INTERNATIONAL CONFERENCE ON LIGHTNING PROTECTION
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Observation of lightning current in the soil by rocket-triggered lightning

Shinji Yasui, Tetsuya Takuwa, Daisuke Morishima
Dept. of Computer Science and Engineering
Nagoya Institute of Technology
Aichi, Japan
yasui.shinji@nitech.ac.jp

Shinichi Sumi, Takeshi Morimoto, Kenji Horii
Dept. of Electrical Engineering, Chubu University, Japan
Faculty of Science and Engineering, Kinki University, Japan
Emeritus professor, Nagoya University

Abstract—In recent years, there has been a significant increase in the damage to electrical and electronic devices owing to lightning surge-induced overvoltage/overcurrent, in Japan. In particular, the lightning surge overcurrent that flows through grounding lines can cause serious damage to electronic equipment. To understand the phenomenon of the lightning surge current propagation in the ground poles, it is important to understand the lightning current propagation in the soil. We have developed a detection circuit for determining the lightning current distribution in the soil and have measured the lightning current caused by rocket-triggered lightning in the soil. We have observed the lightning current in the soil owing to a negative precursor discharge at a depth of 0.1 m, 30 m from the triggered flash point.

Keywords-lightning current; soil; detection circuit; triggered-lightning

I. INTRODUCTION

The invasion routes of lightning surges into typical houses are classified as four main routes: (1) invasion via low-voltage lines, (2) invasion via telecommunication lines, (3) invasion via coaxial lines for CATVs or TV antennas, and (4) invasion via grounding. [1-3] Several protection measures have been proposed for mitigation against these lightning surges. [2, 3] However, the realization of practical measures for protecting electrical equipment from lightning surges via grounding poles is considerably difficult because the propagation phenomenon via the grounding lines has not been sufficiently understood.

When lightning strikes objects such as mobile phone towers, tall poles or tall trees, the potential close to the ground is considerably increased. In Japan, the TT grounding system has been adopted for reducing overvoltage in equipment and for electric shock protection. In this grounding system, each ground pole is constructed individually, depending on the functions, as the neutral lines and grounding lines of the enclosures of each equipment. In several cases, the ground pole for the neutral line at the substation equipment is separated from the structure in the building. Then, the lightning surge current flows from the ground lines by the potential difference between these ground poles. Even if a minor lightning surge current passes through the ground, equipment operating at lower voltages will fail. In particular, information devices operating using several voltages will be significantly damaged.

To comprehend the lightning surge propagation phenomenon through the ground poles, it is important to understand the propagation of lightning current in the soil. Several reports have focused on the voltage distribution in the soil, step voltages, and lightning currents in the soil near the lightning flash points, using high-voltage lightning impulse generators. [4, 5] In addition, investigations of the step voltage at the actual lightning flashes were conducted using triggered lightning flashes by means of the rocket-and-wire technique. [6]

We are interested in the behaviour of the lightning surge current in the soil in a wide area under a thundercloud at the location of the lightning strike under an existing high electric field on the ground, as shown in Fig. 1. As the ground electric field is high in a wide area under the thundercloud, the lightning current may flow over a wide area and not only at the lightning strike point. The purpose of our research is to determine the lightning current distribution in the soil for a large area during the actual lightning flash. In this research, we have observed the lightning currents in the soil using rocket-triggered lightning experiments. We have described the prototype detection circuits for the observation of the lightning current and the results of the lightning current observed in the soil, using rocket-triggered lightning experiments.

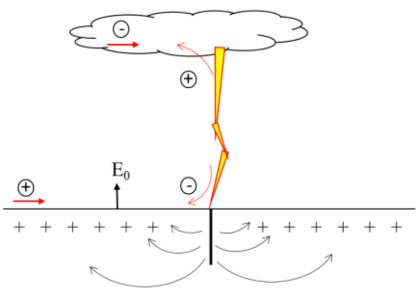


Fig. 1 Behaviour of the lightning current in the soil under an existing high electric field.

II. Estimation of the Lightning Current in the Soil

We estimate the lightning current behaviour in the soil under the conditions of a high electric field. When a thundercloud approaches, a high electric field appears on the surface of the ground in response to the charge in the thundercloud, as a result of which charges appear in the ground. This underground charge is subject to an upward force of attraction by the thundercloud charge. The upward force of attraction (F) of the ground charge, q (d), located at a depth between d – (d + Δd), exerted by the thundercloud charge is calculated. The source of the upward attractive force (F) is the underground electric field (E). The underground electric field, E (d), at a depth, d, decreases from the surface electric field (E_0) by the underground charge on the layers from the surface to a depth, d, and is expressed by equation (1).

$$\boldsymbol{E(d) = E_0 - \frac{1}{\varepsilon\varepsilon_0}\int_0^d q(d)\Delta d} \qquad (1)$$

The reduced amount of $E(d)$ per Δd layer is expressed as Eq. (2).

$$\boldsymbol{\Delta \mathrm{E}(\mathrm{d}) = -\frac{q(d)}{\varepsilon\varepsilon_0}\Delta d} \qquad (2)$$

This electric field becomes the force of attraction, F, applied to the charge on a layer at a depth, Δd.

$$\boldsymbol{F = \frac{\Delta E(d)}{\Delta d} = -q(d)/\varepsilon\varepsilon_0} \qquad (3)$$

On the other hand, the underground charge moves to neutralize the charge triggered by the lightning strike. Then, the downward repulsive force (F') acts on the underground charge causing a voltage drop owing to the earth's resistance. An underground lightning current, i (d), flows owing to the underground charge q (d), at a depth, d, moving at velocity, υ.

$$\boldsymbol{i(\mathrm{d}) = \upsilon \cdot q(d)} \qquad (4)$$

The voltage drop owing to this current is expressed by Eq. (5).

$$\boldsymbol{\rho \cdot i(\mathrm{d}) = \rho\upsilon \cdot q(d)} \qquad (5)$$

Because the voltage drop reduces with the depth, d, the downward force, F' that is proportional to the current change, (Δi)/Δd), with respect to the depth, is applied to q (d), i.e., i (d) for homogenizing the voltage drop.

$$\boldsymbol{F' = \Delta \mathrm{i}(\mathrm{d})/\Delta \mathrm{d} = \upsilon \cdot \Delta q(d)/\Delta d} \qquad (6)$$

When the underground current flows uniformly in the ground, the downward force, F', disappears because Δi/Δd = 0. However, the downward force will continue to work as long as the lightning current is reduced in accordance with the ground depth.

The condition of the equilibrium of the forces mentioned as F and F' is expressed by Eq. (7).

$$\boldsymbol{-\frac{q(d)}{\varepsilon\varepsilon_0} = \upsilon \cdot \Delta q(d)/\Delta d} \qquad (7)$$

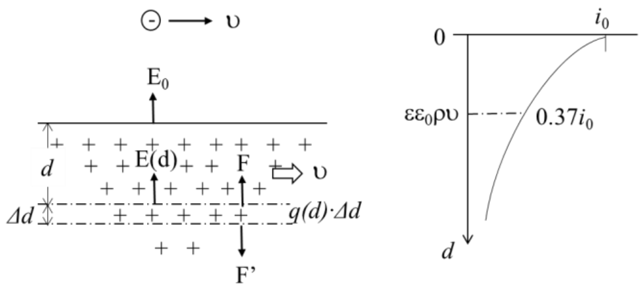
As $i = \upsilon \cdot q$, Eq. (7) is replaced by Eq. (8).

$$\boldsymbol{-\frac{i(d)}{\varepsilon\varepsilon_0} = \upsilon \cdot \Delta i(d)/\Delta d} \qquad (8)$$

By integrating Eq. (8), the underground current is obtained by Eq. (9).

$$\boldsymbol{i(d) = j_0 \exp(-\frac{d}{\varepsilon\varepsilon_0 v})} \qquad (9)$$

The underground current, i(d), decreases exponentially with the depth, d. Figure 2 (a) shows the relationship diagram of the depth, d, the underground charge, q(d), the underground current, i(d), the underground electric field, E(d), the upward attractive force, F, and the downward repulsive force, F'. Figure 2 (b) shows the change in the underground current, i (d), with the depth, d. The underground current is reduced to 1/2.73 of the surface current at a depth, $d = \varepsilon\varepsilon_0\upsilon$. When the relative dielectric constant of the ground is 'ε = 10', i.e., $\boldsymbol{\varepsilon\varepsilon_0 \fallingdotseq 10^{-10}}$, the ground resistivity is '$\rho = 10^3$–10^2' and the velocity of the underground charge is '$\upsilon = 10^7$–10^8'; then, the depth of the underground current becomes to $\boldsymbol{\varepsilon\varepsilon_0\rho v}$ = 0.1–1 m. The ground resistivity of the wetlands is further reduced; hence, the depth of the underground current lightning is also reduced. In the case of a lightning strike to the sea because the resistivity is 1/100 or less than the ground, the lightning current is allowed to flow to less than 1 cm from the surface of the sea.



(a) Forces on the underground charge (b) Distribution of the underground current

Fig. 2 Flow of charge and current underground

III. Observation Method

A. Evaluation of the lightning current in the experimental site

The method used to detect the lightning current in the soil involves determining the potential difference generated because of the lightning current flow between the electrodes that have been buried in the soil. In order to design the detection circuit, it is necessary to evaluate the potential difference generated across the earthed electrodes. Assuming that the lightning current flows uniformly in the soil in a radial direction up to a depth of 1 m, as shown in Fig. 3 (a), the lightning current value per unit area (*I*r) at a distance of 30 m from the lightning flash point is calculated using Eq. (10).

$$\boldsymbol{I_r = \frac{I}{2\pi r} = I/60\pi \cong 5.3 \times 10^{-3} \cdot I} \quad [\mathrm{A/m^2}] \qquad (10)$$

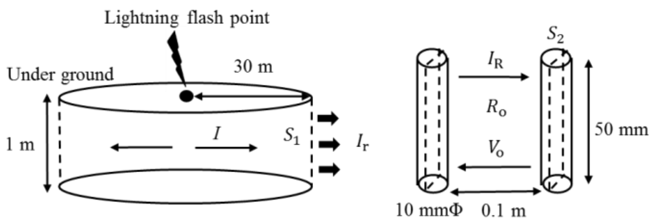
To detect the lightning current, we have designed electrodes with a cylindrical shape, having a diameter of 10 mm and a length of 50 mm, as shown in Fig. 3 (b). Therefore, the cross-sectional area of the electrode is 500 mm^2 and the lightning current that flows between the electrodes (I_R) is calculated using Eq. (11).

$$\boldsymbol{I_R = I_r \times S_2 = 26.5 \times 10^{7} \cdot I} \quad [\mathrm{A}] \qquad (11)$$

The ground resistance between the electrodes at a rocket-triggered lightning test field in Ishikawa Prefecture, Japan, was measured to be approximately 10 kΩ. In addition, as the capacitance between the electrodes is approximately 1.4 pF, the reactance for a steepness of approximately 1 MHz of the lightning current waveform becomes about 100 kΩ; this value is significantly larger than the ground resistance. Therefore, the potential difference across the electrodes caused by the lightning current flow can be calculated by Eq. (12) as follows:

$$\boldsymbol{V_0 = R_0 \times I_R = 265 \times 10^{-4} \cdot I} \quad [\mathrm{V}] \qquad (12)$$

The peak current values of the winter lightning in the Hokuriku areas of the Ishikawa Prefecture were observed to be mainly within a range of 2–20 kA. [6-9] Therefore, we have set the voltage range of the detection circuit to be 53–530 V.



(a) Lightning current model (b) Structure of the electrodes

Figure 3 Detection method for the lightning current in the soil

B. Measurement device

We have fabricated a measurement device for detecting a ground voltage of 50-500 V. The measurement device was operated with batteries because of the lack of power sources at the detection points of the lightning current at the site of the rocket-triggered lightning experiments. In addition, we have endeavoured to fabricate low-cost detection circuits because several detectors are required for measuring the current distribution in the soil. The detection circuit is constructed using resistors for dividing the input voltage, a trigger circuit, an AD converter, an SRAM circuit, a timer circuit, and a microcomputer board. The input impedance of the voltage divider resistors was set to the values greater than 3 MΩ that is significantly larger than the ground resistance of the electrodes. Figure 4 shows the resistors for the input voltage divider and the trigger circuit.

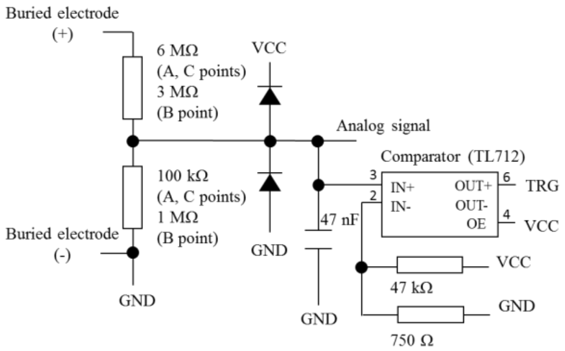


Fig. 4 Divider and trigger circuit

The specifications of the detection circuit include a sampling frequency of 1 MHz and a detection time of 64 kB (65.536 ms). This specification is determined based on the number of measurement results of the current waveform at the lightning point in rocket-triggered-lightning experiments. The trigger-level of the voltage was set at 40 mV and the pre-trigger and post-trigger times were set at 16.384 ms and 49.152 ms, respectively. We have used a through-hole type AD converter with an 8-bit resolution (AD7822BNZ, Analog Devices) and the detection data written into the SRAM were saved onto the micro SD card by a microcomputer (Arduino Uno R3). The writing time from the SRAM to the micro SD card is 30 min and the detector can be used for repetitive operations after writing the data, by programing the microcomputer. The detection rage of the voltage was set to 0–2.5 V so that a long-term operation with 9 V batteries is possible. Therefore, the detection sensitivity is 9.8 mV. A continuous operation time of 30 h by the measurement device is confirmed using five batteries of 9 V, each. A photograph of the measurement device is shown in Fig. 5. The detection circuit was housed in an aluminium case for preventing external electrostatic disturbance. In addition, the wiring to be connected to the electrode is also shielded for preventing external electromagnetic disturbance by twisting the wiring.

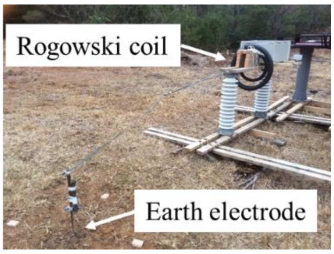
Figure 5 Measurement device for the lightning earth current

IV. ROCKET-TRIGGERED LIGHTNING EXPERIMENT

Rocket induced lightning experiments are best suited for observation of earth currents because they can trigger a lightning strike at the desired location. In Japan, a number of rocket-triggered lightning experiments for triggering lightning flashes in winter were successful. [6-9] The location for the rocket-triggered lightning experiments in this study is a camping field site in the Noto Peninsula, facing the Sea of Japan in the Ishikawa Prefecture. A photograph of the experimental field is shown in Fig. 6 (a). The circle in Fig. 6 (a) indicates the location of the rocket launch pad. A photograph of the rocket launch pad is displayed in Fig. 6 (b). A conductive piano wire is connected to the rocket and launched at a speed of 100 m/s. The rocket is connected using rubber and rope to prevent it from rising above an altitude of 200 m. The photograph of the grounding electrode is shown in Fig. 6 (c). The rod-type ground electrode with a diameter of 0.1 m is buried at a depth of 1 m.

(a) Overview

(b) Rocket launchers



(c) Earth electrode

Figure 6 Photograph of the area of the rocket-triggered lightning experiment

The schematic of the experimental area is illustrated in Fig. 7. The eastern-side touches the mountains and the western-side has a landfill that is a flat terrain. The area is surrounded by a forest and faces the Sea of Japan on the northwest. Lightning-current measurement devices were placed at three points that were 30 m (A), 100 m (B) to the west, and 30 m (C) to the east of the earth electrode at the rocket launcher pad. At each point, the electrodes as shown in Fig. 8, for detecting the lightning current were buried at intervals of 0.1 m, as shown in Fig. 9 (a). Our interest is to determine the change in the underground lightning current in the downward direction in the ground and the decay in the underground lightning current with respect to the horizontal distance from the lightning strike point. Therefore, the copper electrodes were buried at depths of 0.1, 0.3, and 1.0 m from the surface of the ground at each point. Figure 9 (b) displays the photograph of the measurement device. The detection circuit can measure only a single-pole voltage. Therefore, two devices were placed 30 m to the west of the lightning flash point for detecting both the polarities. In other places, the measurement devices were placed for measuring the positive voltage.

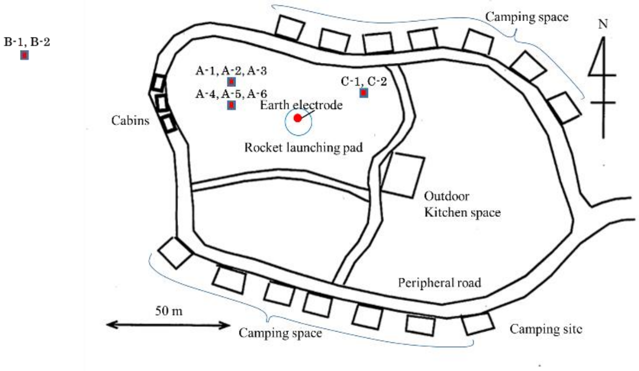
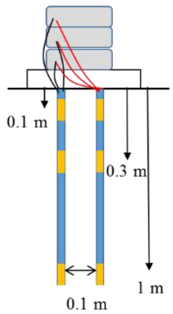


Figure 7 Area of the rocket-triggered lightning experiment

Figure 8 Electrodes for measurement of the lightning earth current



(a) Drawing of the buried electrodes (b) Photograph of the local site

Figure 9 Lightning earth current measurement method

At any point, the soil is approximately homogeneous for a depth of 1 m. The soil at point of A had been backfilled with homogeneous soil for a depth of several meters. The lightning current near the ground electrode at the induced lightning point will vary in the flow direction by this soil discharge; however, it can be expected to be diverted depending on the soil state to a distance from the lightning strike point. There is a mountain in the direction of the C, whereas, there is a swamp in the direction of the B point. Therefore, we have assumed that the underground lightning current flows in the direction of the A and B points more than in the direction of C point. The resistance division ratio of the input voltage of the detection circuit was set to a value that can be converted to a detectable voltage, from the potential difference estimated by the previous discussion and also the electromagnetic field analysis of the rocket-triggered lightning experimental site.

V. OBSERVATION OF THE LIGHTNING CURRENT IN THE SOIL

Rocket-triggered lightning experiments were conducted from the 27th of December 2015 to the 3rd of January 2016. The location of the thundercloud landing from the Sea of Japan has a tendency to shift to the south of the experimental field; therefore, the opportunities for a rocket-triggered lightning flash were less. Only one case of a rocket-triggered lightning flash was successful at 5:05 on the 31st of December.

The waveform of the corona current of the needle terminal at the measurement cabins is shown in Fig. 10. The photograph of the rocket-triggered lightning flash is displayed in Fig. 11. A negative corona current was observed at the time of the triggered-lightning flash; therefore, a negative lightning flash could be induced. As a result, we have obtained data from the measurement devices A4, A5, and A6 for the negative voltage. The measurement devices (A-1, -2, -3, B-1, -2, C-1, -2) for the detection of the positive voltage did not function. The lightning current at the flash point was assumed insignificant at less than 500 A because the measurement device using a Rogowski coil did not function at the lower detection limit. Therefore, we could not obtain the lightning current data at the flash point.

The data obtained from the measurement devices A4, A5, and A6 are displayed in Fig. 12 (a). The voltages of the devices at depths of 0.3 and 1.0 m from the ground surface included sharp pulses of approximately 1 μs that caused the trigger. However, the waveform resulting from the main lightning current was not included. On the other hand, the voltage of the device at a depth of 0.1 m included the lightning waveform at 53 ms, although the waveform at the trigger timing was not observed. The enlarged view of the waveform is shown in Fig. 12 (b). This waveform includes components obtained by amplifying the noise (about 10 mV) by the resistance division ratio. Analysing the waveform, the peak voltage is insignificant at a value of 2.4 V with a front time of 6 μs and a time-to-half-value of 150 μs. When the ground resistance between the electrodes is 10 kΩ, the peak value of the lightning current in the soil is also insignificant at 0.24 mA.

The characteristics of the negative winter-lightning-current waveforms previously observed had a considerable duration of hundreds of ms for the main current and were superimposed with several precursor discharges. [7-9] Therefore, the waveform that has been observed in this study is assumed to be the waveform of the earth current because of the influence of the precursor discharge at the negative lightning flash. We will continue with the investigation of the lightning current in the soil by improving the detector with respect to the sensitivity and time synchronization.

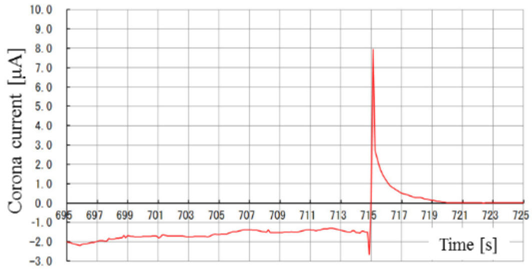
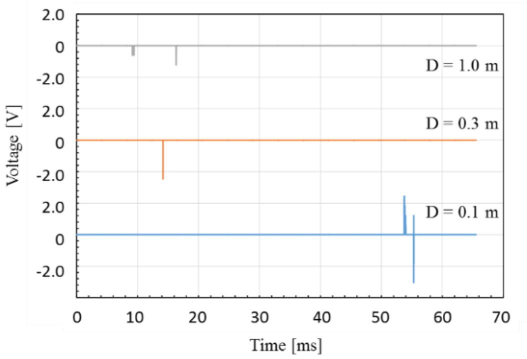
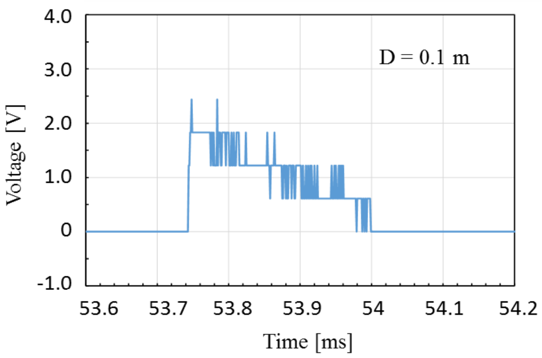


Figure 10 Corona current of the needle terminal at the measurement cabins

Figure 11 Photograph of the rocket-triggered lightning flash



(a) Detecting devices (A-4, A-5, A-6)



(b) Detecting device (A-6)

Figure 12 Lightning current grounding voltage

VI. CONCLUSIONS

In order to clarify the propagation behaviour of the earth current because of a lightning strike, the measurement of the lightning current in the soil was conducted by a rocket-triggered lightning experiment. For detecting the lightning current in the soil, we fabricated several lightning-current measurement devices operated by batteries. During this winter, a negative lightning strike was obtained using rocket-triggered lightning experiments. The lightning current in the soil was detected by electrodes placed at depths of 0.1 m and 30 m from the lightning flash point at the rocket launcher pad. From the analysis of the waveform, the detection current is assumed to be owing to the precursor discharge. In future, we will observe the earth current using an improved detector and will continue to clarify the behaviour of the lightning current in the soil.

ACKNOWLEDGMENT

The authors thank Mr. Kubouchi of Hokkei Industries Co., Ltd., for advice on the lightning current detection circuit.

REFERENCES

[1] *Lightning Protection for Electrical and Electronic Equipment – Supporting the Society of Information and Communication Technology*, Institute of Electrical Installation Engineers of Japan, 2011, pp. 147-171.

[2] A. Asakawa, "Lightning protection design for low voltage distribution systems," *IEEJ Trans. PE*, vol. 133, no. 7, (2013), pp. 575-578.

[3] H. Motoyama, "Experimental study on transient grounding resistance of various grounding electrodes," CRIEPI Report H04010, (2005).

[4] Subcommittee for power stations and substations, Study committee on lightning risk: Guide to lightning protection design of power stations, Substations and underground transmission lines, CRIEPI Report H06, (2011), pp. 417-426.

[5] J. Schoene, et al., "Lightning currents flowing in the soil and entering a test power distribution line via its grounding," *IEEE Trans. on Power Delivery*, vol. 24, no. 3, (2009), pp. 1095-1102.

[6] K. Nakamura, H. Sakurano, Y. Kubouchi, and T. Watanabe, "Statistical analysis of winter lightning current and measurement of step voltage in a wind power generation site," 31th Int. Conf. on Lightning Protection, Vienna, (2012), p 336.

[7] M. Yoda, T. Nakajima, I. Ikeda, and K. Nakamura, "Measurement of lightning current and emission in winter," 10th Int. Symp. on High Volt. Eng., vol. 5, (1997), pp. 21-24.

[8] K. Nakamura, et al., "Lightning discharge parameters by rocket triggered lightning to transmission line in winter," 10th Int. Symp. on High Volt. Eng., vol. 5, (1997), pp. 169-172.

[9] K. Nakamura, et al., "The lightning tests to electric power apparatuses using rocket triggering methods," 16th Int. Aerosp. and Ground Conf. on Lightning and Static Electricity, (1994), pp. 253-260.

[10] IEC 62305-1, "Protection against lightning – Part 1: General Principles," Ed. 1, 2010.