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Experimental study of polarity dependence in repetitive nanosecond-pulse breakdown*

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Pulsed breakdown of dry air at ambient pressure has been investigated in the point-plane geometry, using repetitive nanosecond pulses with 10 ns risetime, 20–30 ns duration, and up to 100 kV amplitude. A major concern in this paper is to study the dependence of breakdown strength on the point-electrode polarity. Applied voltage, breakdown current and repetitive stressing time are measured under the experimental conditions of some variables including pulse voltage peak, gap spacing and repetition rate. The results show that increasing the E-field strength can decrease breakdown time lag, repetitive stressing time and the number of applied pulses as expected. However, compared with the traditional polarity dependence it is weakened and not significant in the repetitive nanosecond-pulse breakdown. The ambiguous polarity dependence in the experimental study is involved with an accumulation effect of residual charges and metastable states. Moreover, it is suggested that the reactions associated with the detachment of negative ions and impact deactivation of metastable species could provide a source of primary initiating electrons for breakdown.

Keywords: gas breakdown, nanosecond-pulse, repetition rate, point-plane geometry, polarity dependence
PACC: 5280M, 5280H, 5150

1. Introduction

Repetitive-pulsed power has received much attention as a crucial area of interest for the works on high-energy physics research, controlled fusion, particle beams, as well as for many industrial applications.[1] One of basic problems is related to fundamental electrical insulation and dielectric breakdown. Breakdown phenomena in a nonuniform electric field with the point-plane geometry have been widely studied with DC, AC and unipolar ms/μs pulses. However, at the timescale of nanosecond or sub-nanosecond, the results of pulse breakdown are relatively scarce, and the limited data are mainly related to a single-nanosecond-pulse breakdown. For instance, breakdown characteristics of small air gaps have been investigated at ambient pressure.[2] The results in this paper show that breakdown time lag changes in a discrete manner when a negative voltage is applied to the point-electrode, and the gap is illuminated. Moreover, the breakdown probability of point-plane gaps is strongly influenced by the variation of negative-ion population, and electrons via the detachment from negative ions would provide a source of initiative electrons.[3] It has been reported that for air, in a high-voltage sub-nanosecond pulse breakdown, E-field strength in the point-cathode case is increased by 30 to 80% that in the point-anode case.[4] When a sub-nanosecond pulse with a voltage below 15 kV is applied to a 1 mm point-plane gap of argon, the increment of breakdown time lag in the point-anode case is about 30% over that in the point-cathode arrangement.[5]

In the traditional discharges, breakdown characteristics of the point-plane geometry depend strongly on the polarity of the voltage applied to the point electrode regardless of DC or unipolar ms/μs pulses. The experimental investigation in this paper is focused on the polarity dependence of repetitive nanosecond-pulse breakdown. Furthermore, the accumulation effect of residual ions and metastable states is discussed for explaining the characteristics of the polarity dependence.

2. Experimental arrangement and measuring method

The experimental arrangement is shown in Fig.1. A nanosecond-pulse generator of inductive energy

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storage type is used, which can produce high-voltage nanosecond pulses with a repetition rate up to 2 kHz. The generator consists of a primary charging unit, a magnetic compression unit and a semiconductor opening switch (SOS) amplifying unit.[6] The negative output pulse has a rise time of about 10 ns and a full-width at half-maximum of 20–30 ns, and the repetition rate is adjusted by a trigger generator. A cycled saltwater resistor, which is connected in parallel with the discharge circuit, is used to change different amplitudes of output pulses. A limiting resistor of 200 Ω is connected in series with the discharge circuit to avoid unexpected damage to the generator and current viewing resistor. The charging time constant of the discharge circuit is below 1 ns. The columned test chamber is made of polymethylmethacrylate, and point-plane brass electrodes are mounted along the axial direction. The diameter of the plane electrode is about 6 cm. The point electrode of 2-cm-diameter and 4-cm-length has a taper geometry with a tip diameter of 2 mm. The gap spacing can be adjusted with an accuracy of ±0.1 mm. The electrodes are polished and cleaned in advance. Dry air in the test chamber is replaced after each breakdown.

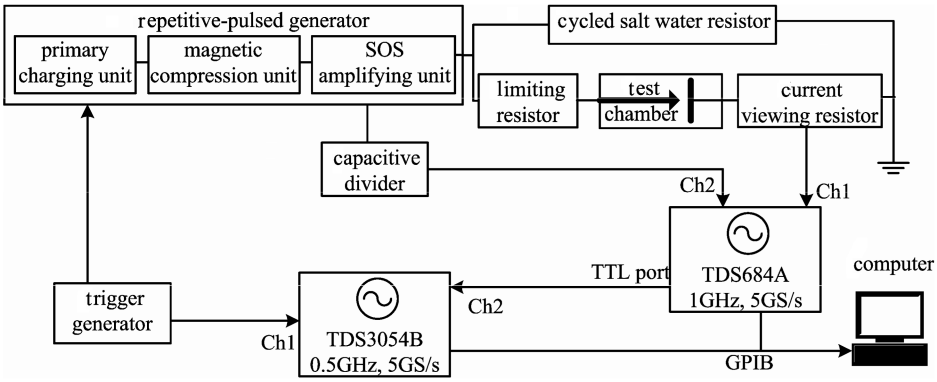


Fig.1. Schematic diagram of the experimental arrangement.

When the gap is bridged, breakdown current is measured by a current viewing resistor of 0.2 Ω, and the applied voltage is detected by a capacitive voltage divider which is inserted between the pulse generator and the limiting resistor. The breakdown current after 20dB attenuation is used as the trigger signal of a digital oscilloscope TDS-684A (1 GHz, 5GS s^{-1}), and both the applied voltage and breakdown current are recorded simultaneously. The typical waveforms are shown in Fig.2(a).

The working modes of a repetitive pulse system can be classified as burst operation and continuous mode, so the experimental investigation must be associated with an applied time duration which is the interval between the first pulse applied to the gap and the last pulse resulting in breakdown. The time duration is defined as the repetitive stressing time (RST) and may last from several seconds to minutes or longer. As shown in Fig.1, the measurement arrangement of RST is given as follows. The first pulse produced by the trigger generator initiates the pulse generator, and a digital oscilloscope TDS-3054B (0.5 GHz, 5GS s^{-1}) also records the signal as in the upper curve in Fig.2(b). When TDS-684A records both applied voltage and breakdown current, one transistor–transistor logic (TTL) port of TDS-684A will produce a low-level voltage signal simultaneously, which is also recorded by TDS-3054B and shown in the lower curve of Fig.2(b). The number of applied pulses (N) is approximately equal to the product of the repetition rate and RST.[7]

The pulse amplitudes of −60, −80 and −100 kV are applied in the experiment, and the corresponding gap spacings are 10, 20, and 30 mm respectively. The dielectric is dry air of $\sim 1\times10^5$ Pa, and all these experiments are performed under ambient conditions. Each data point represents the mean value of 10 measurements. The breakdown probability per data point is

greater than or equal to 50 %. Breakdown time lag (τ) is defined as the time interval between the initial spike (resulting from the displacement current across the gap) and the subsequent large current rise, as shown in the breakdown current waveform in Fig.2(a). In addition, E-field strength is defined as the applied voltage divided by the gap spacing.

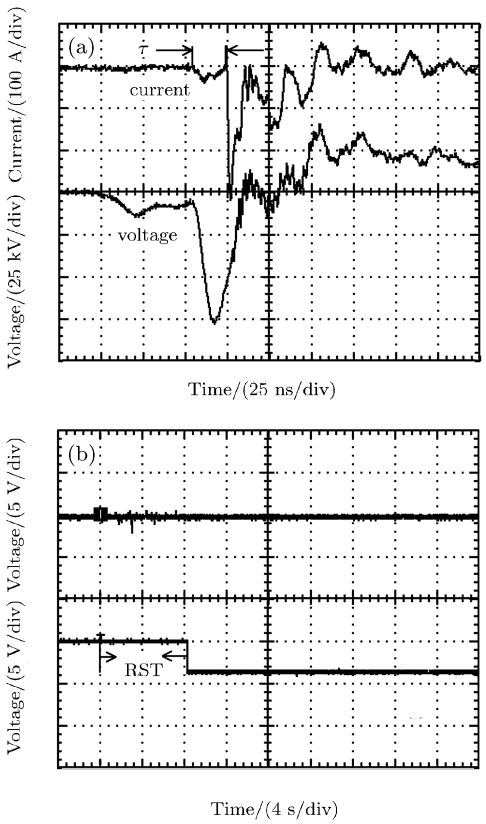


Fig.2. Typical waveforms of applied voltage, breakdown current and RST.

3. Experimental results

Because the pulse generator could only produce negative high-voltage pulses in the existing circumstances, the experimental conditions are met by changing the connection between the electrodes and the generator output terminal. When the plane electrode is connected with the generator and charged by negative pulses, the experimental condition of the plane-cathode is equivalent to the point-anode arrangement. In reverse, when the point electrode is linked to the generator, it is the same as the plane-anode arrangement.

Figures 3–5 show the variations of τ, RST and N with E-field strength and repetition rate. The data under the point-cathode and plane-cathode conditions are presented. The error bars in all these figures indicate the plus and minus standard deviations from the mean value of the measurements.

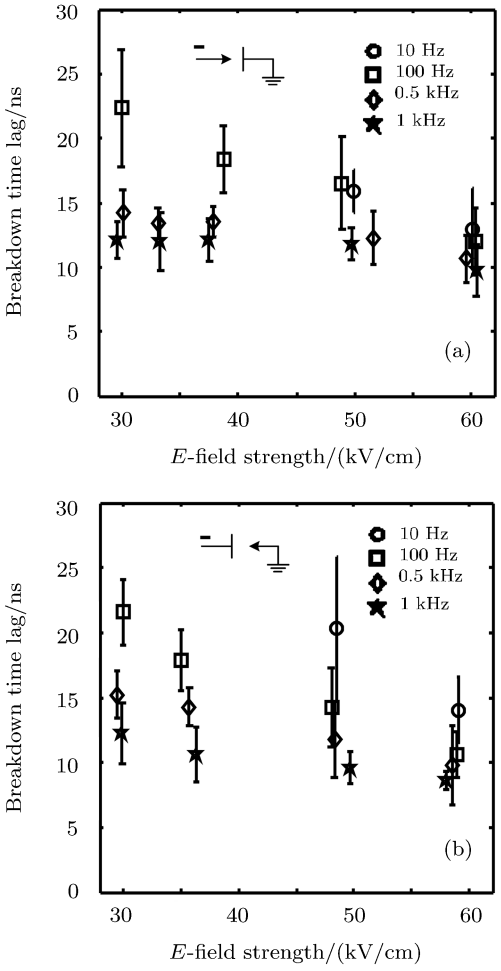


Fig.3. Dependence of breakdown time lag on E-field strength.

Figures 3(a) and 3(b) show that τ decreases with the increase of E-field strength for four repetition rates. It can be found that the reduction trends are different repetition rates. When the repetition rate is 10 Hz, the breakdown takes place at E-field strength above 50 kV/cm, and repetitive nanosecond-pulses at other repetition rates can lead to breakdown in the experimental regimes of the E-field strength. When E-field strength increases from 30 to 60 kV/cm, τ decreases by about 10 ns at 100 Hz, but 2–3 ns at 0.5 or 1 kHz. These results imply that the breakdown is influenced strongly by the applied repetition rate and is related to the accumulation effect of successive pulses.

Figures 4(a) and 4(b) show RST as a function of E-field strength at four repetition rates. It can be found that RST at 10 or 100 Hz is about 10 times bigger than that at 0.5 or 1 kHz. Figures 5(a) and 5(b)

illustrate the dependence of N on E-field strength. It can be seen that the decay dependences at different repetition rates are similar, and N decreases with E-field strength. However, N at 10 Hz may be larger than that at 1 kHz.

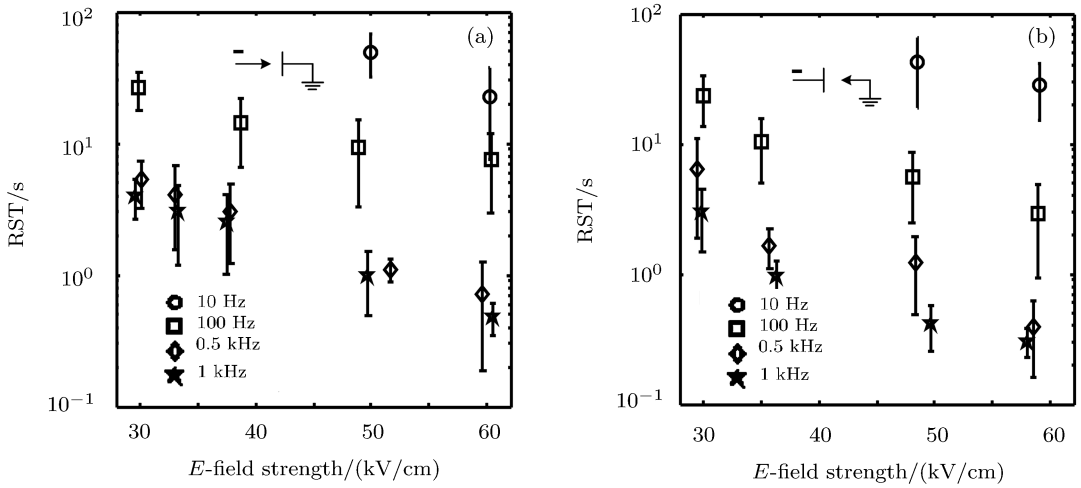


Fig.4. Dependence of RST on E-field strength.

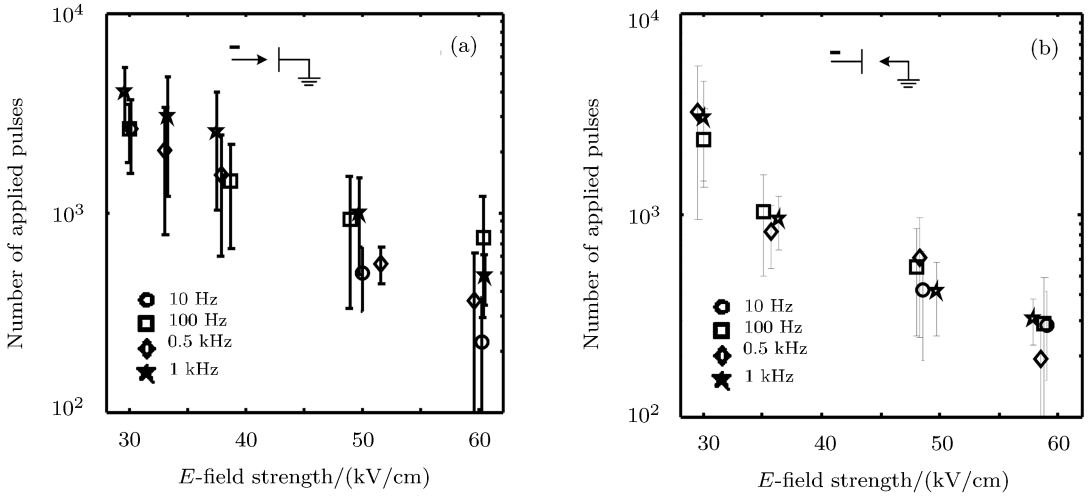


Fig.5. Dependence of the number of applied pulses on E-field strength.

4. Characteristics in repetitive nanosecond-pulse breakdown

One nonlinear fit curve of the experimental data in Figs.3–5 is given for a fixed repetition rate, and the comparisons of the two cases are performed by the fit curves of τ, RST and N versus E-field strength, as shown in Figs.6(a), 6(b) and 6(c), respectively. There are some distinct characters as follows. Firstly, it can be found that the polarity dependence is not distinct and the curves in the two cases have intersections. τ, RST and N in the negatively charged point-electrode case are smaller than those in the negatively charged plane-electrode case in some regions.

Secondly, the curves of negatively charged point electrode are at higher positions than those of negatively charged plane electrode. In other words, the curves of point-cathode are higher than those of plane-cathode. In Fig.6(a) the increment in τ is about 10 %, which is lower than that reported in single-nanosecond-pulse breakdown.[4,5] In addition, N at 0.5 or 1 kHz is larger than that at 10 or 100 Hz.

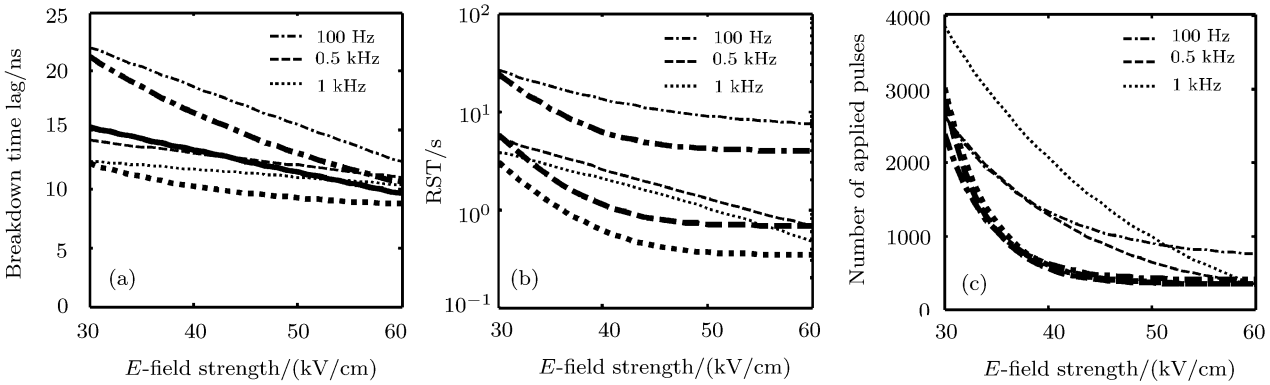


Fig.6. Nonlinear fit curves of breakdown time lag, RST and the number of applied pulses vs E-field strength in the point-cathode and point-anode cases. (The thin curves show the results for negatively charged point electrode and the thick curves show the data for negatively charged plane electrode.)

When the voltage is applied to the point electrode or plane electrode, the absolute value of E-field strength near the point is higher, so corona discharge always takes place near the point electrode regardless of voltage polarity, and the breakdown is polarity-dependent. That is, for a given gap spacing and gas pressure, a point-cathode case has a higher breakdown E-field strength and a longer breakdown time lag than a point-anode case. Polarity dependence still exists even when both rise time and pulse duration are several nanoseconds or sub-nanosecond. However, it is not obvious in the repetitive nanosecond-pulse breakdown; moreover, the differences of breakdown characteristics between negatively charged point and negatively charged plane electrodes are smaller.

Polarity dependence is based on the different electric field effects resulting from different space charges. The effect would increase space E-field strength and accelerate the development of the streamer under the point-anode condition. Otherwise, the adverse effect of decreasing space E-field strength must be overcome by applying a higher E-field strength under the point-cathode condition. However, in our experimental investigation, electric field effect would be weakened by residual ions and metastable states survived from repetitive pulses. Even with a corona current of 70 μA, 10% of the nitrogen molecules could be in an excited state.[8] The population of residual ions and metastable states depends on the repetition rate and electric field applied. It is known that some important metastable states can survive from the pulse intervals, e.g. the N_2 $A^3\sum_u^+$ state has a lifetime of about 2.1 s,[7] the $N_2a^1\Pi_g$ state has a lifetime of a sub-millisecond and can result in stepwise ionization.[9] Because the pulse repetition rate varies from 1 to 1000 Hz and the time interval between two successive pulses ranges from 1 to 1000 ms, some ions and metastable states would accumulate and contribute to the breakdown development.

At the nanosecond-pulse timescale, the time required by the breakdown itself is commensurable with the time duration of the applied pulse, so breakdown development may differ from the conventional DC, AC or μs-pulse breakdown.[10] Due to very short time-to-breakdown, corona discharge at the tip is limited, the effect of space charges formed in corona discharge is also low, and the polarity dependence of single nanosecond-pulse breakdown is lower than that of DC or μs-pulse breakdown. When repetitive nanosecond pulses are applied, the breakdown is different from a single-pulse breakdown because a lot of residual ions and metastable states have existed in the interelectrode space, and the actions of space charges are also different. The conventional explanation of polarity dependence, regarding the repetitive nanosecond-pulse breakdown, is in question, and the corresponding theory is far from being distinct and so needs further studies. Due to the accumulation effect of residual ions and metastable states, the polarity dependence is weakened and not distinct (relative to the traditional polarity dependence).

5. Discussion

The reduction of τ, RST and pulse number N results mainly from the increase of applied electric field.

Moreover, the breakdown characteristic has a notable dependence on the repetition rate and is related to the accumulation effect of the residual charges and metastable species. This accumulation phenomenon may be associated with the memory effect, which could last hours in some extreme cases.[11−13] It can be found that the estimated time of positive-ions recombination is about 30 ms at 1–4 $\times 10^2$ Pa, and the atoms in ground state, such as N (^{4}S), can affect breakdown initiation for a time interval higher than 30 ms.[12] Besides the reactions in nitrogen, some reactions related to atomic and molecular states of oxygen can also make significant influence to breakdown initiation.[14,15] However, all these discharge investigations are conducted under low pressures. In our experimental investigation of air at ambient pressure, corona discharges must be taken into account.

Breakdown takes place after a series of corona discharges with non-observable currents in the experiment. Corona discharge can produce some slow-moving ions of the same polarity as the point electrode.[8] When negative repetitive pulses are applied to the point electrode, the majority in the interelectrode space is a large number of negative ions and metastable states, and when the plane electrode is charged negatively, the number of positive ions should be limited due to the negative polarity of applied pulses. Published experiments have proved that the detachment of negative ions could produce many initial electrons effectively which can lead to a breakdown.[16−18] Gas breakdown depends on the supply of seed electrons for starting the Townsend avalanche. When the point electrode is charged negatively, a lot of residual negative ions are produced during applying repetitive pulses, and the detachment of negative ions provides some electrons which may be the seed electrons for breakdown initiation, so τ would decrease with the repetition rate. At the same time, the increase of electron and metastable states populations can increase ionization and accelerate the streamer propagation for breakdown development,[19,20] so RST would decrease with the repetition rate.

6. Conclusion

Breakdown characteristics have been experimentally investigated in point-plane gaps of dry air with repetitive nanosecond-pulses, and the polarity dependence from the experimental results is found to be weakened and not significant. The reason is related to the accumulation effect of residual ions and metastable states survived from previously repetitive pulses, e.g. the detachment of electrons from negative ions can provide a lot of initial electrons. Further works will attach importance to the relevant physics phenomena and experimental investigations of other gases.

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