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Design and Construction of an Impulse Current Generator for Lightning Strike Experiments

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Abstract—There has been a rising trend in using impulse current generators to investigate the lightning strike protection of materials including aluminum and composites in structures such as wind turbine blade and aircraft body. The focus of this research is to present an impulse current generator built in the High Voltage Lab at Mississippi State University. The generator is capable of producing component A and D of the natural lightning discharges in accordance with the Society of Automotive Engineers (SAE) standard, which is widely used in the aerospace industry. The generator can supply lightning impulse energy up to 400 kJ with the capability of producing impulse currents with magnitudes greater than 200 kA. The electrical circuit and physical components of an improved impulse current generator are described and several lightning strike waveforms with different amplitudes is presented for comparing with the standard waveform. The results of this study contribute to the fundamental understanding the functionality of the impulse current generators and present an impulse current generator developed at the High Voltage Lab of Mississippi State University.

Keywords—Impulse current generator, lightning, society of automotive engineers, capacitor.

I. Introduction

LIGHTENING occurs in any area and is dangerous to any equipment and object such as buildings, antenna, transmission lines, and airplanes. Lightning strike injects high current in the conductive parts of the objects in the current path that creates physical damage [1]. When lightning strikes the objects, the temperature of air channel and object goes up. Depending on the amplitude of the lightning current and electrical conductivity of the conductive materials, the lightning strike can cause serious physical damages such as melting and evaporation of materials [2]. Also, the electromagnetic wave creation due to the lightning current induces overvoltage and overcurrent in the cables and electronic components. Industries such as energy and aerospace are interested in simulating the lightning to increase the reliability and protection of the equipment and structures that are at risk of lightning strike. SAE ARP 5412 standard suggests the use of lightning waveform that resembles those of the natural lightning phenomena for lightning experiments. The standard lightning waveform consists of four components including A, B, C, and D which have different current amplitudes and duration. The standard lightning waveform recommended by SAE for lightning simulations is shown in Fig. 1.

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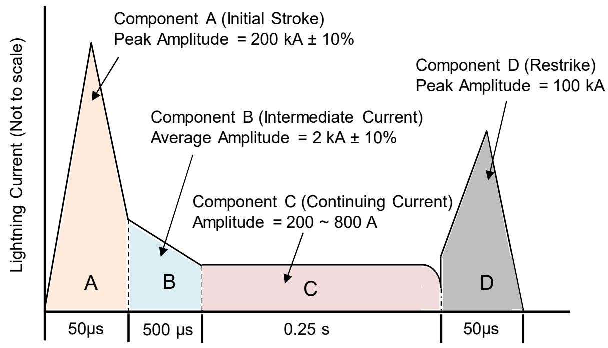

Fig. 1 Standard lightning waveform recommended by SAE [3]

To perform the lightning strike study, it is necessary to simulate at least one of the components from the standard. Impulse current generators are used to produce the lightning current in accordance with the SAE standard. A comprehensive study is necessary for constructing the impulse current generator with accuracy in accordance with the standard and the mathematical equations while providing high-level safety. There have been numerous research studies [2], [3] that investigate the lightning strike damages of materials, but the functionality of the impulse current generators used and their construction and design for generating the lightning current waveform have not been systematically reported. In this paper, the electrical circuit and physical components of a developed impulse current generator are described and several lightning strike waveforms with different amplitudes are presented.

II. Electrical Circuit of Impulse Current Generators

The principle of impulse current generator is same as series Resistor-Inductor-Capacitor (RLC) circuit as shown in Fig. 2 [4], [5]. The charged high voltage capacitors by DC source up to U0 volt discharge suddenly through the test sample. The inductance of circuit L includes the test circuit connection (could be adjustable), stray and test sample inductances. Also, the total resistance of circuit R consists of test circuit connection (could be adjustable) and test sample resistances.

By triggering the spark gap the stored energy in capacitor C discharges through the total L and R, therefore, the circuit's current I(t) is calculated by solving (1):

$$I'' + \frac{R}{L}I' + \frac{1}{LC}I = U_0 \qquad (1)$$

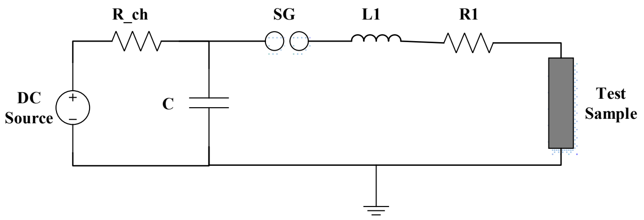

Fig. 2 Equivalent circuit of impulse current generator

Equation (1) is a second-order differential equation and its and its solution depends on the value of (2):

$$\beta = \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \tag{2}$$

Based on the test circuit parameters C, L and R, the β could be:

$$\beta \begin{cases} > 0 & \text{Over\_damping} \\ = 0 & \text{Ciritical\_damping} \\ < 0 & \text{Under\_damping} \end{cases}$$

The lightning waveform can have three waveshapes based on the β and is shown in Fig. 3.

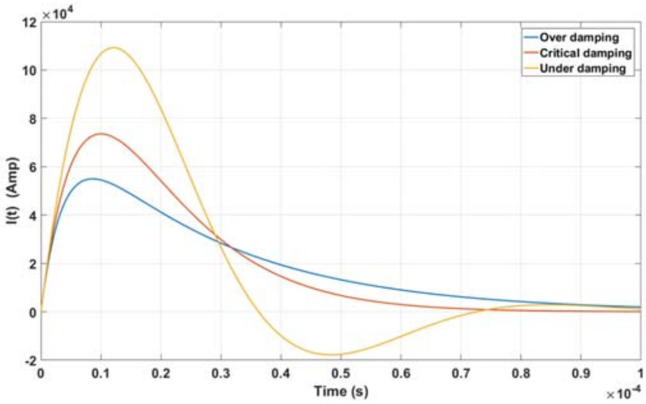

Fig. 3 Three different waveforms of impulse current [6], [7]

In overdamping condition $\beta > 0$, the I (t) is calculated by (3):

$$i_k(t) = \frac{U_0}{Z}\left(e^{\frac{R-Z}{2L}t} - e^{\frac{R+Z}{2L}t}\right) \tag{3}$$

The current waveform used for SAE standard is an over damping waveform with a double exponential driven equation as:

$$I(t) = I_{max}*(e^{-\alpha t}-e^{-\beta t}) \tag{4}$$

The electrical circuit of a conventional impulse current generator in the Mississippi State University – High Voltage Lab (MSU-HVL) is shown in Fig. 4. In this setup, the capacitors will be discharged by triggering the spark gap, and the discharged will be through the 1 ohm resistors to the test article.

When the capacitors are charged completely and the target voltage is obtained, the capacitor bank will be discharged by switching with a triggered gap that applies the voltage of the charged capacitors to the gap which is between the test article and the output electrode. The resulting electrical arc delivers the current stroke to the surface of the test article as it shown with red lines.

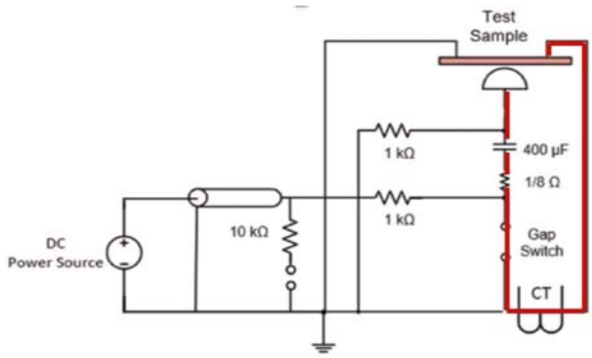

Fig. 4 Equivalent circuit of impulse current generator [3]

Fig. 4 is a RLC circuit as explained in Fig. 2. The red line shows the discharge circuit and the inductance of the circuit is the inductance of the conductors. The two 1 kΩ resistors are the charging and discharge resistors. Also, a 10 kΩ resistor is used for an alternative bypass switch to increase the safety and ground the circuit after discharge. The selection of the standard waveform component for lightning strike evaluation is limited by the type of available impulse current generator. The impulse current generator in this study is capable of producing components A and D. The problem of the old impulse current generator at MSU-HVL was the low efficiency and flexibility. It was not possible to get high currents frequently due to the improper clearance of generator. It was not possible to charge the capacitors to the desired voltage and get the high current because of the bad clearance which caused self-ignition in the circuit before triggering the circuit. So, the test was failed and leaded to some problems. Besides, it was hard and time consuming for amounting the samples on the top of the discharge electrode.

III. Results and Analysis

In order to enhance the performance of the generator, an impulse generator is constructed for lightning impulse tests. The configuration of the impulse current generator at HVL-MSU is shown in Fig. 5.

The impulse current generator can have up to eight 47 µF capacitors connected in parallel, each of which has a voltage rating of 44 kV. This provides total lightning impulse energy up to 400 kJ. Once the capacitors are charged to a targeted voltage with a DC power source and through the charging resistors, lightning current discharge is triggered by a pneumatically actuated gap that directs the voltage of the charged capacitors to the gap between the output electrode and the ground electrode. The lightning current flows from the output electrode through the sample, and into the ground electrode. It is possible that the voltage does not break down the insulation and current does not flow the sample which can be high air gap between the discharge electrode and the ground plane or insulation strength of the test article. In this case, a high energy discharge resistor is mounted to direct the discharge current to the ground. In addition, a control box is designed and made to control the generator from the distance and a safe area. The interface of the power supply is used to control the generator remotely.

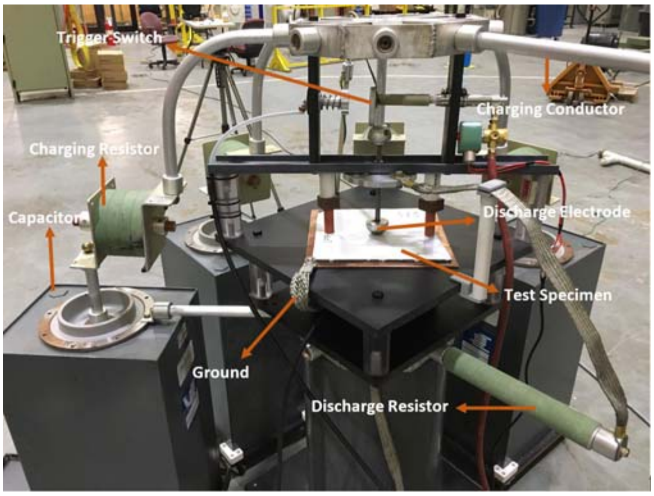

Fig. 5 Equivalent circuit of impulse current generator

Since all parameters of the generator such as capacitors, resistors, and inductance are adjustable, the magnitude of the lightning current can be controlled by either changing the voltage or the number of parallel connections of the capacitors. In order to find out the parameters of the generator, an aluminum panel is used to perform the high current test and predict the inductance and resistance of the circuit. 6 parallel capacitors were charged to 6.2 kV for injecting 50 kA impulse current to the panel. Fig. 6 represents 50 kA impulse current which is a double exponential waveform with time duration less than 500 µs. Curve fitting analysis was performed on the output current of our impulse generator due to finding the circuit element parameters as shown in Fig. 6.

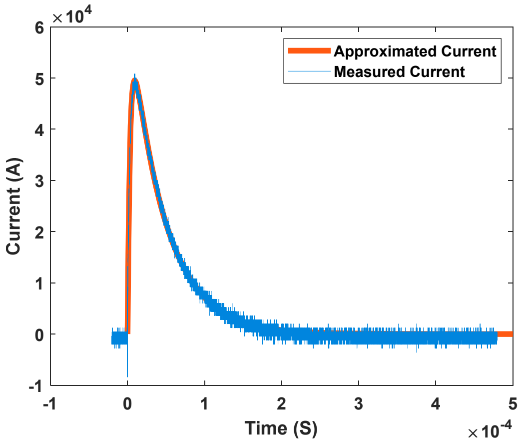

Fig. 6 Curve fitting of measured current

$$a \times (e^{-bt} - e^{-ct}) \Rightarrow \begin{cases} a = 6.560320 * 10^4 \\ b = 2.22221 * 10^4 \\ c = 30.52725 * 10^4 \end{cases}$$

By comparing the obtained values with (3) and considering the total capacitance 6×47 µF and charging voltage about 6.2 kV, the predicted resistance and inductance of existing impulse current test circuit are:

- R = 0.108 Ω
- L = 0.33 µH

The energy of lightning discharge is a factor that damages materials. Six parallel capacitors connected 50 µF are installed and charged to different levels of voltages to get desirable lightning currents which are 50 kA, 100 kA, 150 kA, and 200 kA. Fig. 7 represents the charged energy of the capacitors at different voltage levels.

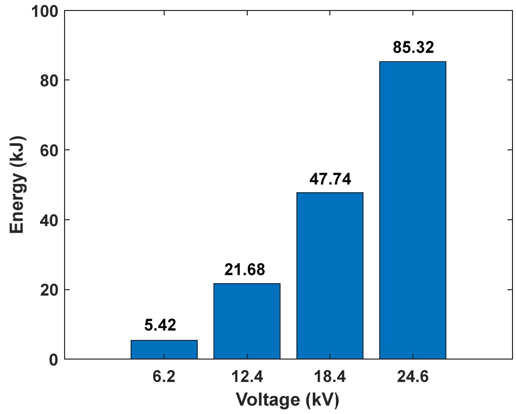

Fig. 7 Energy of capacitors at different voltage levels

Component A of the lightning strike that has a peak amplitude lower than 200 kA and the time duration of equal or less than 500 µs is simulated by our impulse current generator. The lightning current with different amplitudes shown in Fig. 8.

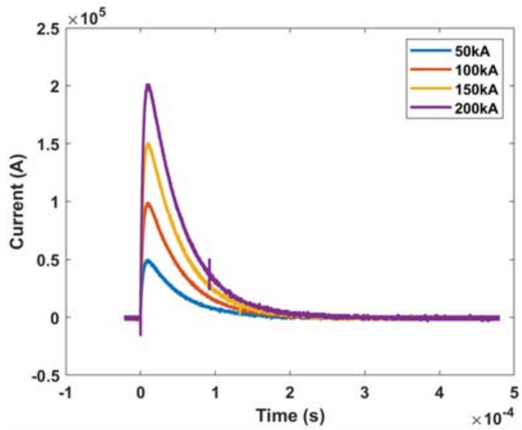

Fig. 8 Impulse current waveforms generated by generator at HVL-MSU

Fig. 9 shows the correlation between the voltage of capacitors and the produced impulse current value. As it can be seen, the correlation in linear which means we can obtain to a desired current amplitude by extrapolating the voltage.

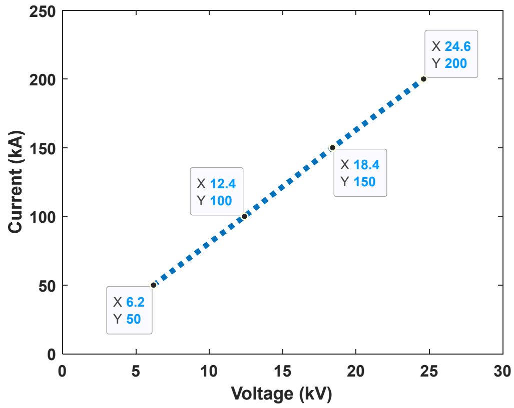

Fig. 9 Linear correlation of voltage and current of generator The linear correlation exists for testing samples with the same resistance

IV. Application of Impulse Current Generator

A. Aerospace Structures

Aerospace industry is highly interested in composite laminates due to its light weight and the manufacturing and operation prices. The investigation of their lightning strike damage characteristics is important due to its lower electrical conductivity that metal. The lightning strikes accompanied with a very loud sound, bright light, and cloud of sparks. Fig. 10 represents the moments of lightning strike to the panel that causes damages such as delamination and decomposition of the matrix.

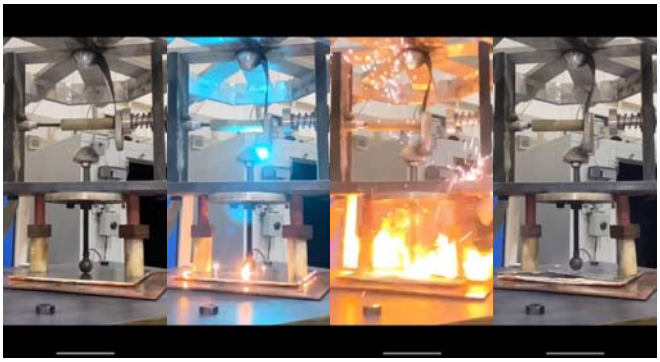

Fig. 10 Frames of lightning strike to composite panels

B. Wind Turbine Blade

Glass fiber-reinforced polymer matrix (GFRP) composites are mainly used in wind turbine blades. To validate the performance of GFRPs, it is necessary to be tested by high voltage and high current impulses.

C. Volcanic Ash

Lightning happens frequently in the areas with volcanic eruptions. Lightning induced volcanic spherules (LIVS) left from explosive volcanic eruptions shows electrical activity in eruption areas. The morphological effect of lightning on LIVS has been recorded and the influence of lightning on the magnetic properties of volcanic ash has been investigated by researchers.

D. Power System's Equipment

Surge arresters are used in the power distribution lines to damp the lightning strike. Several strikes of the lightning can impose sever damage to the arresters. The lightning strike waveform that uses to investigate the functionality of the surge arresters has a specific T1/T2 of 8/20 µs that can be obtained by changing adding resistance and inductance to the current generator at HVL-MSU.

V. Conclusion

The configuration of a developed impulse current generator is described in this paper and lightning strike waveform with different amplitudes is presented. The generator is a RLC circuit and capable of producing lightning impulse current with amplitude of more than 200 kA. The waveform of the generator fulfills the SAE standard requirements for lightning strike test of aerospace structures. The generator is suitable to be used for wind turbine blade and volcanic ash tests. A desired waveform in accordance with the IEC standard for lightning strike test of the surge arresters can be obtained by changing the resistance, inductance, and capacitance of the circuit. The lightning current can be controlled by changing the charging voltage of the capacitors. A preliminary test is required for each test sample to predict the charging voltage of the capacitors to obtain a desired current amplitude. The charging voltage can be predicted from extrapolation of the preliminary results. The output of this study validates the functionality of our impulse current generators at High Voltage Lab of Mississippi State University based on the SAE standard requirement and presents different applications that our generator can be used for lightning strike tests.

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