowski and Rakov [2], based on electric field measurements (*Miki et al.* [18], *Maslowski et al.* [19]) and their consideration of the lightning corona sheath dynamics, inferred the existence of two zones around the lightning channel core during the return stroke stage. The inner zone (Zone 1) has net positive charge, and the outer zone (Zone 2) contains negative charge, with the net charge inside the entire corona sheath being equal to zero after the return stroke stage. Recently, two improved models for prediction of charge motion in the corona sheath are proposed and the radial expansion of Zone 1 and its shrinking was examined [20,21]. Both improved models include the motion of negative leader charge from the outer to the inner zone, towards the core and can be viewed as generalizations of the model proposed by *Maslowski and Rakov* [2]. They enable one to calculate the corona sheath radius and velocity of the expansion and shrinkage of the corona sheath which was of the order of 10^6 m/s at the beginning of the return stroke stage, and it was of the order of 10^4 m/s at the end of the return stroke process. Note that the average speed of the corona sheath expansion calculated theoretically by *Maslowski and Rakov* [2] was of the order of 10^5 m/s.

2. Dynamics of Lightning Channel Corona Sheath for Different Leader Line Charge Density and Return Stroke Speed

At the beginning of the return-stroke stage, the corona sheath expands outward from the channel core inside the leader corona sheath, and then, it shrinks to a nearly zero radius. In order to estimate the rate of expansion and shrinking of the corona sheath, we consider a closed, differential-length cylindrical surface (Gaussian cylinder) that is coaxial with and surrounding a segment of channel core whose length is dz'. According to Gauss' law,

$$\varepsilon_0 \oint_S \mathbf{E} \cdot d\mathbf{S} = Q, \tag{1}$$

where $\mathbf{E}$ is the electric field on closed surface S and Q is the total charge inside this surface. *Maslowski and Rakov* [2, 20] showed that Equation (1) can be rewritten in the equivalent form, as follows

$$2\pi r^{+}_{outer}\varepsilon_0 E^{+}_r = \rho_{tran} + \rho_{dep} + \rho_L\left(1 - e^{-(t-z'/v)/\tau_{\mathrm{CN}}}\right) + \frac{(2\pi r^{+}_{outer}\varepsilon_0 E^{-}_r)^2}{\rho_L} e^{-(t-z'/v)/\tau_{\mathrm{CN}}}. \tag{2}$$

where r^{+}_{outer} is the outer radius of the inner zone of corona sheath (Zone 1) containing positive charge deposited by the radial conduction current flowing during the return stroke stage, $E^{+}_r = 1.0$ MV/m (*Kodali et al.* [6]) is the constant radial electric field on the lateral surface of radius r^{+}_{outer}. The total charge Q enclosed by S consists of the negative charge Q^{-} deposited by the preceding leader and the positive charge Q^{+} associated with the return stroke stage which can be specified using return-stroke models and represented as the sum of two components (*Thottappillil et al.* [22]) as follows

$$Q^{+} = \rho_{tran} dz' + \rho_{dep} dz', \tag{3}$$

The first term of (3) is the charge transferred upward through the channel segment, and the second term represents the deposited charge that is spent to neutralize the leader charge previously deposited in the corona sheath of this segment. Assuming a uniform radial distribution of the negative leader charge just before the return-stroke stage, one can show that Q^-, which is a portion of the total negative charge stored in the corona sheath, located within the radial extent, r_{out}^+, of positive charge Q^+, can be expressed for $t \geq z'/v$ as

$$Q^- = Q_1^- + Q_2^- = k\rho_L dz' + \left(\rho_L - k\rho_L\right)\left(1 - e^{-(t - z'/v)/\tau_{\mathrm{CN}}}\right)dz', \tag{4}$$

where $k = (r_{outer}^+ / r_{outer}^-)^2$, r_{outer}^- is the radial extent of the negative leader corona sheath, and $Q_1^- = k\rho_L dz'$ is the negative leader charge deposited within Zone 1 just before the return-stroke stage, Q_2^- is the negative charge that penetrates Zone 1 from Zone 2, and τ_{CN} is the decay time constant describing reduction of negative charge deposited within Zone 2, and, hence, the rate of motion of the negative charge from Zone 2 to Zone 1. According to Appendix B of *Maslowski and Rakov* [2], Q_1^- can be expressed as

$$Q_1^- = (2\pi\varepsilon_0 r_{outer}^+ E_r^-)^2 dz' / \rho_L, \tag{5}$$

where E_r^- is the negative breakdown electric field which is assumed to be greater (in absolute value) than E_r^+ and equal to 1.5 MV/m (*Kodali et al.*, [6]), and ρ_L is the negative charge density per unit channel length prior to the return stroke stage. Note that we assume $r_{outer}^+ < r_{outer}^-$.

The radius of Zone 1, r_{outer}^+, is a solution of quadratic equation (2) which reduces to (20) of *Maslowski and Rakov* [2] for $\tau_{\mathrm{CN}} \rightarrow \infty$, in which case negative charge from Zone 2 does not penetrate Zone 1. The corona-sheath model enables one to predict both the radial expansion of Zone 1 and its shrinkage to a nearly zero radius, once the decay time constant τ_{CN} is specified.

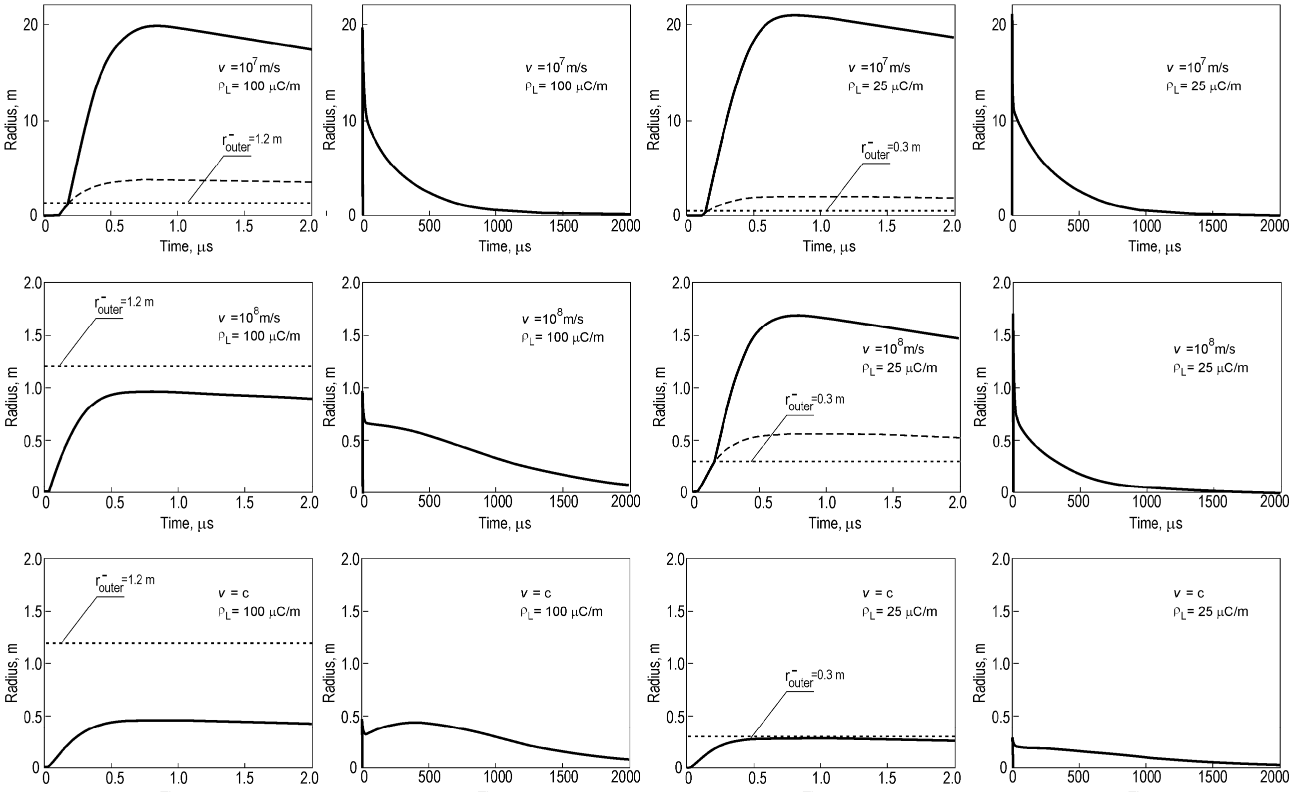

Fig. 1. Comparison of radius r_{outer}^+ of Zone 1 versus time at a height of 1 m for three return stroke speeds and two different leader line charge density values, $\rho_L = 100$ μC/m (typical value for a fully-developed dart leader corona sheath, *Kodali et al.* [6]) and $\rho_L = 25$ μC/m (expected at the channel base, due to insufficient time for corona expansion). Dashed line represents r_{outer}^+ according to the model described by (2) which is not valid for $r_{outer}^+ > r_{outer}^-$.

The model described by (2) has been tested in [2, 20, 21] for $k < 1$, that is, at $r^{+}_{outer} < r^{-}_{outer}$. If the radius of the zone with net positive charge will be temporarily equal or greater than the radial extent of the negative leader corona sheath $r^{+}_{outer} \geq r^{-}_{outer}$ (e.g. at low return stroke speed or very small line charge density), then the radius of the zone with net positive charge can be derived from the following linear equation

$$r^{+}_{outer} = (\rho_{tran} + \rho_{dep} + \rho_{L}) \,/\, 2\pi\varepsilon_{0} E^{+}_{r} \tag{6}$$

It means that the model described by (2) is still valid, but the parameter k should be defined as

$$k = \begin{cases} (r^{+}_{outer} \,/\, r^{-}_{outer})^{2} & r^{+}_{outer} < r^{-}_{outer} \\ 1 & r^{+}_{outer} \geq r^{-}_{outer} \end{cases} \tag{7}$$

Significant positive overshoots of radial electric fields can be expected at $r^{+}_{outer} > r^{-}_{outer}$ when the positive charge during the return-stroke stage is temporarily greater than the negative charge deposited by the preceding leader.

Comparison of radius r^{+}_{outer} of Zone 1 versus time at a height of 1 m for three return stroke speeds and two different leader line charge density values is shown in Fig. 1. Note that the dashed line represents r^{+}_{outer} according to the model specified by (2), which is not valid for $r^{+}_{outer} > r^{-}_{outer}$.

3. Conclusion

The dynamics of lightning channel corona sheath development are influenced by return-stroke speed and leader charge per unit length. Positive transferred charge inside the lightning channel core during the return-stroke stage dominates the total charge when the speed of the return stroke current wave is relatively low and negative leader line charge density is less than typical values inferred from field measurements. As a result, the positive charge inside the channel during the return-stroke stage can be temporarily greater than the negative charge deposited by the preceding leader. This may explain significant positive overshoots in radial electric fields measured close to the lightning attachment point at ground.

4. References

[1] Cooray V.: On the concepts used in return stroke models applied in engineering practice. *IEEE Trans. EMC*, Vol. 45, 2003, 101–108.

[2] Maslowski G., Rakov V.A.: A study of the lightning channel corona sheath. *J. Geophys. Res.*, Vol. 111, doi:10.1029/2005 JD006858, 2006.

[3] Maslowski G., Rakov V.A.: Equivalency of lightning return stroke models employing lumped and distributed current sources, *IEEE Trans. EMC*, Feb. 2007, 123–133.

[4] Rakov V.A., Uman M.A.: *Lightning: Physics and Effects*. Cambridge University Press, Cambridge, UK, 2003.

[5] Baum C.E., Baker L.: Analytic return-stroke transmission-line model. Ed. R.L. Gardner, in *Lightning Electrom.*, New York, pp.17-40, 1990.

[6] Kodali V., Rakov V.A., Uman M.A., Rambo K.J., Schnetzer G.H., Schoene J., Jerauld J.: Triggered lightning properties inferred from measured currents and very close electric fields. *Atmospheric Research*, Vol. 75, pp. 335-376, 2005.

[7] Wagner C.F., Hileman A.R.: The lightning stroke (1). *AIEE Trans*., 77, 1958, 229–242

[8] Rao M., Bhattacharaya H.: Lateral corona currents from the return stroke channel and the slow field change after the return stroke in a lightning discharge. *J. Geophys. Res.*, Vol. 71, 1966, 2811-2814.

[9] Lin Y.T., Uman M.A., Standler R.B.: Lightning return stroke models. *J. Geophys. Res.* 85, 1980, 1571–1583.

[10] Heckman S.J., Williams E.R.: Corona envelopes and lightning currents. *J. Geophys. Res.*, Vol. 94, pp. 13287-13294, 1989.

[11] Arima I., Watanbe T., Takagi N., Kakihara M.: Experimental study of the corona current In lightning return stroke. *9th International Conference on Gas Discharge and their Application*. Venice, Italy, 1998.

[12] Cabrera V., Cooray V.: On the mechanism of space charge generation and neutralization in a coaxial cylindrical configuration. *J. Geophys. Res.*, Vol. 38, 1992, 187-196.

[13] Cooray V.: A model for positive return strokes. *9th International Conference on Electrostatics*, Ontario, 1995.

[14] Cooray V.: A model for subsequent return strokes. *J. Electrostat.*, 30, 1993, 343–354.

[15] Cooray V.: A model for negative first return strokes in lightning flashes. *Physica Scripta* 55, 1997, 119–128.

[16] Gorin, B.N.: Mathematical modeling of the lightning return stroke, *Elektrichestvo 4*, 1985, pp. 10-16.

[17] Takagi N., Wang D., Watanabe T., Arima I., Takeuchi T., Simizu M., Katuragi Y., Yokoya M., Kawashima Y.: Expansion of the luminous region of the lightning return stroke channel. *J. Geophys. Res*., 103, D12, 1998, 14131–14134.

[18] Miki, M., Rakov V.A., Rambo K.J., Schnetzer G.H., Uman M.A.: Electric fields near triggered lightning channels measured with Pockels sensors. *J. Geophys. Res*., vol. 107, pp. D11-D16, 2002.

[19] Maslowski G., Rakov V. A., Miki M.: Some inferences from radial electric fields measured inside the lightning-channel corona sheath, *IEEE Trans. EMC* doi 10.1109/TEMC.2011.2109063, in print.

[20] Maslowski G., Rakov V.A., Cvetic J., Miki M.: An improved model for prediction of the dynamics of lightning channel corona sheath. *20th Int. Zurich Symp. on Electromagnetic Compatibility*, Zurich, Switzerland, 2009.

[21] Maslowski G.: *Analysis and modeling of lightning discharges for overvoltage protection*. AGH University of Science and Technology Press, Poland, Krakow 2010, in Polish.

[22] Thottappillil R., Rakov V.A., Uman M.A.: Distribution of charge along the lightning channel: Relation to remote electric and magnetic fields and to return-stroke models. *J. Geophys. Res*., Vol. 102, pp. 6987-7006, 1997.