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This study aimed to clarify the basic process of streamer propagation in mineral oil at bipolar oscillating impulse voltage. Shadow images and light signals of streamers showed that under bipolar oscillating impulse, positive and negative streamers propagated in an alternating manner: after polarity reversal, new streamers with opposite polarity were initiated and propagated first through the gaseous channels left behind by former streamers and then toward the ground electrode. The velocity of positive streamers was found nearly an order of magnitude higher than that of negative ones; thus, positive streamers are primarily responsible for the insulation failure of mineral oil. Negative streamers played the role of maintaining gaseous channels and facilitating positive streamers initiation due to their strong heat effect. High oscillation frequency and large damping factor decreased the durations and amplitudes of positive peaks, which restrained positive streamer propagation and further resulted in the increase in the breakdown voltage. Experiments on dielectric behavior of mineral oil were conducted to verify above inferences. *Published by AIP Publishing*. https://doi.org/10.1063/1.5041527

I. INTRODUCTION

Mineral oil is a common insulating medium in electrical equipment such as transformers and reactors; it is popular for its high dielectric strength and cost effectiveness. Many researchers and developers have investigated the dielectric behaviors of mineral oil in recent years,[1–3] while most of the extant studies on liquid prebreakdown phenomena have been conducted under either unipolar impulse voltage or steady-state voltage.[4–6]

Some recent reports indicate that as the complexity of the power grid increases, oil-insulated equipment are frequently stressed by bipolar oscillating impulses due to the wave processes in transmission lines or inside the windings which also pose a serious risk to the oil insulation.[7,8] The invasive bipolar oscillating impulse usually has a steep front and an oscillation frequency that varies from tens of kHz to several MHz.[9,10] So far, few researchers have conducted experiments on the breakdown of oil-paper insulation under bipolar oscillating impulse voltage with different waveform parameters,[11–13] and the mechanism underlying the dielectric behavior was not clarified. Mineral oil, as the main component of oil-paper insulation, is a crucial research object, but there have been no previous studies on prebreakdown in mineral oil under bipolar oscillating impulse; further, though streamer propagation under unipolar impulses, such as the lightning impulse, has been widely studied, the basic propagation process under bipolar impulse remains unclear, and it is believed that unique phenomena are very likely to be observed because of the existence of zero crossing points. Besides, the awareness of streamer propagation under the bipolar oscillating impulse is the basis of evaluating its damage to oil-insulated equipment.

In this study, shadowgraphs and light signals of streamers were recorded to clarify the basic process of streamer propagation in mineral oil under the bipolar oscillating impulse. The different characteristics and roles of positive and negative streamers were discussed. We also analyzed the effects of the damping factor and oscillation frequency on streamer propagation and discharge characteristics, verified by corresponding experiments.

II. EXPERIMENTAL TECHNIQUES

A. Definition of waveform parameter

As shown in Fig. 1, we defined the waveform parameters of the bipolar oscillating impulse to provide visual representation of our experimental results. The components of the graph include the following: (1) a homo-peak and a hetero-peak—oscillating peaks with polarity that is consistent with the first peak are denoted as homo-peaks, while others are denoted as hetero-peaks. (2) Voltage polarity: the applied impulse polarity is defined as the polarity of the first homo-peak. (3) Amplitude U_p: the applied impulse amplitude is defined as the peak value of the first homo-peak. (4) Oscillation frequency f: the reciprocal of the time duration between the nth and $n+2$th zero crossing points ($n > 1$). (5) Damping factor D_f: the voltage difference between the first and second homo-peak divided by U_p (similar to the definition in IEC 60060-3[14]). (6) Front time T_1: the definition we use here is the same as that in IEC 60060-1.[15] (7) Polarity reversal: polarity reversal hereinafter refers to either the voltage peak polarity changes from positive to negative or from negative to positive.

B. Experimental procedure and method

Figure 2 shows a schematic diagram of the experimental platform and the test chamber. The response time of the

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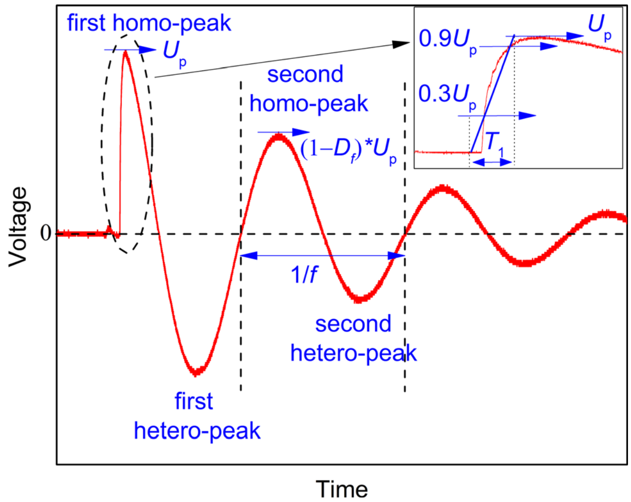

FIG. 1. Waveform parameters of bipolar oscillating impulse (positive impulse as an example).

resistive-capacitive voltage divider is 15 ns, and its ratio is 5208:1. We used Kunlun KI25X transformer oil as our test mineral oil. Before experiments, the oil was degassed and dried in a vacuum drying oven (70 °C) under 4 kPa pressure for 48 h to guarantee the moisture content below 12 ppm. We used stainless steel rod and plane electrodes to minimize the effect of electrode erosion and would be polished (surface roughness $< 0.5\,\mu$m) before each series of experiments. The curve radii of the rod and plane are 0.25 and 15 mm, respectively, and the gap distance was fixed at 3 mm. Oil circulation was done for 5 min after each breakdown to guarantee insulation recovery, and the chamber was reloaded with new portion of oil after every 30 breakdowns. The shadow imaging system including the high speed framing camera (HSFC, HSFC Pro manufactured by PCO Corporation) and xenon lamp (GLORIA-500A manufactured by Zolix Corporation) was utilized. A photomultiplier tube (PMT, PMTH-S1 manufactured by Zolix Corporation) was used to record light signals of streamers.

We adopted the step-up method to acquire the probability distributions of breakdown voltages under impulses with various waveform parameters:[18] the initial amplitude of the applied impulse is u_0, which is very unlikely to result in insulation failure; the voltage is then increased at an increment of Δu until breakdown occurs. 50% breakdown voltage was then calculated as the reference value. The increment Δu was 2 kV ($<4\%$ u_0) in our experiment, and each series of experiments included no fewer than 30 breakdowns.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Basic process of streamer propagation

Figure 3 shows typical shadow images of streamer propagation under the positive bipolar oscillating impulse. The shadows are gaseous channels induced by the heating of streamers.[5,6] Our shadow images indicate that the streamers under bipolar impulse propagate in an alternating manner. During the first homo-peak, bush-like positive streamers are initiated and move forward, leaving behind gaseous channels (images A and B). After polarity reversal, some thin shadow channels dissipate, but main shadow channels are observed to become thicker gradually from the root, indicating that filamentary-like negative streamers are initiated and propagate from the surface of the rod electrode (image C). Contrary to those under the unipolar impulse, negative streamers under the bipolar impulse are much more directional: they first propagate through the main gaseous

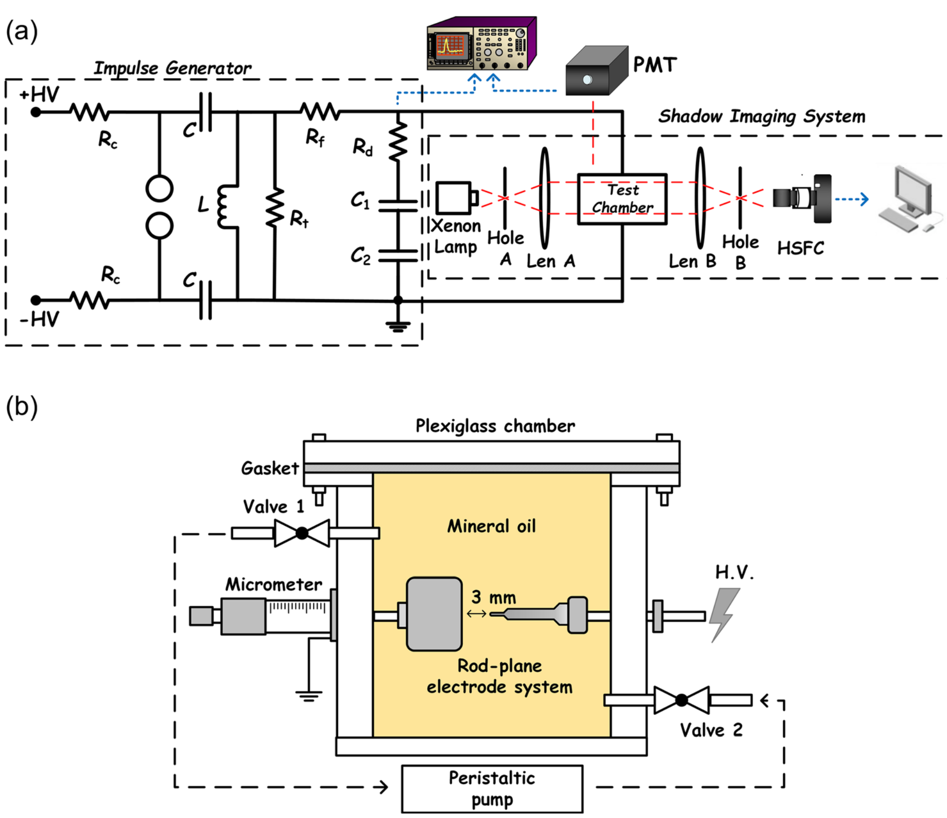

FIG. 2. Experimental platform (a) and test chamber (b).

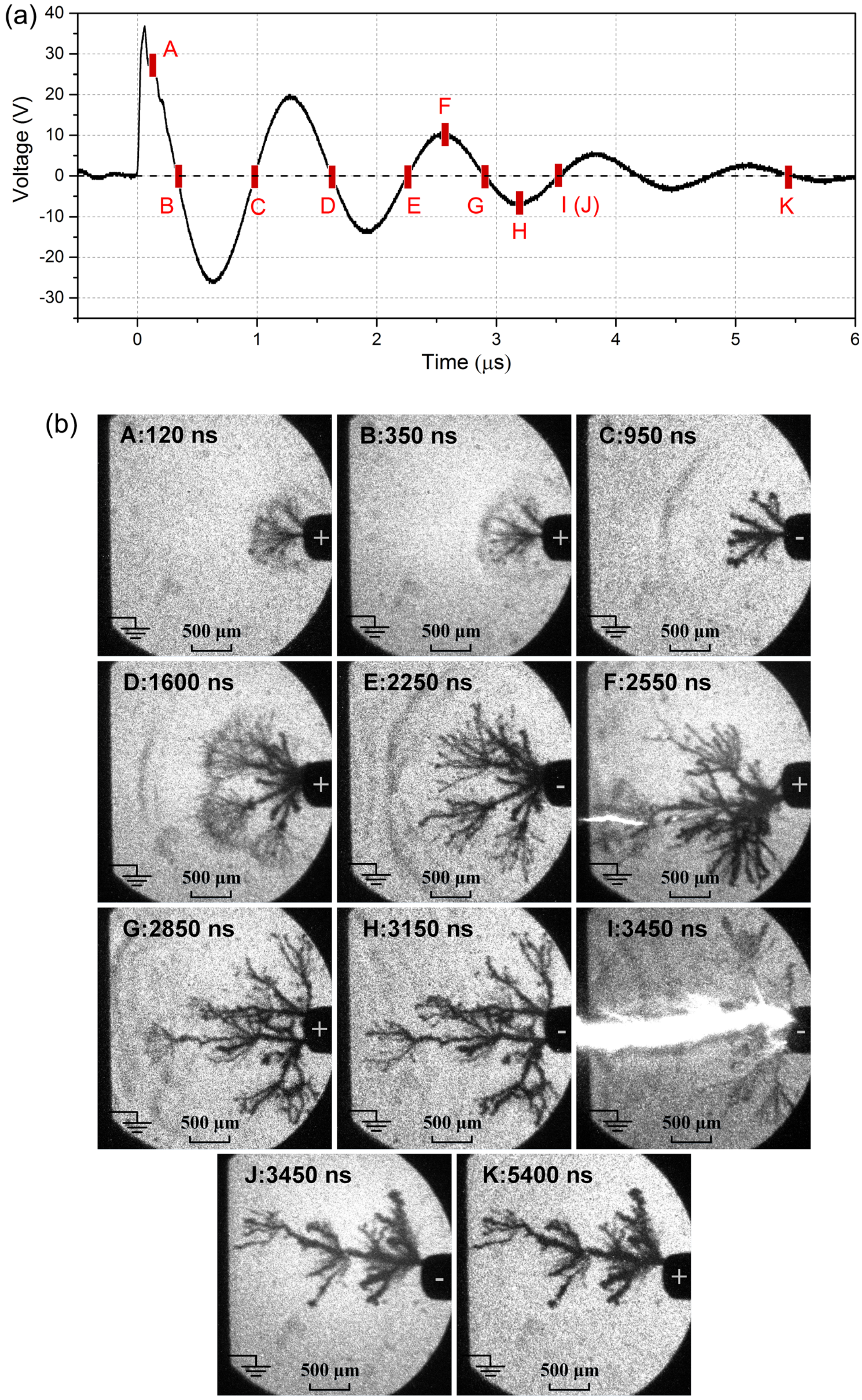

FIG. 3. Alternating propagation of streamers under bipolar impulse. (a) Impulse waveform and shoot moment: oscillation frequency $f = 788$ kHz and damping factor $D_f = 0.45$. (b) Shadow images of streamers, exposure time: 100 ns. Note that images in the same row are photographed during the same discharge process; images in the second, third, and fourth rows show breakdown occurring at the positive peak, negative peak, and lacking discharge, respectively. The sign +/- on the needle electrode indicates the voltage polarity at the imaging moment.

channels left behind by previous positive streamers due to their lower electrical strength, and then continue to propagate. When mineral oil is stressed by the second homo-peak, positive streamers are initiated again and propagate through the gaseous channels left by negative streamers. The positive streamers then continuously propagate toward the plane and form new traces (image D). Contrary to those formed by negative streamers, gaseous channels formed by positive streamers are much thinner and always covered by former channels initially. Thus, the inference that new positive streamers are also initiated at the rod electrode and then propagate through the gaseous channels, instead of being initiated directly at the end of gaseous channels, is not based on the shadow images but on the recorded light signals. Figure 4 shows typical light signals of streamers recorded by PMT. We found that when the applied impulse enters into a positive peak, a light signal pulse with a much higher amplitude can always be observed, indicating the occurrence of

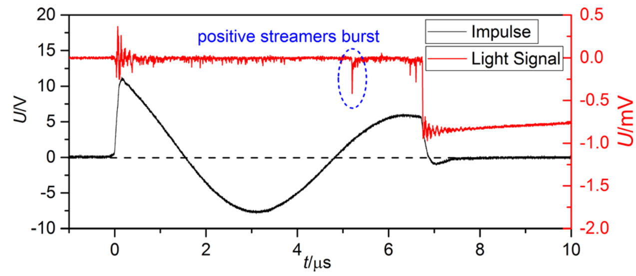

FIG. 4. Light signals of streamers under the bipolar impulse. Oscillation frequency $f = 155$ kHz and damping factor $D_f = 0.45$.

streamer discharge. However, none of the shadow images recorded around this moment showed the occurrence of bush-like positive streamers, and only gaseous channels left behind by former negative streamers were observed. Hence, it is arguably to believe that the burst of the light signal is induced by the discharge in gaseous channels, i.e., new positive streamers are initiated at the rod electrode and propagate through the gaseous channels first after polarity reversal.

Above phenomena continue until one kind of streamer reaches the ground electrode or the propagation stops at a certain positive peak (because initiation voltage of the positive streamer is comparatively higher). Shadow images D–I in Fig. 3 show the breakdown processes caused by positive and negative streamers, respectively.

For better understanding of the basic process, a schematic model of streamer propagation is depicted in Fig. 5: (1) Before the first polarity reversal, positive streamers initiate and propagate, leaving gaseous channels behind; (2) After first polarity reversal, negative streamers initiate and propagate through the main (thicker) gaseous channels left behind by former positive streamers. Some thin gaseous channels dissipate. Due to the low velocity, negative streamers could only advance a little further after passing through the gaseous channels. (3) After the second polarity reversal, positive streamers initiate again and propagate first through the gaseous channels left behind by former negative streamers, then continuously toward the plane. Positive streamers could propagate much further because of the higher velocity. (4) Above processes revolve until one kind of streamer reaches the plane or the propagation stops due to the decrease in applied voltage. The propagation of streamers under a negative bipolar oscillating impulse is similar, except that the streamers first initiated at the surface of the rod electrode are negative.

B. Different characteristics and roles of positive and negative streamers

Based on shadow images, we calculated the velocities of negative and positive streamers under the bipolar oscillating impulse with different waveforms and amplitudes. We found that the positive streamer velocity is 3–6 km/s, and the negative streamer velocity is 300–600 m/s; an increase in applied impulse amplitude increases the velocity of streamers, i.e., allows the streamers to propagate further. The streamer velocities are quite similar to those under a double-exponential impulse.[16] Besides, the velocity of negative streamers propagating through the gaseous channels may exceed 5 km/s, while the velocity of positive streamers passing through the channels is difficult to be calculated because the positive streamers are difficult to be tracked in gaseous channels.

Considering that negative streamers could only move forward slightly after passing through the gaseous channels because of the low velocity while the positive streamer propagation is remarkable, the initiation and propagation of positive streamers contribute significantly to the insulation failure of oil gap. The propagation of positive streamers are strictly controlled by the durations of positive peaks, but their initiation is greatly affected by the negative streamers, to be more precise, the gaseous channels left behind by negative streamers. We found that in all cases, the positive streamers are bound to be initiated if former negative streamers exist until breakdown occurs or the amplitude of the positive peak lowers to about 20% U_P [e.g., the 4th homo-peak in Fig. 3(a)]. This is understandable because, according to the bubble theory for impulse breakdown in liquids,[17] the first step for the positive streamers to be initiated is to heat the oil around the high-voltage electrode to the gaseous state. Thus, the requirement for positive streamer initiation can be markedly reduced if gaseous channels already exist. Besides, it is found that gaseous channels left behind by positive streamers are thin and dissipate in hundreds of nanoseconds, while those left behind by negative streamers are much thicker and can last for tens of microseconds, indicating their stronger ability of heating oil to the

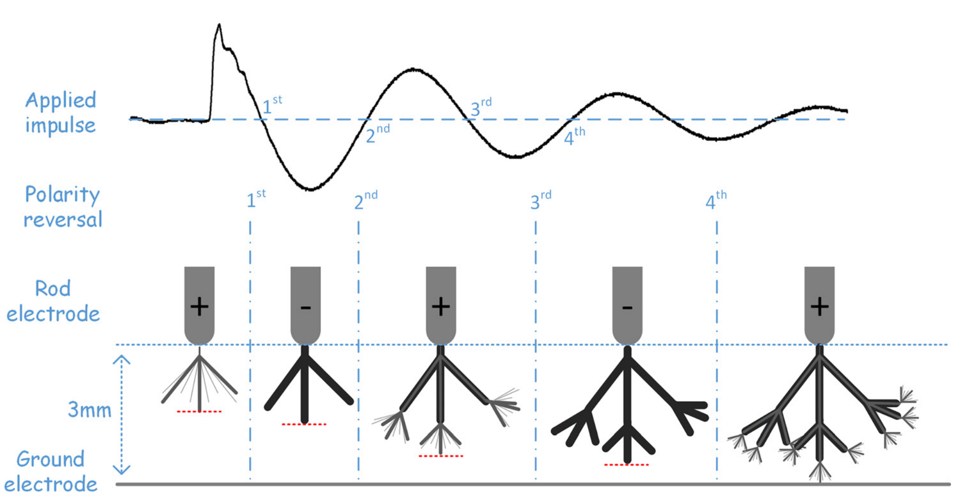

FIG. 5. Schematic model of streamer propagation under bipolar oscillating impulse. Lines in black, dark grey, and light grey represent gaseous channels left by negative streamers, primary positive streamers, and secondary positive streamers, respectively. Line thickness is corresponding to the thickness of a gaseous channel. The sign +/- on the needle electrode indicates the voltage polarity at the imaging moment.

gaseous state. Consequently, the role played by negative streamers is to maintain gaseous channels and facilitate positive streamers initiation.

The density perturbations shown in Fig. 3(b) (images B C) are believed to be shock waves, because their velocity is 1.6–1.8 km/s, similar to the sonic speed in liquid. As a result, these perturbations were only observed when the oil was stressed by negative peaks, because their velocity is lower than positive streamers but higher than negative streamers.

C. Effects of the damping factor and oscillation frequency on discharge characteristics

Considering that discharge characteristics of mineral oil under bipolar oscillating impulse with various waveforms are usually concerned by researchers, we conducted a series of experiments on the effects of the damping factor and oscillation frequency on the breakdown of mineral oil. Figures 6 and 7 show the variations of 50% breakdown voltages under bipolar impulse with different damping factors and oscillation frequencies. We found that both the positive and negative 50% breakdown voltages linearly increase as the damping factor increases; both the positive and negative 50% breakdown voltage decreases sharply as oscillation frequency decreases, but stabilizes at the low-frequency portion. Considering that the bubble theory about impulse breakdown in liquids remains unchanged when the duration of applied impulse changes from tens of nanoseconds to hundreds of microseconds,[17] it is believed that the change laws are valid when the oscillation frequency is higher than 10 kHz but lower than 10 MHz.

As mentioned earlier, positive streamer propagation dominates the discharge in mineral oil under the bipolar impulse; thus, the breakdown voltage is generally related to the durations of positive peaks. As the damping factor or oscillation frequency increases, the durations of positive peaks are compressed and the time for positive streamers to propagate is shortened. As a result, a higher voltage is crucial to increase the streamer velocity to ensure that streamers advance the same distance in a shorter time. When the oscillation frequency is only tens of kHz, the 3-mm oil gap is bound to be bridged at the first few positive peaks where the pulse duration is sufficiently long. This weakens the effects of oscillation frequency, which explains our experimental observation that the breakdown voltage tends toward stability at the low-frequency region. For that the oscillation frequency of bipolar impulse invading into oil-insulated equipment is usually determined by the external circuits and cannot be changed randomly, it is more appropriate to increase the damping factor to protect the equipment.

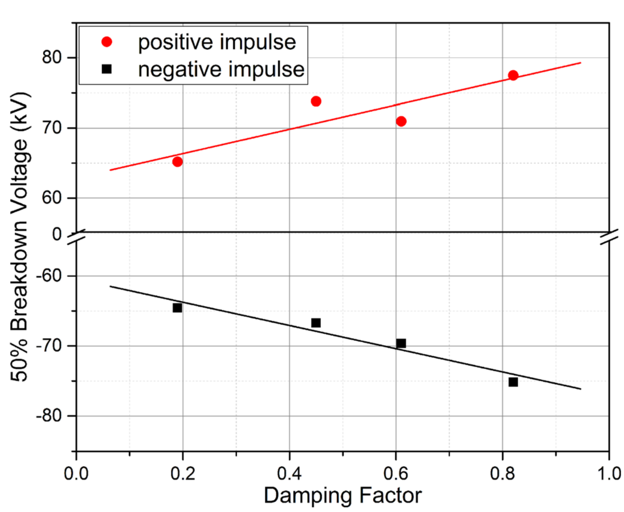

FIG. 6. Relationship between 50% breakdown voltage and the damping factor. Oscillation frequency $f = 77$ kHz.

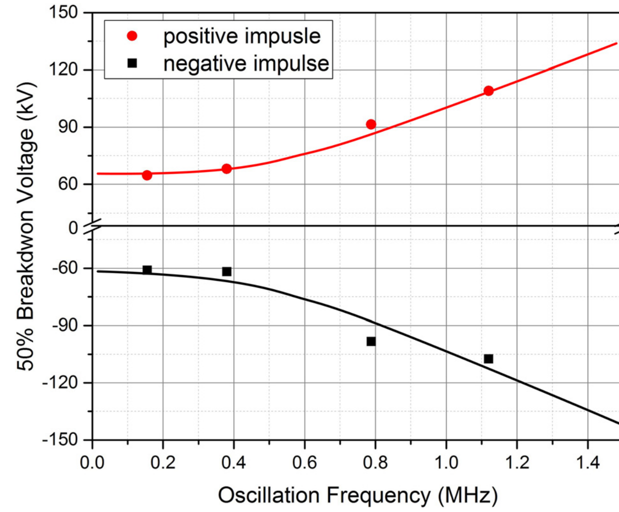

FIG. 7. Relationship between 50% breakdown voltage and the oscillation frequency. Damping factor $D_f = 0.45$.

Typical breakdown moments statistics are shown in Fig. 8. We found that breakdown frequently occurs at positive peaks in all cases, and as the damping factor and oscillation frequency increase, the breakdown moment tended to move back to later peaks. These phenomena offer another perspective on the dominance of positive streamers in mineral oil discharge and sufficient durations of positive peaks is proved to be a significant condition for breakdown.

IV. CONCLUSIONS

In this study, the basic process of streamer propagation in mineral oil at bipolar oscillating impulse voltage was clarified based on shadow images of streamers. The differences between the positive and negative streamers were revealed, and the roles played by them were discussed. Experiments on dielectric behavior of mineral oil were conducted to determine the effect of the damping factor and oscillation frequency. Our conclusions can be summarized as follows.

(1) Shadow images of streamers show that streamers in mineral oil under the bipolar oscillating impulse propagate in an alternating manner: positive/negative streamers are initiated at the first homo-peak; after polarity reversal, new streamers with opposite polarity are initiated and first propagate directionally through the main gaseous channels left behind by former streamers and then toward the ground electrode at random, forming new gaseous channels; above phenomena continue until one kind of streamer reaches the ground electrode or the propagation stops at a certain positive peak.

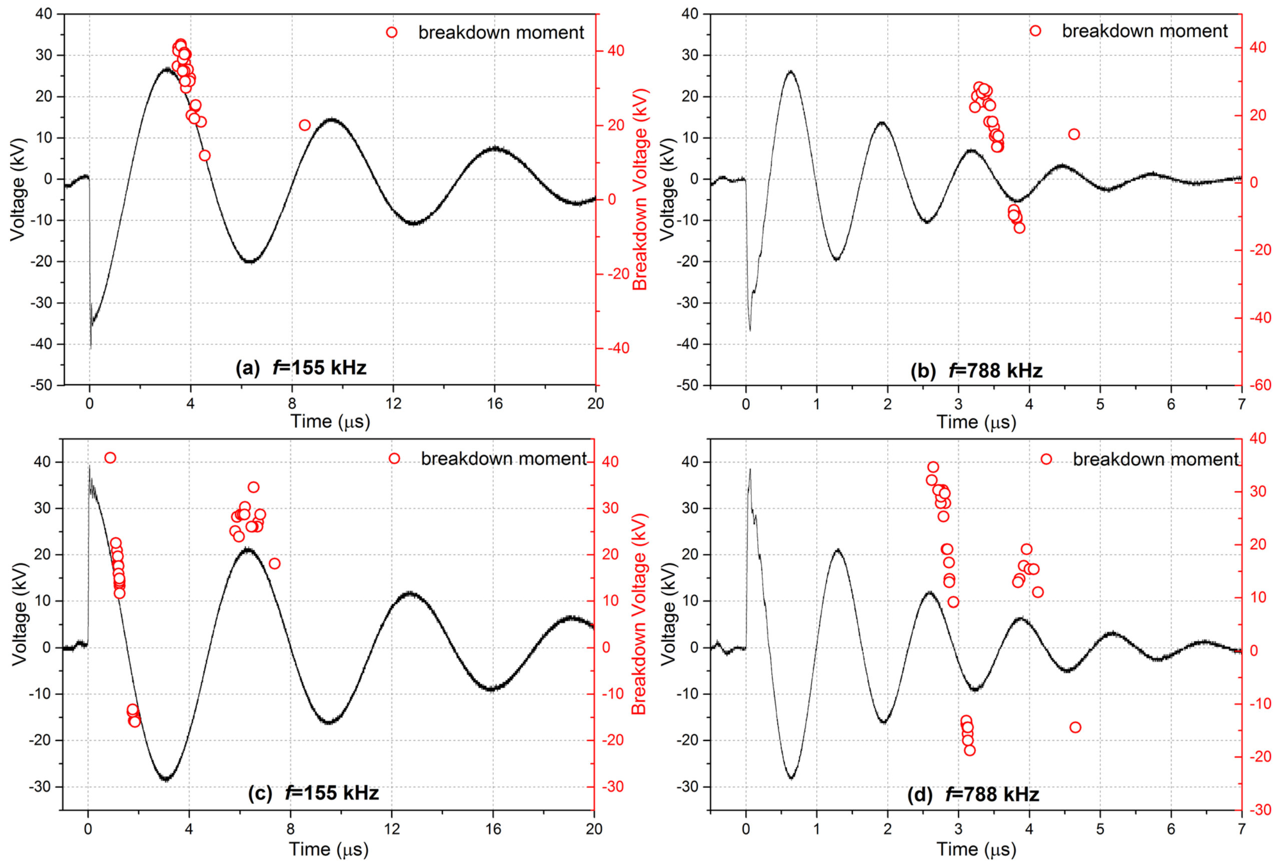

FIG. 8. Typical distributions of breakdown moments under bipolar oscillating impulse. Damping factor $D_f = 0.45$.

(2) Differences between the positive and negative streamers mainly lie in their velocity and heat effect. Positive streamers significantly contribute to the insulation failure of mineral oil due to their high velocity, which also accounts for the high probability of discharging at positive peaks. Negative streamers play the role of maintaining gaseous channels and facilitating positive streamers initiation due to their strong heat effect.
(3) High oscillation frequency or large damping factor decreases the duration of positive peaks, in which case high voltage is needed to accelerate the propagation of positive streamers and guarantee breakdown. Considering that the oscillation frequency of bipolar impulse invading into oil-insulated equipment is usually determined by the external circuits and cannot be changed randomly, it is more appropriate to increase the damping factor to weaken the damage to equipment.

ACKNOWLEDGMENTS

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