STREAMER INCEPTION ELECTRIC-FIELD CRITERION UNDER POSITIVE LIGHTNING IMPULSE VOLTAGE CONSIDERING VOLTAGE RISE RATE

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ABSTRACT

Streamer performance is the main mechanism of long air gap discharge; the inception characteristic of streamer has been widely used in engineering. The streamer inception characteristic under DC voltage has been researched by many researchers, but the characteristic under impulse voltage especially under lightning impulse voltage with large voltage rise rate has been studied rarely. The inception characteristics of streamers in 1m rod-plane air gap energized by positive lightning impulse voltage have been researched. The new diagnosis of streamer inception has been given, and the streamer inception voltages and electric fields under different electrode and voltage rise rate have been recorded. According to experiment results, the streamer inception electric field criterion considering voltage rise rate has been proposed. The criterion in this paper is also be verified for widely parameter ranges.

1. INTRODUCTION

Streamers are the initial stage of gas discharge in a long air gap. The concept of streamer has been accepted widely. Under positive DC voltages, the streamers occur where the ionization coefficient is equal to the attachment coefficient near the electrodes. During the development of the avalanches, the number of the electrons in the head grows until the streamer inception. The streamer inception criterion is described as the total number of the charge in the head more than the critical value. The critical value is usually taken as 10^8 [1-3]. Another streamer inception criterion is that the number of electrons in the secondary avalanches is equal to the first avalanches [4]. The above streamer inception criterion are both based on the total number of electrons in the head of the avalanches, which is not suitable for engineering. Now widely used streamer inception criterion under positive DC voltages is focus on electric field on the tip of electrodes, considering the relationship between streamer inception electric field and electrode radius [5].

Under positive impulse voltages, the streamer inceptions need two conditions: one is that the applied voltages must be higher than the minimum critical voltages; the other one is that there must be effective free electrons in the tip volume of electrodes. Since the effective free electrons appearance needs time, the streamer inception voltage or electric field under positive impulse voltages would be higher than which is under positive DC voltages. Les Renardiess proposed critical volume model as streamer inception criterion under positive impulse voltages [6]. Allen [7], Poli [8] and Diaz [9] modified the model respectively, considering different shape electrodes and humidity’s effect. However, it is difficult to calculate critical volume for complex structure electrodes in in actual engineering. This restrict the application of the critical volume model in the field of engineering.

In this paper, we present experimental results on long streamer in a 1m rod-plane gap in atmospheric air. The inception voltages and time delays of long streamers under lightning impulse voltages were measured. Based on the inception voltages, the electric field on the surface of the rods were considered as critical values to describe streamer inception. The variation of the streamer inception electric field were obtain for different rod radius and different voltage rising rates. A modified analytical criterion that considers the influence is proposed.

2. EXPERIMENT SETUP

A scheme of experimental set-up is given in Fig.1. An IEC-standardized lightning impulse voltage was generated by the four-stage 400 kV Marx generator. The rise time and the half-wave time of the waveform are 1.2 μs and 50 μs, respectively. The impulse voltage was applied to a 1m rod-plane gap. The plane was a 3 m × 3 m square aluminium sheet. The stem length of the rod is 60cm and the diameter is 2 cm. The rod is mounted with three types of tips, which are also shown in figure 1. They are a 2.5-cm-radius sphere, a 1-cm-radius hemisphere, and a cone with a tip radius of approximately 0.5 cm. A coaxial shunt for the current measurement is connected between the rod electrode and the high voltage lead. The current signal is sampled by an NI USB-5133 data acquisition card and transmitted through an optical fibre to a oscilloscope.

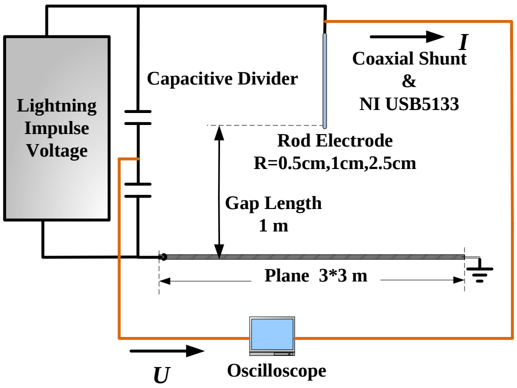

Fig.1 Experiment Setup

The typical results are shown in Figure.2. When the applied voltage is low, the streamer inception condition cannot be meet. Because of geometric capacitance between the rod-plane gaps, it will products displacement current. The wave shape of displacement current is same as the rising rate of the applied voltage, and its magnitude is proportional to the geometric capacitance. The displacement current can be calculated as:

$$i_{\text{disp}} = C_{\text{gm}} \frac{\mathrm{d}U}{\mathrm{d}t} \quad (1)$$

Where, C_{gm} is geometric capacitance. When the amplitude of the applied voltage is higher, the streamer will be generated. The streamer inception is accompanied by continual ionization process, which products large number free electrons and positive ions. The free electrons will move towards the positive electrode rapidly, and as the same time the positive ions will move back to the positive electrode in the electric field. This process will cause discharge current, as shown in Figure.2. After Δt time delay, the streamers incept and the measured current increases sharply. The current pulse is caused by electrons moving into rod which are produced by ionization process in streamer.

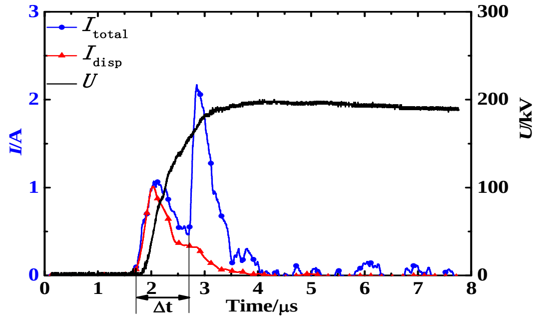

Fig.2 Typical measured results

3. STREAMER INCEPTION CRITERION

According to the measurement current, we can obtain the time of the streamer inception and the corresponding voltage, which is the streamer inception voltage. The streamer inception voltages under different radius and different voltage rising rates are shown in Fig.3. It can be concluded that for the same radius, the streamer inception voltages increase with the voltage rising rates; for the same voltage rising rates, the streamer inception voltages increase with rod electrode radius.

As we analyze above, the streamer inception voltages under positive lightning impulse voltages are largers than those under positive DC voltages. Therefore, the streamer inception voltages under impulse voltages can be described as:

$$U_{\text{i-impulse}} = U_{\text{i-dc}} + \Delta U \quad (2)$$

Where, $U_{i\text{-impulse}}$ is the streamer inception voltages under impulse voltages, and $U_{i\text{-dc}}$ is the streamer inception voltages under DC voltages. After we acquire the streamer inception voltage, the E-field on the tip of rod electrode can be calculated as the streamer inception E-field. The streamer inception electric field under impulse voltage can also be expressed as:

$$E_{\text{i-impulse}} = E_{\text{i-dc}} + \Delta E \quad (3)$$

Where, $E_{i\text{-impulse}}$ is the streamer inception electric field under impulse voltages, and $E_{i\text{-dc}}$ is the streamer inception electric field under DC voltages.The electric field increment can be explained by the radius of electrodes and voltage rising rate.

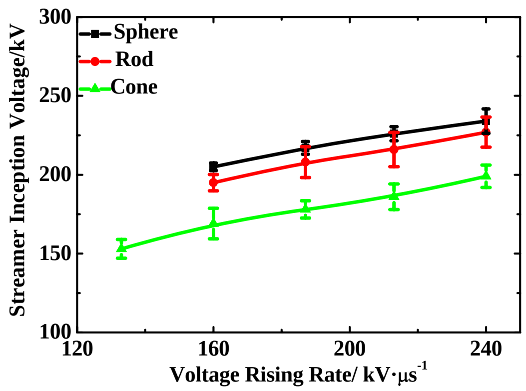

Fig.3 Streamer inception voltage varied vs rod radius and voltage rising rate

According to other researchers, the streamer inception electric field under DC voltages can be expressed as:

$$E_{i-\text{impulse}} = 22.8\left(1 + \frac{1}{\sqrt[3]{R}}\right) \tag{4}$$

We define the voltage rising rate to decribe the waveform of impulse voletages, using 10% and 90% amplitude voltages and corresponding time:

$$\frac{dU}{dt} = \frac{U_{0.9} - U_{0.1}}{t_{0.9} - t_{0.1}} \tag{5}$$

Then, the streamer inception electric field under impulse voltages considering electrode radius and voltage rising rate can be expressed as (6), where k is a coefficient.

$$E_{i-\text{impulse}} = 22.8\left(1 + \frac{1}{\sqrt[3]{R}} + k\sqrt{\frac{dU}{dt}}\right) \tag{6}$$

In our experiments, the streamer inception voltages of three different radius rods under positive lightning impulse voltage in range from 160~300kV are measured. The radius are 0.5cm, 1cm and 2.5cm respectively. The voltage rising rates are in range from 133~240 kV/μs. The streamer inception electric field and with voltage rising rate are shown in Fig.4. Different radius are corresponding different k, and k is function of radius. Fig.5 shows the relationship between coefficient k and electrode radius.

$$k = \frac{0.22R + 0.08}{R^2} \tag{7}$$

Therefore, the streamer inception E-fields are researched as function of electrode radius and impulse voltage rising rates, which can be proposed as follow.

$$(E_i)_{\text{impulse}} = 22.8\left(1 + \frac{1}{\sqrt[3]{R}} + \frac{0.22R + 0.08}{R^2}\sqrt{\frac{dU}{dt}}\right) \tag{8}$$

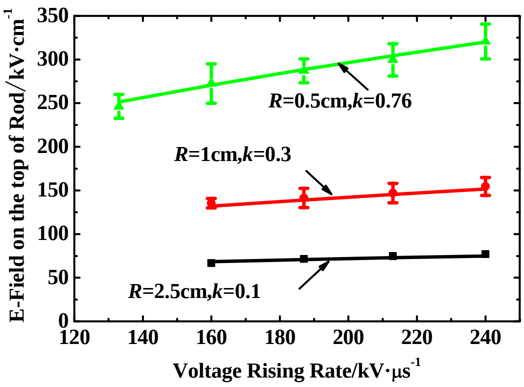

Fig.4 Streamer Inception Electric Field Varied with Voltage Rising Rate under Different Rod Radius

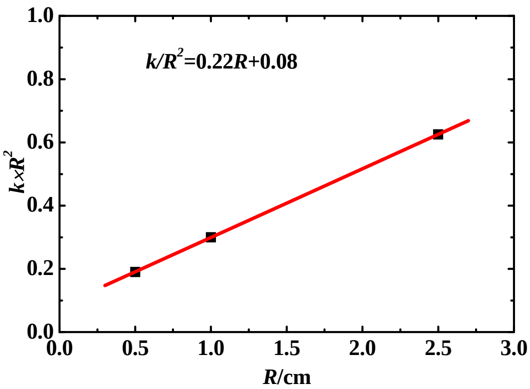

Fig.5 Impulse Coefficient k Varied with Rod Radius

4. CRITERION VERIFICATION

Allen [7] measured streamer inception voltages under positive switching impulse voltages. The radius is 1.416cm and the gap length is 60cm. The voltage rising rate is in range from 9 to 34 kV/μs. Table.1 shows the calculation results and experiment data. The comparison illustrates that the streamer inception electric field proposed in this paper is also suitable for small voltage rising rates. The Renardières Group [6] measured streamer inception voltages and electric fields under large radius electrodes. Using this criterion calculates the streamer inception voltages and electric fields under the same conditions and the results are shown in Table.2. The results instruct that the criterion is also can be used for large type electrode.

5. CONCLUSION

The streamer inception characteristic of 1m rod-plane gap under positive lightning impulse voltages are proposed in this paper. The current measurement system based on coaxial shunt are used to measure discharge current. Typical results show that when the streamers incept, there will be current impulse. According to the waveform of measured current, the time of the streamer inception can be determined. Moreover, the streamer inception voltage and the electric field on the tip of the electrodes are also can be obtained. The latter can be considered as the streamer inception electric field criterion, which would be widely used in engineering.

The streamer inception electric fields under different radius electrodes and different voltage rising rates are obtained. The influences on streamer inception electric field of electrode radius and voltage rising rate are considered. According to these results, the streamer inception electric field criterion is proposed. The streamer inception criterion is also verified by other researchers' experiment results.

Table.1 Streamer Inception Electric Field under Positive Switching Impulse Voltages

Voltage Rising Rate (kV·μs-1)	9	17	34
Inception Voltage measurment results(kV)	103~115	104~125	103~130
Inception Eletric Field results(kVcm-1)	52~59	53~64	52~66
The crirerion calculation results(kVcm-1)	56.4	61.4	69

Table.2 Streamer Inception Electric Field under Large Scale Electrode Conditions

Radius(cm)	Voltage Rising Rate (kV·μs-1)	Inception Electric Field Experiment Data (kV·cm-1)	Inception Electric Field Calculation Results (kV·cm-1)
30	10.2	30.2	30.7
	3.35	30.2	30.5
	2.22	31.3	30.4
10	22.4	37.5	35.9
	7.35	33.2	34.8
	4.64	35.3	34.5

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