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Parameters Optimization of Impulse Generator Circuit for Generating First Short Stroke Lightning Current Waveform

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Abstract – This paper presents the parameters optimization technology for generating the first short stroke lightning current waveform(10/350 μs) which is necessary for the performance tests of components of lightning protection systems, as required under IEC 62305 and the newly amended IEC 62561. The circuit using the crowbar device specified in IEC 62305 was applied to generate the lightning current waveform. To find the proper parameters of the circuit is not easy because the circuit consists of two parts; circuit I, which relates to the front of current waveform, and circuit II, which relates to the tail. A simulation in PSpise was carried out to find main factors related to the front and tail of 10/350 μs. The lightning current generator was developed by utilizing the circuit parameters found in the simulation. In the result of experiments, new parameters of the circuits need to be changed because of the difference between the simulation and the experiment results. Using the iterative method, the optimized parameters of the circuits was determined. Also a multistage-type external coil and a damping resistor were proposed to make the efficiency of generation to enhance. According to the result in this paper, an optimized first short stroke lightning current waveform was obtained.

Keywords: First short stroke lightning current, Crowbar device, IEC 62305, IEC 62561

1. Introduction

Following the amendment to the IEC 62305 standard, IEC 62561, which deals with the requirements for the components of lightning protection systems, has also recently been amended. IEC 62305 describes the general requirements for lightning protection systems, whereas IEC 62561 presents the concrete requirements for the components of lightning protection systems [1]. These components in buildings are exposed to direct lightning strokes; consequently, their physical performance should correspond to the magnitude of the current of the direct strokes. IEC 62305 divides the magnitudes of the first short stroke lightning current into values that a range from 100 kA to 200 kA based on lightning protection levels [2]. In order to satisfy the requirements of the IEC 62305 standard, lightning protection systems should be composed of components that have the physical performances to be able to withstand the magnitude of direct lightning strokes.

Lightning protection systems are divided into external and internal lightning protection systems. External lightning protection systems are directly exposed to direct lightning strokes and up to 200 kA of lightning current may flow into these systems. With internal lightning protection systems, the lightning current that flows into the external lightning protection system is divided into different lightning protection systems. Therefore, only around 50 % of the magnitude of the first short stroke lightning current flows into the internal lightning protection system [3]. A lightning current waveform generator which is able to make a current up to 100 kA is necessary to test the performance of internal lightning protection systems. Generally, impulse current generators are composed of R, L, C circuits. However, large-capacity condensers are necessary to generate lightning current waveforms with large amounts of energy, such as first short stroke lightning. When the impulse generator is manufactured, large-capacity condensers are also subject to economic or spatial limitations. Therefore, the development of more efficient methods is urgently required.

Non-Korean impulse generator manufacturers have technologies to develop the generator that produces the first short stroke lightning current waveforms larger than 200 kA and to conduct performance tests for the components of lightning protection systems [4-7]. On the other hand, Korean manufacturers only recently perceived the necessity for developing the lightning current generator when the IEC 62305 standard was introduced as a domestic standard. The technology level of Korea for generating the lightning current waveform is much lower than that in advanced countries, and all of lightning current generators are imported from foreign countries. In Korea, lightning protection system related to the international standards have been introduced. The global market for lightning protection systems is also continuously expanding. Therefore, in-depth studies on first short stroke lightning current waveform generating technology are urgently

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required.

In this study, the technology of generating the first short stroke lightning current waveform using the crowbar device presented in the IEC 62305 standard is introduced. Methods to optimize the parameters of generator circuit are also proposed by carrying out simulations and experiments.

2. Operating Principle

Generally, impulse generators consisting of RLC circuits are frequently used in generating waveforms that have small energy outputs, such as the standard lightning impulse current of 8/20 µs. However, the first short stroke lightning current waveform of 10/350 µs involves large amounts of energy; consequently, a number of restrictions exist in the implementation of generators consisting of RLC circuits. One method that is used to address this problem is the crowbar devices, as presented in IEC 62305 [3]. Crowbar devices enable the generation of first short stroke lightning current waveforms even with a small capacity of condenser. Each crowbar device is composed of three spark gaps, two main electrodes, and one auxiliary electrode for operating the main electrodes. The voltage supplied to the auxiliary electrode electrically connects the two main electrodes to momentarily make the wave tail part of the circuit [8].

Fig. 1 shows the circuit diagram of an impulse current generator using crowbar devices. $Circuit\ 1$ generates oscillating current waveforms that determine the wave front time and peak value of the current. If the crowbar gap is operated at the point in time when the peak value of the oscillating current is reached, $S_{crowbar}$ will be closed, and $Circuit\ 2$ is to be made, which is the wave tail part of the circuit of the current waveform.

When the switch S in Fig. 1 is closed, current i_1 is as follows:

$$i_1 = \frac{U_{ch}}{\omega L} \cdot \sin(\omega t) \cdot e^{\frac{R}{2L}t} \tag{1}$$

where $R = R_{\text{int}} + R_{ext} + R_{load}$, $L = L_{\text{int}} + L_{ext} + L_{load}$ and

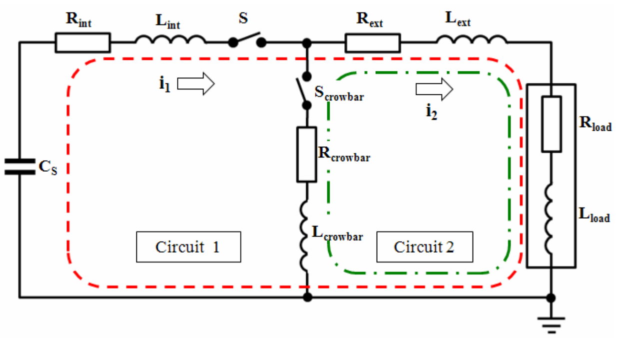


Fig. 1. Circuit diagram for an impulse current generator using crowbar devices

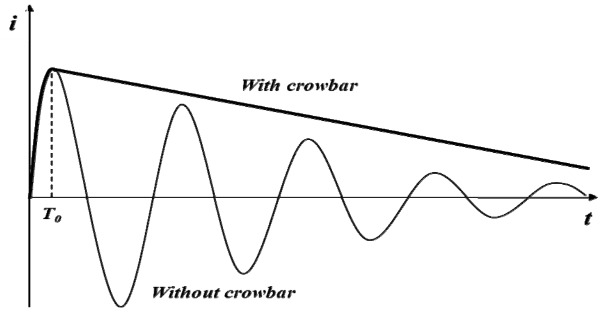


Fig. 2. Current waveforms with and without crowbar operation

U_{ch} are the charging voltages of the condenser C_s. Eq. (1) is an over-damped current that appears under the condition of $R < 2\sqrt{L/C_s}$. An over-damped current is used because it makes easy to generate the wave front part of the first short stroke lightning current waveform; therefore, current waveforms which have a short rising time and high peak values can be generated. If the crowbar gap ($S_{crowbar}$) is closed due to an external impulse voltage when the first current peak value appears in the over damped current waveforms, $Circuit\ 2$ will be made, and the current generated by the counter electromotive force accumulated in L_{ext} will flow. The current i_2 that flows in this case is as follows:

$$i_2 = U_{ch}\sqrt{\frac{C_s}{L}}e^{-\frac{R_c}{2L_{ext}}(\tau - T_0)} \tag{2}$$

where $R_c = R_{ext} + R_{load} + R_{crowbar}$ and T_0 is the crowbar gap operating time.

The two current waveforms made by the respective circuits, which are i_1 under Eqs. (1) and i_2 under Eq. (2), are combined to make the first short stroke lightning current waveform as shown in Fig. 2. The thin line represents an oscillating current waveform (i_1) generated before a trigger of the crowbar gap, which forms the wave front part of the current waveform. The thick line represents an exponentially decreasing current waveform (i_2) generated by a trigger of the crowbar gap, which becomes the wave tail part of the current waveform.

3. Simulation

In the first short stroke lightning current waveform, the wave front part and the wave tail part of the current waveform consist of respective circuits which are physically separated. However, the circuit parameters that contribute to the formation of the wave front part directly affect the wave tail part. The current (i_2) that forms the wave tail part is generated by the counter electromotive force accumulated in the external coil (L_{ext}). This counter electromotive force is determined by the current (i_1) that forms the wave front part.

The attenuation time constant τ is directly related to the wave tail time of the first short stroke lightning current waveform and is as follows:

$$\tau = \frac{L_{ext} + L_{load} + L_{crowbar}}{R_{ext} + R_{load} + R_{crowbar}} \tag{3}$$

Therefore, the wave tail time is determined only by the resistance and inductance composed of $Circuit\ 2$ in Fig. 1. Current i_1 under Eq. (2), which affects the counter electromotive force that is accumulated in the external inductance, is also affected by the capacity and charging voltage of the capacitor. The parameters included in circuits and the factors affecting the parameters are closely related to the determination of the wave front and wave tail parts of the current waveform. Therefore, in order to generate the first short stroke lightning current waveform with a peak value of 100 kA, an analysis of the relationship between the circuit parameters that constitute each circuit and the current waveform parameters should be carried out. The scope of application of the circuit parameters should be also determined to make the generator. Therefore, simulations were carried out with PSpice using the impulse current generator circuit shown in Fig. 1.

As with most the circuit parameter values, the values presented in IEC 62305-1 were selected. The capacitor and charging voltage of the condenser were set to 20 μF and 160 kV, respectively. The connection line between the condenser and the external coil is very short, usually not exceeding 1 m, so the internal resistance and inductance were set to 1 mΩ and 1 μH, respectively. The inductance and resistance of the crowbar device were assumed to be constant, and thus the resistance value of the external coil would not be affected by the change of the inductance. Simulations were carried out as a function of load resistance R_{load} and external inductance L_{ext}, which were the circuit parameters having the largest effect on the attenuation time constants.

Two types of load were used: (1) a ZnO varistor, which is a voltage limiting-type element, and (2) a spark gap, which is a voltage switching-type element. They were applied in accordance with the components of the surge protective device (SPD) for Class I. In case of the varistor, a series circuit which is composed of the inductance of the lead wire and bulk resistance (ρ =1~10 Ω · cm) was simulated, and the internal resistance at a time when the varistor is operated was set to 0.1 Ω [9]. It was assumed that a spark gap results in a state of short circuit when it comes into operation; thus, only the resistance and inductance of the lead wire were considered. When the inductance of the external inductor is set to 15 μH, the current waveforms simulated as a function of the type of load are shown in Fig. 3.

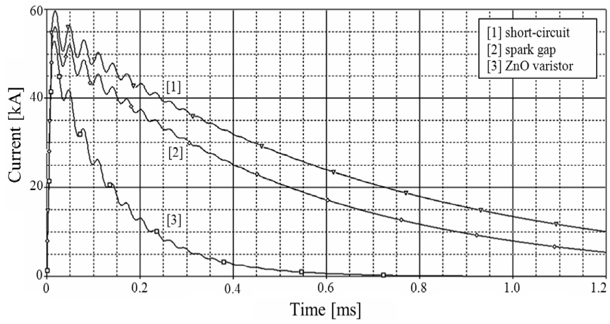


Fig. 3. Current waveforms by types of loads

In the case of a spark gap, approximately 56 kA of a 10/350 μs current waveform was generated and an oscillating phenomena appeared together with all the current waveforms after the current peak value. The oscillating waveform needs to be minimized, as it can shorten the lifespan of condenser when crowbar devices did not be triggered. As shown in Fig. 1, a damping resistor was added to $Circuit\ 1$ to minimize the oscillating waveform in the first short stroke lightning current waveform. This addition was made despite $Circuit\ 2$ affecting the wave tail part of the current. If the damping resistor is to be included in $Circuit\ 2$, the attenuation time constant shown in Eq. (3) would become smaller, resulting in the wave tail time of the current not being satisfied. Therefore, if the damping resistor is added to $Circuit\ 1$, the current waveform that forms the electromotive force of the external coil, which is to be the source of current i_2, will be changed. Also, the attenuation time constant of current i_1 will increase, and the oscillating current waveform will be attenuated faster. This current will appear in addition to current i_2, which exponentially decreases, and as a result, the oscillating part will be reduced in the first short stroke lightning current waveform. The simulation was performed as a function of the value of the damping resistance, and 100~150 mΩ was determined as an appropriate range of resistance.

In the case of a short circuit under the condition shown in Fig. 3, the wave tail time increased from at least 100 μs to 450 μs. In the case of a spark gap, the first short stroke lightning current waveform that had a current peak value of 56 kA and a wave tail time of 350 μs was satisfied. In the case of a varistor with the largest internal resistance, the wave tail time decreased to around 100 μs and the current peak value decreased to 53 kA. In cases where the load is a ZnO varistor, as in the given case, the wave tail time becomes very short. Therefore, the inductance of the external coil in Eq. (3) needs to be increased to satisfy the wave tail time of 350 μs. When the load is a short circuit, the simulation was performed while changing the inductance of the external coil from 10 to 25 μH, without changing the other circuit parameters; the results are shown in Fig. 4. In this case, a 125 mΩ damping resistor was added to minimize the oscillating phenomena after the

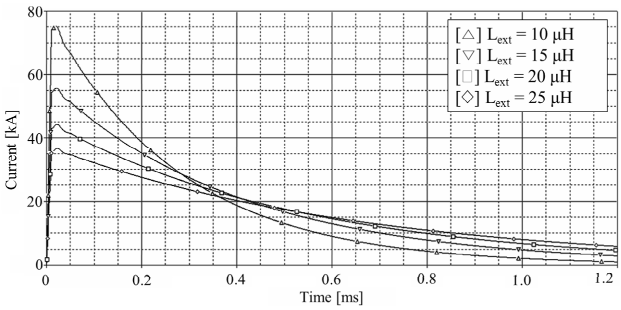
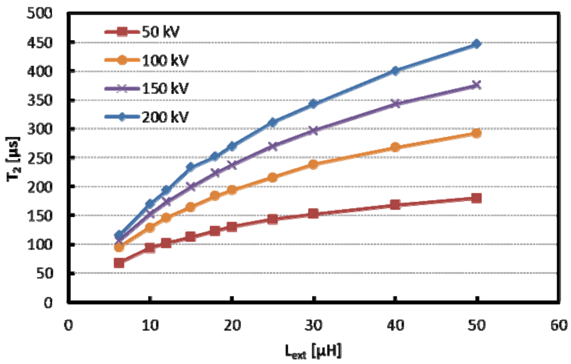
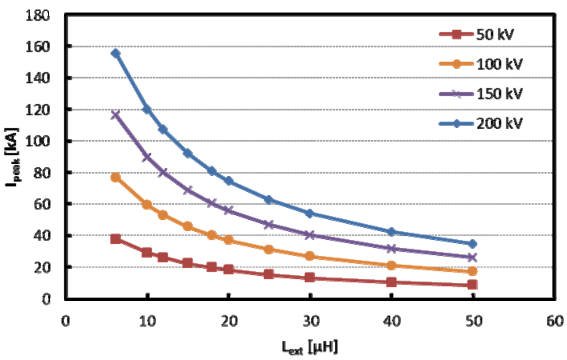


Fig. 4. Current waveforms in relation to changes in inductance



(a) Current wave tail time



(b) Current peak value

Fig. 5. Relationships between external inductance and current parameters under different charging voltages

current peak value.

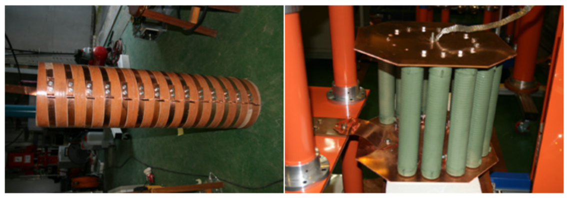
The wave tail time was around 200 and 452 μs when the inductance of the external coil is 10 and 25 μH, respectively. The simulation results in Fig. 4 show that as the inductance of the external coil increases, the wave tail time also increases. However, the peak value of the current is to be decreased because the impedance increased as a result of the rise in the inductance of the external coil. Therefore, it needs to determine the factors which are able to change the inductance of the external coil directly related to the wave tail time, while still controlling for the increases/decreases in the current peak value caused by changes in impedance. The purpose is to generate a desired magnitude of the first short stroke lightning current waveform. This goal can be achieved by changing the magnitude of the charging voltage and the capacitance of condenser. Generally, the magnitude of the capacitance is determined based on the values presented in IEC 62305 in relation to the energy values of the current waveform.

A simulation was performed while changing the charging voltage of the condenser when the capacitor of the condenser is 20 μF, and the results are shown in Fig. 5. Similar to the results in Fig. 4, Fig. 5(a) indicates that as the inductance increases, the wave tail time also increases. However, increasing the charging voltage of condenser rather than the inductance is a more effective method to be able to increase the wave tail time. In Fig. 5(b), the external coil inductance and the current peak value are inversely proportional. However, the current peak value exponentially decreases depending on the inductance; consequently, so changing the charging voltage of the condenser will cause smaller changes in the current peak value. Changing the charging voltage rather than the inductance of the external coil is also more efficient when the current waveform using a generator is generated.

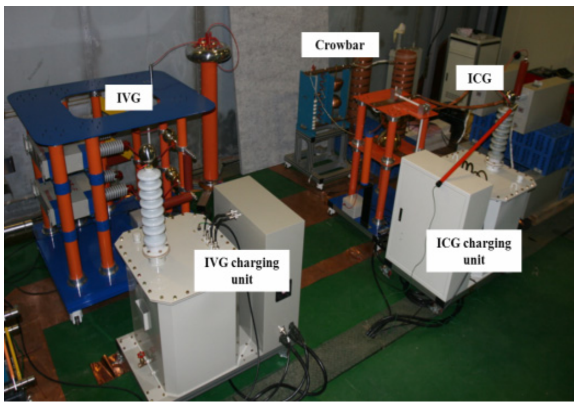
4. Generation and Optimization

A multistage-type coil which is possible to easily select the desired inductance of the external coil and a damping resistor with a capacity of 100 kA for the first short stroke lightning current were made as shown in Fig. 6(a).

A crowbar device, an impulse voltage generator for



(a) External coil and damping resistor



(b) First short stroke lightning current generator

Fig. 6. Components and generator

controlling the crowbar device, a peaking circuit for enhancing the operational reliability of the crowbar sphere gap, and a trigger sphere gap to serve as a switch to complete the first short stroke lightning current generator are shown in Fig. 6(b). The peaking circuit, which is composed of a small-capacity condenser and a sphere gap, generates current waveforms with having a short rising time and high peak values [10-11].

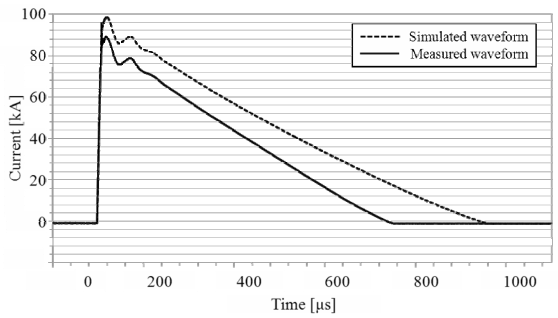
Using the first short stroke lightning current generator shown in Fig. 6, current waveforms were produced by utilizing the circuit parameters applied in the simulation. A capacitor with a capacitance of 10 μF was used to generate current up to 50 kA. Additionally, a capacitor with a 20 μF capacitance was used within a range of 50 kA to 100 kA. With the circuit parameters in the simulation being equally employed in the experiment, the waveforms of both the simulation and measurement results can be seen in Fig. 7(a).

As shown by the solid line in Fig. 7(a), the current peak value decreased by around 10 kA, and the wave tail time also decreased by around 50 μs. Consequently, this waveform does not meet with the requirement of 10/350 μs. This result was attributed to the losses in each circuit parameter. In particular, the electromotive force in the external coil becomes a major cause of heat loss, which is, in turn, produced by the resistance of the coil. The differences between the simulation and experiment results can be attributed to energy loss; thus, the circuit parameters need to be revised.

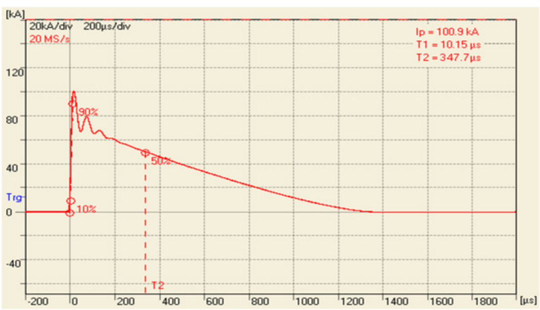
However, it is difficult to rapidly find the exact circuit parameters. Consequently, an iterative method was applied to find the optimized circuit parameters. The circuit parameters can be optimized by changing the charging voltage of the condenser and the inductance of the external coil. If a generated waveform satisfies the tolerance of a first short stroke lightning current, the values for both the charging voltage and the inductance are set to be the optimized circuit parameters. In the optimized current waveform shown in Fig. 7(b), the charging voltage and the inductance are 75 kV and 1.5 μH, respectively. The inductance of the external coil was calculated from Wheeler's formula. It was considered that the impedance of load should be ignored due to the short circuit. In addition, the resistance of the external coil is very small because there are only three turns in the coil.

In order to find the optimized circuit parameters across the wide range of current peak values, a lengthy iterative method was again carried out. When the charging voltage of the capacitor changes under the same conditions, the range of both the inductance and the charging voltage, which satisfies the tolerance of the first short stroke current waveform, is very narrow. Thus, it is very difficult to rapidly find the optimized circuit parameters for a required peak current. The results of iterative experiments are shown in Fig. 8.

The optimal circuit parameters were selected within a 10% tolerance range of the peak current. The charging voltage is proportional to the peak current. However, the inductance is inversely proportional to the peak current. When the peak current increases, the range for the charging

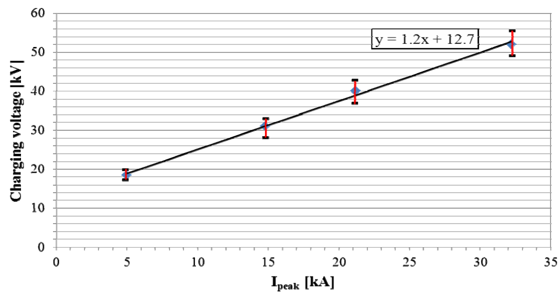


(a) Simulation and experimental results

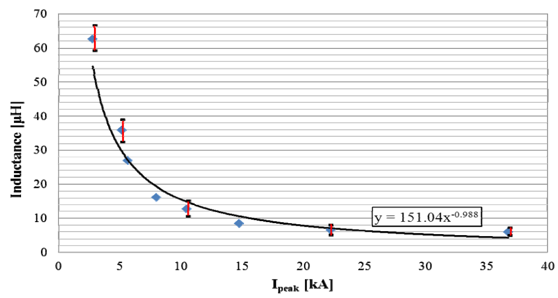


(b) Optimized current waveform

Fig. 7. First short stroke lightning current waveform



(a) Charging voltage



(b) Inductance

Fig. 8. Relationship between circuit parameters and peak current

voltage that satisfies the 10/350 μs tolerance is wide. Yet, when the peak current increases, the range for the inductance that satisfies the 10/350 μs tolerance is narrow. A perfect combination between the charging voltage and the inductance is necessary to generate the 10/350 μs current waveform which is desired. Using the results from this paper, a 10/350 μs current waveform within the tolerance limits of IEC 62305 can easily be generated.

5. Conclusion

This paper presented the technology to generate the first short stroke lightning current waveform which is necessary for the performance tests of lightning protection systems' components as required under IEC 62305, and the newly amended IEC 62561. Methods to optimize the current waveform were also discussed.

The first short stroke lightning current waveform generator using the crowbar device is possible to generate large lightning current even with small-capacity condensers. In this case, the first short stroke lightning current waveform is divided into two parts of circuits according to the operation of the crowbar device. The current waveform consists of one circuit related to the wave front part and the other circuit related to the wave tail part. The wave tail time of the current is substantially affected by changes in the resistance of load and external inductance value. A surge protection device used as an internal lightning protection system was applied to perform the simulation before developing the generator. The relationship between the resistance of the load and the current wave tail time, which is determined by the inductance of the external inductor, was analyzed so that the circuit parameters could be easily determined. A first short stroke lightning current waveform generator with a peaking circuit was made to enhance the reliability of the operation of crowbar devices. A multistage-type external coil was also made so that the inductance could easily be selected to generate the desired magnitude of the lightning current. The simulation results showed that oscillating phenomena appeared together with the first short stroke lightning current waveform at its wave tail part. A damping resistor was then developed and applied to minimize the generation of oscillating currents. With the generator using the circuit parameters obtained by the iterative method, an optimized first short stroke lightning current waveform was obtained.

Acknowledgements

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