Parameters of Main Stage of Discharge between Artificial Charged Aerosol Cloud and Ground in Presence of Model Hydrometeor Arrays

D. S. Zhuravkova, A. G. Temnikov, O. S. Belova, L. L. Chernensky, T. K. Gerastenok, I. Y. Kalugina, N. Y. Lysov, A.V. Orlov

Abstract**—**Investigation of the discharges from the artificial charged water aerosol clouds in presence of the arrays of the model hydrometeors could help to receive the new data about the peculiarities of the return stroke formation between the thundercloud and the ground when the large volumes of the hail particles participate in the lightning discharge initiation and propagation stimulation. Artificial charged water aerosol clouds of the negative or positive polarity with the potential up to one million volts have been used. Hail has been simulated by the group of the conductive model hydrometeors of the different form. Parameters of the impulse current of the main stage of the discharge between the artificial positively and negatively charged water aerosol clouds and the ground in presence of the model hydrometeors array and of its corresponding electromagnetic radiation have been determined. It was established that the parameters of the array of the model hydrometeors influence on the parameters of the main stage of the discharge between the artificial thundercloud cell and the ground. The maximal values of the main stage current impulse parameters and the electromagnetic radiation registered by the plate antennas have been found for the array of the model hydrometeors of the cylinder revolution form for the negatively charged aerosol cloud and for the array of the hydrometeors of the plate rhombus form for the positively charged aerosol cloud, correspondingly. It was found that parameters of the main stage of the discharge between the artificial charged water aerosol cloud and the ground in presence of the model hydrometeor array of the different considered forms depend on the polarity of the artificial charged aerosol cloud. In average, for all forms of the investigated model hydrometeors arrays, the values of the amplitude and the current rise of the main stage impulse current and the amplitude of the corresponding electromagnetic radiation for the artificial charged aerosol cloud of the positive polarity were in 1.1-1.9 times higher than for the charged aerosol cloud of the negative polarity. Thus, the received results could indicate to the possible more important role of the big volumes of the large hail arrays in the thundercloud on the parameters of the return stroke for the positive lightning.

Keywords**—**Main stage of discharge, hydrometeor form, lightning parameters, negative and positive artificial charged aerosol cloud.

D. S. Zhuravkova, A.G. Temnikov, O.S. Belova, L.L. Chernensky, T.K. Gerastenok, I.Y. Kalugina, N.Y. Lysov, A.V. Orlov are with the Department of Electrophysics and High Voltage Technique, National Research University “Moscow Power Engineering Institute”, Moscow, Russia (corresponding author e-mail: ZhuravkovaDS@gmail.com).

The reported research has fulfilled due to the grant of the Russian Science Foundation (project No. 16-19-00160).

I. Introduction

ONE of the modern problems that is nowadays in the consideration in the physics of lightning and lightning protection is the understanding of the physical mechanisms of the lightning return stroke formation and the determination of its parameters [1]-[4]. Thundercloud “microstructure” (different parts of the thundercloud could contain of the large volumes of the charged hydrometeors of the different type and size) could significantly influence on the return stroke formation when it approaches the thundercloud boundaries [5]-[7]. Arrays of the large hydrometeors could influence on the processes of the cloud charge neutralization during return stroke stage and determine the possibility of the subsequent formation of the lightning discharge between the thundercloud and the ground. Moreover, such affection could be different for the negative and positive lightning [8]. Wide application of the lightning detection system for the determination of the return stroke parameters requires the correction of the applied algorithms due to the possible influence of the thundercloud hydrometeors as on the frequency characteristics of the electromagnetic radiation of the channel and cloud discharges as on the return stroke parameters [9]-[11].

Application of the artificial charged water aerosol clouds of the negative and positive polarity (artificial thunderstorm cells) opens the new possibilities in the physical simulation of the lightning return stroke between the thundercloud and the ground in the presence of the large hydrometeors arrays and its possible influence on the return stroke parameters.

II. Experimental Complex

Investigations of the parameters of the main stage of the discharge between the charged water aerosol clouds of the negative or positive polarity and the ground in the presence of the different model hydrometeor arrays have been fulfilled on the experimental complex described in [12], [13]. Single charged water aerosol cloud of the negative or positive polarity has been used in the presented investigation. Cloud had a volume of some cubic meters and has been situated at the height of the meter above the ground. During the experiments, potential of the charged cloud was (the outlet current of a charged aerosol generator of 110-120 μA) approximately one million volts. The maximal electric field strength near the bottom cloud boundary could achieve of the values of 16-18 kV/cm.

Model hydrometeors simulating the large hail particle have been produced from the conducted materials. Three forms of the model hydrometeors have been used in the experimental investigation: "volume model hydrometeor" (ellipsoid of revolution, cylinder), and "plate model hydrometeor" (rhombus). The longitudinal size of the model hydrometeors was in the range of 3.0-4.0 cm. Each model hydrometeor has been independently suspended in the gap using the dielectric strings. Group from four model hydrometeors has been used in experiments. Distance of the air gap between the neighboring model hydrometeors was approximately 2.5-3.0 cm. Common length of the hydrometeor array was 22-27 cm. Disposition of the model hydrometeor array in the gap "artificial charged water aerosol cloud of the negative or positive polarity - ground" has shown in Fig. 1.

Group of the model hydrometeors has been situated near the bottom boundary of the artificial charged aerosol cloud when the upper hydrometeor of the array could partly be inside the charged aerosol cloud.

A rod electrode (4 in Fig. 1) has been posed on the grounded plate to register and to analyze the parameters of the main stage of discharge in the gap "artificial charged water aerosol cloud of the negative or positive polarity - ground" in presence of the model hydrometeor array.

Three broadband plate antennas have been used for the registering of the electromagnetic radiation of the main stage of the discharge between the artificial charged aerosol cloud and the ground. First Antenna 1 has been posed near the rod electrode near the ground level. Second Antenna 2 has been posed on the height of the model hydrometeor array disposition at the distance of some meters. Third Antenna 3 has been posed at the distance of some meters from the rod electrode near the ground level.

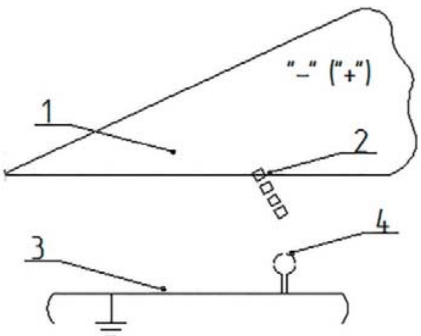

Fig. 1 Disposition of the hydrometeor array 2 and the rod electrode 4 in the gap "artificial charged aerosol cloud 1 – ground 3"

Common picture and dynamics of the return stroke formation on the model hydrometeor array of the different forms in the gap "artificial charged water aerosol cloud – ground" and the peculiarities of the preceding discharge processes have been registered using digital photocamera DMC-50 and fast programmable nine-frame CCD camera K011.

III. Experimental Results and Discussion

Experimental investigations of the parameters of the main stage of the discharge between the charged water aerosol clouds of the negative or positive polarity and the ground in the presence of the different model hydrometeor arrays have shown the significant influence of the charged cloud polarity and the model hydrometeor form on the return stroke parameters.

Characteristic picture of the main stage of the discharge in the gap "artificial negatively charged water aerosol cloud - ground" in the presence of the model hydrometeor array is shown in Fig. 2.

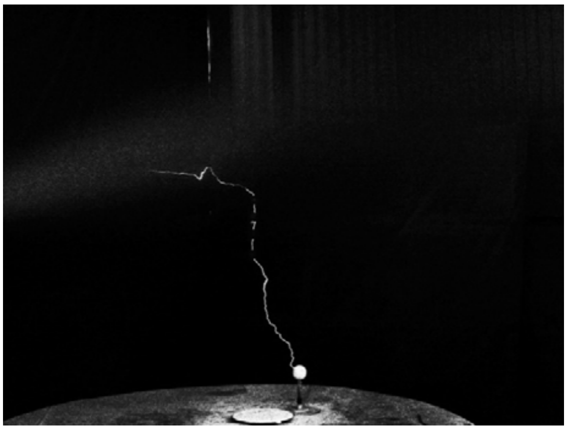

Fig. 2 Formation of the main stage of discharge in the gap "negatively charged aerosol cloud – ground" in the presence of the array of the hydrometeors of ellipsoid form

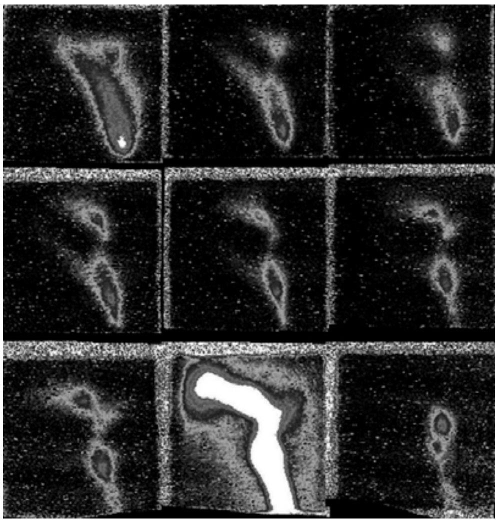

Fig. 3 Formation dynamics of the main stage of the discharge between the artificial thunderstorm cell of negative polarity and the ground in presence of the group of the model hydrometeors of cylinder form (frame size 85*85 cm, frame duration 2.5 μs, interval between frames 0.1 μs)

Typical dynamics of the final stage of the discharge from the artificial cloud of the negatively charged water aerosol, when the model hydrometeors participate in the channel discharge initiation and propagation, are shown in Fig. 3.

Characteristic oscillograms of the current of the main stage of discharge between the negatively charged aerosol cloud and the grounded rod electrode beneath it passing through the model hydrometeor array and of the corresponding electromagnetic radiation registered by the plate antennas are shown in Fig. 4.

Characteristic picture of the main stage of the discharge in the gap “artificial positively charged water aerosol cloud - ground” in the presence of the model hydrometeor array near the cloud boundaries is shown in Fig. 5.

Fig. 4 Oscillograms of the discharge current (curve 1, shunt 0.5 Ohm), of the signal registered by the plate antennas A1 (curve 2, shunt 0.5 Ohm), A2 (curve 3, shunt 0.5 Ohm), A3 (curve 4, shunt 0.5 Ohm) for the main stage of discharge in the gap “negatively charged aerosol cloud – ground” in the presence of the array of the hydrometeors of ellipsoid form

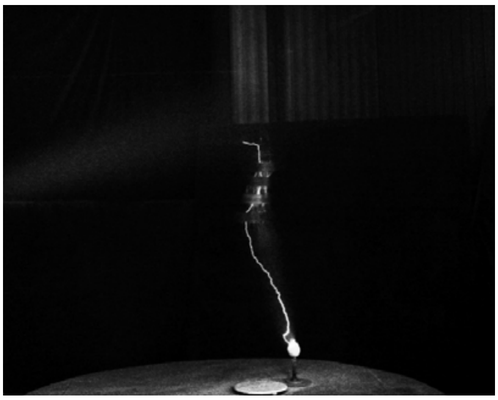

Fig. 5 Characteristic picture of the formation of the main stage of discharge in the gap “positively charged water aerosol cloud – ground” in the presence of the array of the model hydrometeors of cylinder form

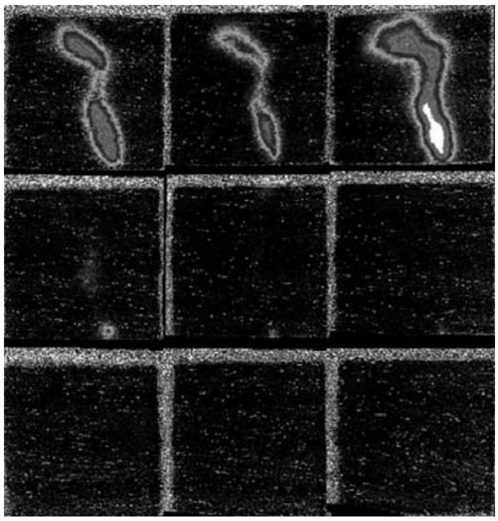

Fig. 6 Formation dynamics of the main stage of the discharge between the artificial thunderstorm cell of positive polarity and the ground in presence of the group of the model hydrometeors of ellipsoid form (frame size 85*85 cm, frame duration 2.0 µs, interval between frames 0.1 µs)

Typical dynamics of the formation of the main stage of the discharge between the artificial thunderstorm cell of positive polarity and the grounded rod on the plate beneath the charged cloud in presence of hydrometeors group are shown in Fig. 6.

Characteristic oscillograms of the impulses of the current and of the electromagnetic radiation registered by the plate antennas for the main stage of discharge in the gap “cloud of the positively charged water aerosol – ground” for the case when the discharge passes through the model hydrometeor array are shown in Fig. 7.

A series of experiments not less than thirty experimental approaches has been carried out for every configuration of the model hydrometeor array, the polarity of the artificial charged water aerosol cloud.

The following parameters have been determined and generalized: maximal current steepness a_m (a_{30} - measured on the levels of $0.3I_m$ and $0.9I_m$), current amplitude I_m, charge Q_m neutralized during the main stage of discharge, duration T_i of the main discharge current impulse, maximal amplitude of signal registered by the antennas A_m, duration of the signal registered by the antennas T_{ai}.

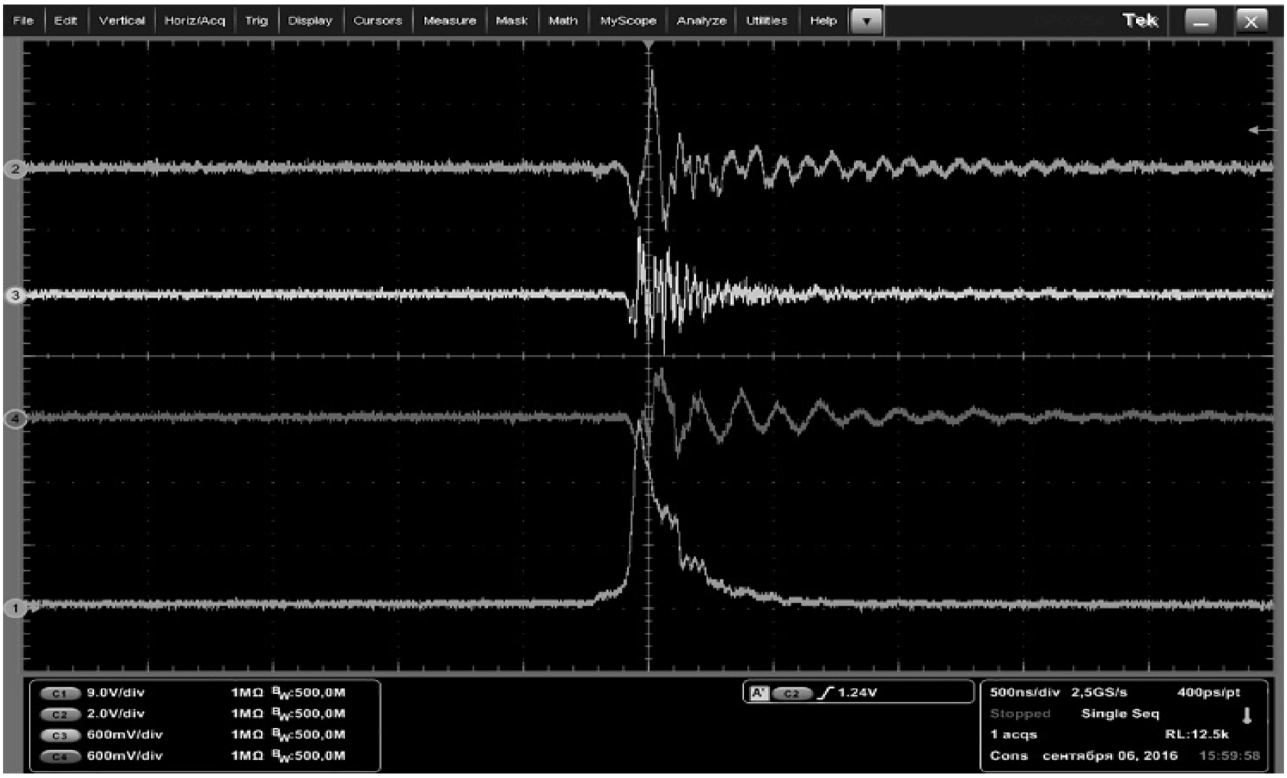

Fig. 7 Oscillograms of the impulse of the discharge current (curve 1, shunt 0.5 Ohm), of the signal registered by the plate antennas A1 (curve 2, shunt 0.5 Ohm), A2 (curve 3, shunt 0.5 Ohm), A3 (curve 4, shunt 0.5 Ohm) for the main stage of discharge in the gap “positively charged aerosol cloud – ground” in the presence of the array of the hydrometeors of ellipsoid form

Results of the influence of the model hydrometeor form on the parameters (average meaning of measured values and their range) of the impulse current of the main stage of the discharge in the gap “artificial charged aerosol cloud of the negative or positive polarity - ground” and the corresponding electromagnetic radiation of the discharge have been generalized in Tables I, III and Tables II, IV for the negatively and positively charged aerosol clouds correspondingly.

Analysis of Table I has shown that the array of hydrometeors of the cylinder revolution form has in average more high values of the current amplitude (in 1.3-1.8 times), maximal current steepness (in 1.1-1.7 times), and charge neutralized during the main stage of the discharge between the artificial charged water aerosol cloud of the negative polarity and the ground (in 1.35-1.65 times) than the model hydrometeors of other form. At the same time for the main stage of the discharge between the artificial charged water aerosol cloud of the positive polarity and the grounded electrode (Table II) more high values of the current amplitude (in 1.25-1.85 times) and the maximal current steepness (in 1.3-1.7 times) have been observed for the array of the model hydrometeor of the plate rhombus form.

It could be seen from the comparison of the experimental data received for the artificial charged water aerosol cloud of the negative or positive polarity that the parameters of the main stage of discharge in the presence of the array of model hydrometeors of the different forms in common have the higher values for the artificial positively charged water aerosol cloud than for the negative charged aerosol cloud. Such difference could exceed the 1.5-1.9 times. These results correlates with the data for the natural lightning where the return stroke for positive lightning could more powerful that the return stroke for negative lightning [1], [8], [14], [15]. Moreover, the large volumes of the hailstones presented in the thundercloud could strongly modify the parameters of the return stroke current [4], [7].

TABLE I
PARAMETERS OF CURRENT IMPULSE OF MAIN STAGE OF DISCHARGE BETWEEN ARTIFICIAL CHARGED WATER AEROSOL CLOUD OF NEGATIVE POLARITY AND GROUND IN PRESENCE OF ARRAY OF HYDROMETEORS OF DIFFERENT FORM

Parameters of the current impulse of the main stage	Form of Hydrometeors in Array		
	Ellipsoid of revolution	Cylinder of revolution	Plate rhombus
Current amplitude (A)	33.2 (5.1 - 117.1)	57.4 (34.7 - 124.2)	46.2 (17.6 - 182.4)
Maximal current steepness measured on the levels of $0.3I_m$ and $0.9I_m$ (A/ns)	0.49 (0.02 - 3.13)	0.83 (0.27 - 3.0)	0.75 (0.13 -4.56)
Charge being neutralized during the main stage (μC)	10.37 (1.44 - 17.22)	12.98 (8.4 - 18.97)	9.92 (5.69 - 21.69)
Duration of the main stage (μs)	2.12 (0.52 - 5.22)	0.97 (0.29 - 2.62)	0.7 (0.29 - 1.45)

(Average Meaning of Measured Values and their Range)

TABLE II
PARAMETERS OF CURRENT IMPULSE OF MAIN STAGE OF DISCHARGE BETWEEN ARTIFICIAL CHARGED WATER AEROSOL CLOUD OF POSITIVE POLARITY AND GROUND IN PRESENCE OF ARRAY OF HYDROMETEORS OF DIFFERENT FORM

Parameters of the current impulse of the main stage	Form of Hydrometeors in Array		
	Ellipsoid of revolution	Cylinder of revolution	Plate rhombus
Current amplitude (A)	69.3 (13.2 - 145.4)	102.0 (23.8 - 193.6)	120.8 (8.0 - 180.8)
Maximal current steepness measured on the levels of $0.3I_m$ and $0.9I_m$ (A/ns)	1.59 (0.15 - 6.46)	1.95 (0.22 - 12.95)	2.56 (0.11 - 5.87)
Charge being neutralized during the main stage (μC)	11.61 (1.96 - 17.52)	14.36 (1.17 - 24.51)	13.13 (0.79 - 22.04)
Duration of the main stage (μs)	1.22 (0.35 - 1.88)	0.47 (0.19 - 1.28)	0.32 (0.2 - 0.49)

(Average Meaning of Measured Values and their Range)

TABLE III
PARAMETERS OF ELECTROMAGNETIC RADIATION OF MAIN STAGE OF DISCHARGE BETWEEN ARTIFICIAL CHARGED WATER AEROSOL CLOUD OF NEGATIVE POLARITY AND GROUND IN PRESENCE OF ARRAY OF HYDROMETEORS OF DIFFERENT FORM

Model hydrometeor form	Signal Amplitude (A)			Impulse Duration (μs)		
	Antenna 1	Antenna 2	Antenna 3	Antenna 1	Antenna 2	Antenna 3
Hydrometeor of ellipsoid revolution form	4.05 (1.39-7.36)	0.84 (0.31-1.38)	0.67 (0.31-1.18)	1.63 (1.12-2.12)	0.60 (0.15-1.27)	1.48 (0.81-2.40)
Hydrometeor of cylinder revolution form	5.30 (1.76-12.8)	1.25 (0.32-3.89)	0.96 (0.45-2.72)	1.80 (0.58-2.68)	0.51 (0.10-1.42)	1.60 (0.69-2.30)
Hydrometeor of plate rhombus form	5.56 (1.39-7.36)	1.37 (0.22-7.11)	0.65 (0.16-3.08)	0.85 (0.17-2.33)	0.44 (0.10-1.18)	1.17 (0.17-2.20)

(Average Meaning of Measured Values and their Range)

TABLE IV
PARAMETERS OF ELECTROMAGNETIC RADIATION OF MAIN STAGE OF DISCHARGE BETWEEN ARTIFICIAL CHARGED WATER AEROSOL CLOUD OF POSITIVE POLARITY AND GROUND IN PRESENCE OF ARRAY OF HYDROMETEORS OF DIFFERENT FORM

Model hydrometeor form	Signal Amplitude (A)			Impulse Duration (μs)		
	Antenna 1	Antenna 2	Antenna 3	Antenna 1	Antenna 2	Antenna 3
Hydrometeor of ellipsoid revolution form	4.09 (0.54-14.6)	1.46 (0.19-4.08)	0.99 (0.11-4.12)	1.13 (0.23-2.28)	0.77 (0.24-1.87)	1.04 (0.40-1.99)
Hydrometeor of cylinder revolution form	7.87 (2.40-23.0)	2.60 (0.56-8.13)	1.88 (0.64-4.93)	1.32 (0.75-1.97)	0.54 (0.30-1.02)	0.97 (0.25-1.46)
Hydrometeor of plate rhombus form	14.6 (0.39-29.5)	4.59 (0.39-7.11)	2.42 (0.28-5.32)	1.23 (0.12-2.56)	0.73 (0.28-0.98)	1.64 (0.88-2.52)

(Average Meaning of Measured Values and their Range)

Analysis of Tables III and IV has shown that the electromagnetic radiation from the main stage of the discharge has been high (up to some times) for the artificial charged water aerosol clouds of the positive polarity that for the clouds of the negative polarity for all considered forms of hydrometeors. It is necessary to take such results into account in the lightning detection system operation when they analyze the registered signals and determines the proposed parameters of the return stroke [4], [10], [11], [16].

IV. CONCLUSION

Influence of the arrays of the model hydrometeor of the different forms on the parameters of the main stage of the discharge between the artificial positively and negatively charged water aerosol clouds and the ground has been established.

It was established that the array of the model hydrometeors of the cylinder form gives the maximal values (up to some times) of the parameters of the main stage of the discharge between the negatively charged cloud and the ground. Analogues influence has been found for the positively charged water aerosol cloud and the model hydrometeors of the rhombus form.

It was found that parameters of the main stage of the discharge and of the corresponding electromagnetic radiation are high for the positively charged cloud than for negative one for all investigated forms of the model hydrometeors. Such result could be useful for clarification of the return stroke parameters especially for powerful thunderstorms with the prevailing of the positive lightnings. Received results could be used and for the lightning detection system improvement: for correct separation of the cloud and channel lightning discharges and modification of algorithms of the data (signals registered by the antennas) processing.

References

[1] V. A. Rakov, M. A. Uman, *Lightning: physics and effects.* Cambridge University Press, Boca Raton, 2003.

[2] V. A. Rakov, F. Rachidi, “Overview of recent progress in lightning research and lightning protection,” *IEEE Transact. On Electromagnetic Compatibility*, vol. 51, no. 3, pp. 428-442, 2009.

[3] J. R. Dwyer, V. A. Uman, “The physics of lightning,” *Phys. Rep.*, vol. 534, pp. 147-241, 2014.

[4] *Lightning Parameters for Engineering Applications.* TB 549, CIGRE, Working Group C4.407, 2013, 118 p.

[5] M. Stolzenburg, T. C. Marshall, “Charge structure and dynamics in thunderstorms,” *Space Science Reviews*, vol. 137, 2008, DOI: 10.1007/s112214-008-9338-z.

[6] F. G. Zoghzoghy, M. B. Cohen, R. K. Said, S. S. Basilico, R. J. Blakeslee, and U. S. Inan, “Lightning activity following the return stroke,” *J. of Geophys. Res.: Atmospheres*, 2014, doi: 10.1002/2014JD021738.

[7] N. Pineda, T. Rigo, J. Montanyà, O. A. van der Velde, “Charge structure analysis of a severe hailstorm with predominantly positive cloud-to-ground lightning,” *Atmos. Res.*, vol. 178–179, pp. 31–44, 2016.

[8] V. A. Rakov, “Comparison of positive and negative lightning”, *in 1998 Intern. Lightning Detection Conference*, Tucson, Arizona, USA.

[9] *Lightning: Principles, Instruments and Applications. Review of Modern Lightning Research.* Eds.: H.D. Betz, U. Schumann, P. Laroche. Springer, 2009.

[10] V. A. Rakov, “Electromagnetic Methods of Lightning Detection,” *Surveys in Geophysics (Springer)*, vol. 34, no. 4, 2013, DOI 10.1007/s10712-013-9251-1.

[11] A. Nag, M. J. Murphy, W. Schulz, K. L. Cummins, “Lightning location systems: Insights on characteristics and validation technique,” *Earth and Space Science,* AGU Publications, vol. 2, 2015, DOI: 10.1002/2014EA000051.

[12] A. G. Temnikov, A. V. Orlov, V. N. Bolotov, Y. V. Tkach, "Studies of the parameters of a spark discharge between an artificial charged water-aerosol cloud and the ground," *Tech. Phys.*, vol. 50, no. 7, pp. 868-875, 2005.

[13] A. G. Temnikov, “Using of artificial clouds of charged water aerosol for investigations of physics of lightning and lightning protection,” *IEEE Conference Publications: Lightning Protection (ICLP), 2012 International Conference on*, 6344279, 2012.

[14] “Lightning and Insulator Subcommittee of the T&D Committee. Parameters of Lightning Strokes: A Review”, *IEEE transactions on power delivery*, vol. 20, no. 1, pp. 346-358, 2005.

[15] E. M. Bazelyan, Y. P. Raizer, *Lightning Physics and Lightning Protection.* IoP Publishing, Bristol and New York, 2000.

[16] K. L. Cummins and M. J. Murphy, “An overview of lightning locating systems: History, techniques, and uses, with an in techniques, and uses, with an in techniques, and uses, with an in techniques, and uses, with an in -depth look at the U.S. NLDN,” *Electromagnetic Compatibility, IEEE Transactions on*, vol. 51, no. 3, pp 499-518, 2009.