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Full Length Article

Influence of pulse front steepness on vacuum flashover characteristics

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ABSTRACT

Studying flashover characteristics in vacuum environment is extremely significant for designing reliable insulation structures. The waveform of applied voltage excitations greatly affects the flashover process. In this study, the influence of nanosecond pulse front steepness on flashover process in vacuum is investigated. Firstly, flashover experiments with nanosecond pulses are conducted. Nanosecond pulses with different front steepness are generated and used to trigger flashovers on sample surface. The relationship between pulse front steepness and flashover voltage is studied. Meanwhile, a particle-in-cell with Monte Carlo collision (PIC-MCC) two-dimensional self-sustaining discharge model based on secondary electron emission avalanche (SEEA) scheme is established. The distribution of charged particles, electric field and their evolution during flashover process are presented. Furthermore, pulses with various rising steepness are applied to the model. The multiplication and propagation of charged particles in different pulse waveform conditions are studied. In all conditions, two stages during flashover process can be obviously distinguished based on charged particle number evolution which divides the overall flashover delay time into two parts. By analyzing the voltage development in these two time slots, the quasi-linear relationship between pulse front steepness and flashover voltage in nanosecond pulse flashover in vacuum is explained.

1. Introduction

Flashover is a typical kind of failure mode in power pulse devices, which has been a prolonged topic that attracts worldwide attentions. It occurs along insulator surfaces, and generally has a much lower breakdown threshold than that of bulk insulator structure and vacuum gap. The flashover pulse waveform affects the flashover process to a great extent. Especially, when a pulse flashover with nanosecond time scale occurs, instantaneous power and voltage rush to an extremely high level, which poses great challenges to the insulation structure design for pulse power devices [1–3]. Therefore, it is crucial to have a comprehensive understanding for how voltage waveform, especially front steepness of the voltage affects nanosecond pulse flashover.

The effects of pulse waveform on flashover voltage have been extensively studied in the last several decades [4–7]. Most studies indicate that the flashover voltage decreases with the increase of pulse duration [8]. More specifically, for the pulse with nanosecond time scale, it was reported that higher pulse rising rate leads to an obvious increase in flashover voltage [8–10]. To explain this relationship, most researchers tend to analyze this from the perspective of the number and distribution evolution of charged particles, as well as time characteristics during flashover.

As the classic secondary electron emission avalanche (SEEA) theory [11,12] describes, the whole flashover process in vacuum can be regarded as a conductive plasma path formation phenomenon above the insulator surface. Generally, the overall process can be divided into two stages according to the main multiplication methods of charged particles. The first stage starts from the application of the pulse excitation. The electrons emitted by field emission from the cathode junction (the point where the insulator, cathode, and vacuum meet) impact insulator surfaces, causing secondary electron emission (SEE). Some of the secondary electrons will again strike the insulator surfaces, generating more electrons. When the energy and number of electrons reach to a certain level, the electrons start to ionize the desorbed gas molecules and fragments segmented from surface materials through effective collision. The second stage starts when collisional ionization gradually dominates the charged particle multiplication. In this process, the number of electrons and ions on the insulator surface increase exponentially, finally forming a conducting path between two electrodes. Based on these two stages of flashover process, the entire delay time for triggering flashover can also be divided into

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two parts: a statistic time and a plasma formative time [13,14]. It is implied that the delay time and the multiplication process of charged particles during flashover are key factors for the flashover voltage difference with different nanosecond pulse front steepness [9]. However, this inference is mainly based on empirical analysis. The actual spatial distribution of charged particles and their evolution over time is hard to be observed solely by experiments. Therefore recently, particle-in-cell/Monte Carlo collisions (PIC-MCC) method has been gradually applied in the numerical study on vacuum flashover [15–19].

In this manuscript, the influence of nanosecond pulse front steepness on flashover process in vacuum is investigated. Firstly, a flashover testing platform is established. Nanosecond pulses with different front steepness are generated. They are applied on polystyrene samples to trigger flashovers on surfaces to observe the flashover characteristics. Meanwhile, a two-dimensional model based on PIC-MCC method is established. The distribution of charged particles, electric field and their evolution during flashover process are presented. The pulses with various front steepness are applied to the model. Charged particle accumulation behaviors during flashover processes with different pulse front steepness are analyzed. The relationship between pulse front steepness and flashover voltage is thoroughly studied.

2. Experiments

A group of polystyrene (PS) samples are prepared by hot-pressing method. The PS polymer granules are purchased from Aladdin Reagent Inc., Shanghai. All the samples are ultrasonically cleaned in ethanol and deionized water, and then dried in vacuum chamber prior to the experiments.

Vacuum flashover tests with nanosecond pulses are first conducted. The tests are performed in a flashover-testing platform consisting of a MARX pulse generator, a vacuum chamber system and a test system as Fig. 1 shows. The MARX pulse generator is set up with eight stage switches and capacitors, with a charging capacitance of 5.6 nF. A loading resistor R_{load} (1.2 kΩ) and a limiting resistor R_{limit} can be controlled to adjust the output pulse waveform. And the voltage divider with a divided ratio of 12050:1 is employed for the measurement of flashover voltage waveform. The high voltage side is a 10kΩ metal-film resistor, and the low voltage side is a 0.83 Ω metal-film resistor, connecting with an oscilloscope (LeCroy, WaveSurfer 104MXs-B) to record the flashover waveform and voltages. During the flashover testing, the vacuum level in the vacuum chamber is controlled under 5×10^{-4} Pa. Two finger type electrodes are set on the samples surface with a 10-mm charging gap, as shown in Fig. 1(b).

The voltage waveform of the output pulses from the MARX pulse generator can be adjusted by changing the DC charging voltage and value of R_{limit}. The value of R_{limit} includes 1.6 kΩ, 1 kΩ and 0.6 kΩ; while the DC charging voltage includes 7 kV, 7.5 kV and 8 kV. Thus, all together nine conditions with different circuit parameters are tested as Table 1 shows and nine pulses with different pulse front steepness can be obtained.

3. Simulation model

A 2-D PIC-MCC model is established to simulate the vacuum flashover process according to the SEEA scheme. The simulation is implemented through VSim composer, a commercial simulation platform that has been proven suitable for simulating the dynamic process of plasma.

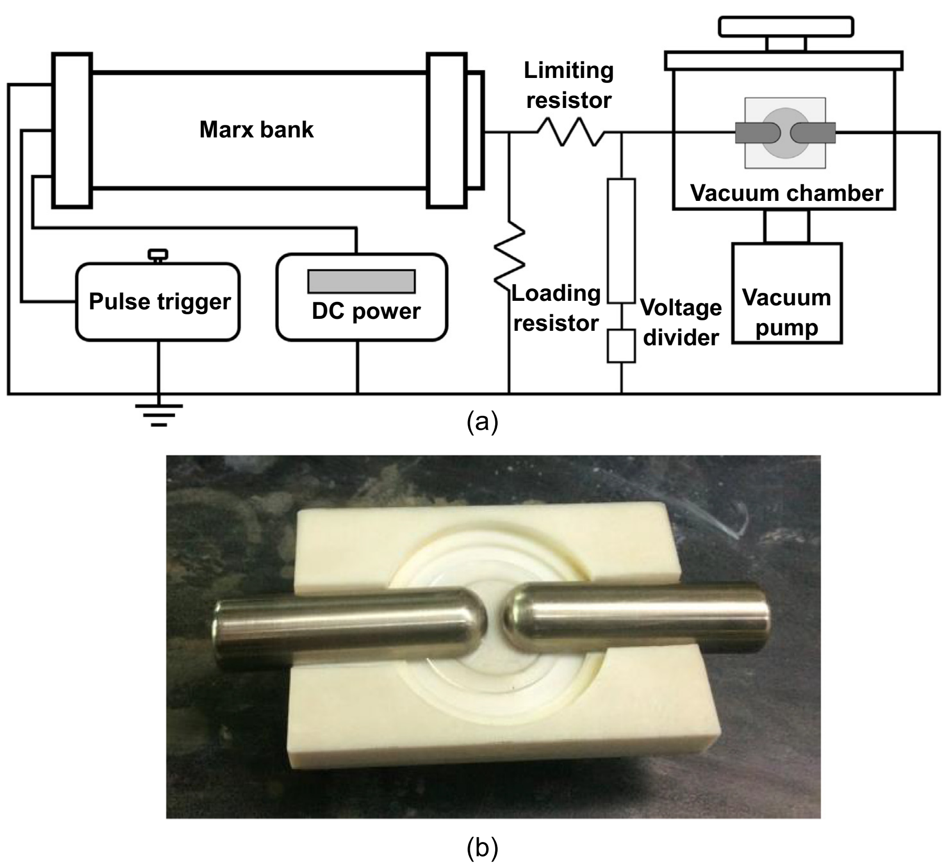

Fig. 1. (a) The schematic of nanosecond pulse flashover testing platform. The nanosecond pulse is generated by a MARX pulse generator. And the flashover testing is performed in a vacuum chamber. (b) The sample holder for flashover testing.