Measurement and control for a repetitive nanosecond-pulse breakdown experiment in polymer films*

Shao Tao(邵 涛)†, Zhang Cheng(章 程), Long Kai-Hua(龙凯华), Wang Jue(王 珏), Zhang Dong-Dong(张东东), and Yan Ping(严 萍)

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, *China*

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In order to perform data acquisition and avoid unwanted over-current damage to the power supply, a convenient and real-time method of experimentally investigating repetitive nanosecond-pulse breakdown in polymer dielectric samples is presented. The measurement-acquisition and control system not only records breakdown voltage and current, and time-to-breakdown duration, but also provides a real-time power-off protection for the power supply. Furthermore, the number of applied pulses can be calculated by the product of the time-to-breakdown duration and repetition rate. When the measured time-to-breakdown duration error is taken into account, the repetition rate of applied nanosecond-pulses should be below 40 kHz. In addition, some experimental data on repetitive nanosecond-pulse breakdown of polymer films are presented and discussed.

Keywords: nanosecond-pulse breakdown, repetitive nanosecond pulses, polymer film, time-to-breakdown duration

PACC: 0650C, 2960G, 7750, 7755

1. Introduction

A high repetition rate, high reliability and long lifetime are required for pulsed power generators to meet the demands of expanding applications.[1−4] Data on electrical insulation and dielectric breakdown are a critical factor in the accurate assessment of reliable application and expected lifetime of a repetitive pulsed power apparatus.[5−10] Besides the conventional conditions of electrical insulation and breakdown, some special states should be considered in a pulsed power system. For example, both the rise-time and pulse-width of applied pulses are at timescales of nanoseconds or sub-nanoseconds. Compared with single pulse breakdown, repetitive nanosecond-pulse breakdown has a time-to-breakdown duration (TBD) which might last tens of seconds to several minutes or longer. Therefore, the parameters, including breakdown voltage and current, TBD, and the number of applied pulses, should be acquired for determining electrical breakdown properties.

A digital system and convenient control are desirable for data acquisition of breakdown experiments.[11−13] In general, a high-speed oscilloscope can provide two modes to record successive pulses, i.e. using envelope or sequence modes. The former method only obtains an overlay of applied pulses, and the latter one can acquire limited pulses and the recorded pulse number depends on the memory length of the oscilloscope. As for an experimental investigation of repetitive pulse breakdown, neither of these modes can provide enough information on breakdown characteristic. Therefore, some special design circuit combined with a high-speed oscilloscope should be considered. For example, for a repetitive μs-pulse breakdown, a programmable instrumentation system was needed to solve the problem of data acquisition.[14] It was found that the system could miss some pulses at a repetition rate above 40 Hz and the maximum applicable pulse repetition frequency (PRF) was 20 kHz.[14] Moreover, the instrumentation system needs some specially designed circuits which cannot be used in the measurement of repetitive nanosecond-pulse breakdown experiments directly. In the experimental investigations of repetitive nanosecond-pulse breakdown in gases,[8−10] a high-power resistor was connected in series with the

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†Corresponding author. E-mail: st@mail.iee.ac.cn

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test chamber to avoid damage when breakdown occurred, and the power supply was turned off manually. However, using the resistor might affect the breakdown characteristic of dielectrics, so the measurement and control system still needs further improvement. In this paper, we present a convenient real-time measurement and control system, and describe some experimental data on repetitive nanosecond-pulse breakdown of polymer films.

2. Experimental description

An experimental schematic diagram is shown in Fig. 1. A solid-state pulse supply with a semiconductor opening switch was used to produce high voltage repetitive nanosecond-pulses. The power supply was of an inductive energy storage type, consisting of a primary charging unit, a magnetic compression unit and an amplifying unit.[8−10] The output pulse had a rise-time of about 15 ns and a full width at half maximum of 30–40 ns. PRF varied from a single shot to 2 kHz and was controlled by an impulse signal generator. A pair of hemisphere-plane brass electrodes were mounted in a test chamber filled with transformer oil. Some polytetrafluoroethylene (PTFE) films with different thicknesses were chosen for the breakdown experiments. Two oscilloscopes (Lecroy WR204Xi with a bandwidth of 2 GHz and a time resolution of 10 GS/s, Tek TDS220 with a bandwidth of 100 MHz and a time resolution of 1 GS/s) were used to record all these signals, and a signal transferring circuit (STC) was designed to trigger the shutoff of the power supply, shown in Fig. 2. 10-cm-long connecting signal cables with double shields and a personal computer were used to save all signals for post-processing. All instrumentation was placed in a shielded room.

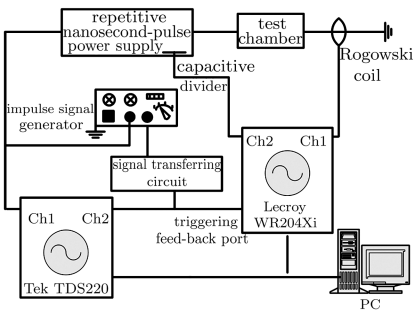


Fig. 1. Experimental schematic diagram and measurement arrangement.

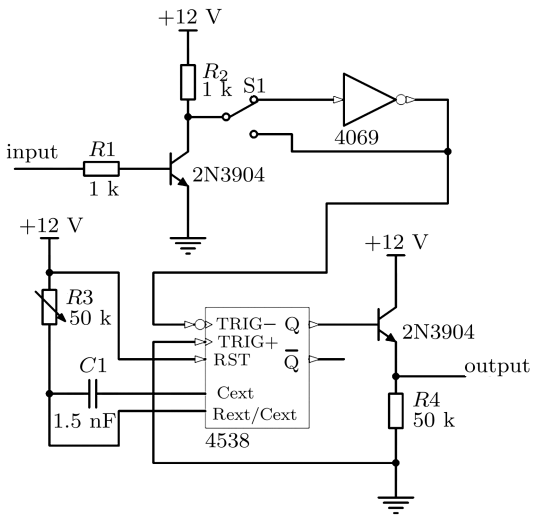


Fig. 2. Schematic of the signal transferring circuit.

3. Measurement acquisition and control

In the experiment, similar to that for a lifetime test, an applied voltage was fixed at a certain value. The PTFE film was not fully bridged after a series of pulses prior to the onset of breakdown, and breakdown was a single event from the application of the first pulse to the film breakdown. Breakdown voltage was measured by a capacitive voltage divider connected with the SPG200 output end, and discharge current was detected by a Rogowski coil. The voltage ratio of the divider was approximately 10000 and the sensitivity of the coil was approximately 35 mV/A. The system to measure voltage and current had been calibrated, and the measurements of both the divider and the coil were checked.

Besides the electrical measurements of voltage and current, TBD and the number of applied pulses should also be acquired. The measurement method of TBD is given as follows. When the impulse signal generator provided a pulse signal for initiating the power supply, the pulse signal was also recorded by one channel of TDS220 simultaneously, triggering the start of TBD. After consecutive pulses were applied and breakdown occurred, breakdown voltage and discharge current were detected by WR204Xi. At the same time, a 20-ms pulse-width generated by the triggering feed-back port of WR204Xi was also recorded by TDS220. Accordingly, the time interval from the start signal to the impulse signal was TBD. Furthermore, the impulse signal provided by the triggering

feed-back port of WR204Xi can also be processed through STC, and then, a signal satisfying power-off signal interface standard of the impulse signal generator can be obtained and used to trigger the shutoff of the power supply. A typical STC design is shown in Fig. 2, and the signal satisfying power-off signal interface standard provided by STC should be a positive pulse of 10 V with a pulse-width of about 10 μs. However, as for different high-speed oscilloscopes, the impulse step signal generated by the triggering feed-back port is of a high-level type or low-level type, and the corresponding peak value is about 3–5 V. Consequently, a flip-flop chip, triode amplifier and reverser were used in the STC design.

The principle of STC is described as follows. In the case of an input high-level signal, it is elevated to 12 V by using a triode amplifier circuit and reversed to low-level via a reverser 4096. When the input signal is a low-level signal, it is increased to 12 V and transmitted to the triggering interface of chip 4096 directly. Resistor R3 and capacitor C1 can be used to adjust the pulse width of the output pulse signal of flip-flop 4538. Furthermore, due to the influence of bypass capacitance in the power-off signal interface of the impulse signal generator, an emitter follower circuit using triode Q2 and resistor R4 can improve the output current and enhance the loading performance. With 3 V, an input step signal, a 10-V and 10-μs positive pulse can be produced, shown in Fig. 3.

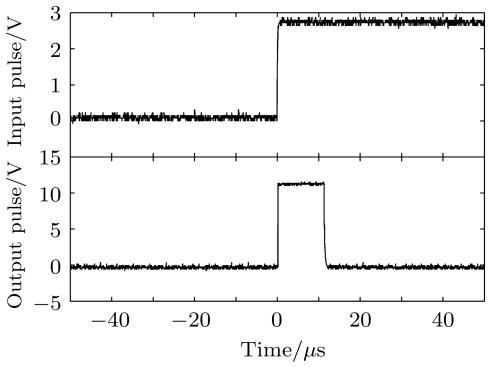


Fig. 3. Input and output waveforms of the signal transferring circuit.

4. Measurement result and discussion

The measurement results of the repetitive nanosecond-pulse breakdown experiment are shown in Figs. 4 and 5. In this case, the thickness of the PTFE film was 0.5 mm, applied voltage was 80 kV, and PRF was 250 Hz. Applied voltage, breakdown voltage and current, and displacement current were recorded by WR204Xi. After repetitive pulses were applied and the breakdown occurred, the power supply was turned off and the measured TBD was given in Fig. 5. It can be found that breakdown voltage is about 40 kV and repetitive nanosecond-pulses last about 1.16 s. In addition, figure 4 gives the waveforms of applied voltage and displacement current, which were measured when only one pulse was applied and there occurred no breakdown. Generally, the pulse number can be counted by a counter connected with the trigger modulator.[6,14] In this case, the number of applied pulses can be calculated and it is about the product of TBD and PRF. For the case in Fig. 5, the calculated number of applied pulses was about 290. However, it should be pointed out that because the pulse number was calculated by using TBD and PRF, the calculated number was also subject to some error and would be magnified with applied PRF.

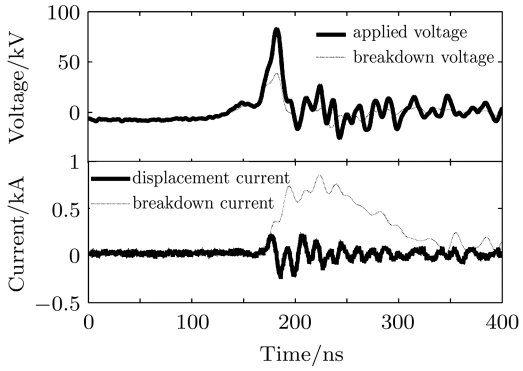


Fig. 4. Typical waveforms of voltage and current.

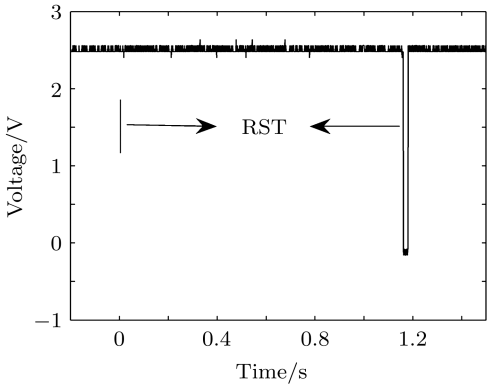


Fig. 5. Measured time-to-breakdown duration.

When the first pulse was applied and breakdown occurred, both of the output pulses produced by the impulse signal generator and the step pulse provided

by the triggering feed-back port of WR204Xi were produced and are illustrated in Fig. 6. It can be seen that a pulse signal was imposed on the output pulse produced by the signal generator and the breakdown occurrence is indicated. Moreover, the time interval was about 22 μs, and the actual TBD can be obtained by subtracting the time interval from the measured data. Therefore, in order to ensure the reliable shutoff of the power supply, PRF of applied repetitive pulses should be below about 40 kHz to ensure the reliable shutoff of the power supply. If the applied PRF exceeded 40 kHz, when breakdown was observed and before STC turned off the power supply, some high voltage pulses would still be applied to the broken-down dielectric sample, and the consecutive over-currents would damage the power supply.

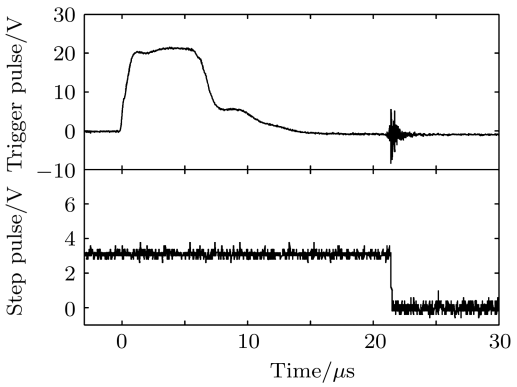


Fig. 6. Measured time-to-breakdown duration error.

Figure 7 represents experimental data of TBD as a function of PRF for four applied voltages, i.e. 75, 77.5, 80 and 85 kV. In this case, the tested PTFE film was 0.5 mm in thickness and each experimental data point was repeated 3 times. It can be seen from Fig. 7 that the measured TBD reduces rapidly with the increase of applied PRF, and the experimental value of TBD is nearly zero when PRF is up to 1 kHz. It can also be found that there is little difference in measured TBD value when both PRF and applied voltage are elevated. Therefore, the current experimental data and trend are in agreement with our early experimental results in electrical breakdown of air.[8−10] It can be concluded that repeated pulse breakdown is characterized by an accumulation or memory effect. In this case, the gap is not fully bridged after consecutive pulses until the appearance of a breakdown pulse and the breakdown is a single event. Though the bridge of the gap is not complete during consecutive pulses, these repeated pulses might result in the appearance of many ions and excited neutral species. It can be speculated that the species created by the repetitive pulses will remain between the electrode gaps. The population of residual charges and metastables depends strongly on the applied PRF and TBD, and the loss is mainly due to the basic processes of recombination, attachment, deactivation, and diffusion. Furthermore, the remarkable reduction of TBD with applied PRF would be attributed to thermal breakdown,[8,14,15] and the importance of thermal effects should also be taken into account.

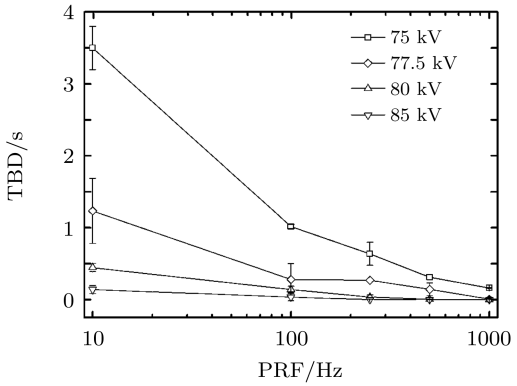


Fig. 7. TBDs as a function of PRF for four applied pulse-voltage values.

5. Conclusion

The measurement and control system is simple, accurate and real-time, which can meet the requirement of the experiments. To avoid over-current damage, an STC using the triggering feed-back port of the recorder is designed to turn off the power supply. Moreover, TBD can be measured and the applied pulse number can be calculated. This system could also be used in other breakdown experimental investigation and some occasions where the power supply needs a real-time shutoff. For example, in a repetitive nanosecond-pulse dielectric barrier discharge,[16] discharge current may exceed an allowable value and the system can be used to avoid large current damage to the power supply.

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