# Inception and Breakdown Voltages of Insulating Liquids under DC Stress

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# Inception and Breakdown Voltages of Insulating Liquids under DC Stress

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*Abstract*—**This paper investigated the streamer inception and breakdown properties of a mineral oil and a synthetic ester liquid under DC stress up to 100 kV. To observe the effect of tip radius on streamer inception, the point-plane electrodes configuration with a fixed gap distance of 10 mm and point electrode with the radii of 5 µm, 10 µm, 20 µm and 50 µm were used. To observe the effect of gap distance on breakdown voltage, a point-to-plane electrode configuration with a fixed tip radius of 10 µm and variable gap distances of 2 mm, 5 mm, 10 mm, 20 mm and 30 mm were used. Streamer current and emitted light signals were measured by using a 10 Ω current shunt and photomultiplier tube (PMT) respectively. The results indicated that initiation voltages of the synthetic ester liquid are slightly lower than those of the mineral oil for all the tip radii under both positive and negative polarities. Moreover, the synthetic ester liquid has lower breakdown voltages than the mineral oil for all the gap distance under both positive and negative polarities**

***Keywords— Transformer, Streamer, insulating liquids, dc voltage, breakdown***

## I. Introduction

Transformers as one of the major components were introduced in high voltage power networks since the late nineteenth century. Nowadays there is an increasing interest in applying High Voltage Direct Current (HVDC) transmission lines in long-distance or submarine bulk energy transmission [1]. In HVDC transmission systems, converter transformers are the essential components. The insulation systems of HVDC converter transformers could suffer from dc biased ac stress [2]. In recent decades, discharge and breakdown of insulating liquids under ac and impulse voltages have been studied extensively. To understand discharge phenomena in HVDC convertor transformer, it is worth investigating the phenomena under dc stress and dc biased ac stress.

In the insulation system of transformers, transformer oil is a key component, as it performs as the dielectric material, the cooling medium as well as the information carrier. Ester liquids including both natural ester and synthetic ester are being considered as potential alternatives to mineral oil, due to their better environmental performance and for some liquids their higher fire point. It is well known that the breakdown in transformer oils is strongly linked to the pre-breakdown phenomena called streamer [3]. To understand the dielectric performances of mineral oils and ester liquids in an HVDC converter transformer, it is worth investigating the pre-breakdown (streamer) and breakdown phenomena of insulating liquids under dc stress.

In past decades, some studies on pre-breakdown and breakdown phenomena of transformer oil under dc stress have been published. Different techniques including discharge current measurement technique [4], ultra-high frequency (UHF) technique [3, 5] and acoustic emission technique [2] were employed. Various insulating liquids including Hexane, mineral oil and semi-conductive nanofluids (SNFs) have been investigated in these papers. In [4], it described that the partial discharge current is in the form of a pulse train which is corresponding to the linear growth of the streamer. The streamer shape and stopping length in Hexane under dc stress have been studied in [4- 6]. Partial discharges under negative polarity were found to closely resemble the structure and growth of the slowest (subsonic) cathode events emanating from a tip under the application of negative impulse voltages. In addition, effect of background pressure on streamer expansion was studied in [7]. The results indicated that the streamer expansion velocity decreases with the increasing pressure under negative polarity. However, a similar experiment using a positive needle indicated no pressure dependence.

This paper focuses on investigations of streamer inception and breakdown voltage of a mineral oil and a synthetic ester liquid under dc voltages. A point-plane electrode configuration with variable gap distances up to 50 mm was used. The point electrodes with the various tip radii of 5 µm, 10 µm, 20 µm and 50 µm were the etched tungsten wire. Streamer current and emitted light signal were recorded for identifying streamer inception and breakdown. The effect of tip radius on inception voltages and the effect of gap distance on breakdown voltages are discussed.

## II. Experimental Descriptions

### A. Etched Tungsten Tips

Due to various tip radii of needles are required to study streamer inception, an electrochemical method to etch tungsten wire according to [8] was adopted. To process etching, a piece of tungsten wire is used as the cathode electrode in the potassium hydroxide (KOH) liquid solutions. Another smooth and straight tungsten wire to be etched is used as the anode electrode. A 5 mol/L KOH is used as the electrolyte for tungsten etching.

Based on the electrochemical method, needles with various tip radii could be produced under carefully controlled procedures. In this paper, needles with tip radii of 5 µm, 10 µm, 20 µm and 50 µm were produced by using original 200 µm tungsten wire. After the etching, all etched needles were examined and selected by using a microscope to ensure the tip surface is smooth, as shown in Fig. 1. The acceptable tip radius range is set as ± 10 % of the expected value.

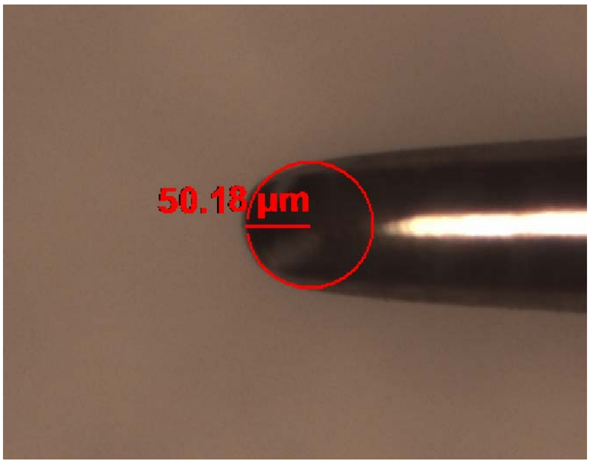



Fig. 1. Typical etched tungsten wire with tip radius of 50 µm, zoomed in under microscope

### *B. Test Setup*

The test setup used in measuring inception and breakdown voltages under dc stress is shown in Fig. 2. A 10 ×10 ×10 cm cubic test cell with a volume of 1 litre made by Perspex materials was used to hold the point electrode. A high-voltage dc source with a maximum voltage of 125 kV was used to deliver the continuous dc voltage. A 2 MΩ resistor was placed in series with the dc source and the test cell to limit the breakdown current as well as to protect the high-voltage dc source. A compensated RC voltage divider (VD-100) was used to measure the dc output voltage. A current shunt (10 Ω) was placed at the low voltage potential side of the test cell to record the current signals. A photomultiplier (PMT) next to the test cell was employed to capture emitted light signals. The test cell contained a point-to-plane electrode system with an adjustable gap distance ranging from 0 to 50 mm. The point electrodes with the tip radii of 5 µm, 10 µm, 20 µm and 50 µm were produced based on electrochemical technique as mentioned in section A. The plane electrode is a brass electrode with a diameter of 70 mm. All the experiments were carried out at room temperature and ambient pressure.

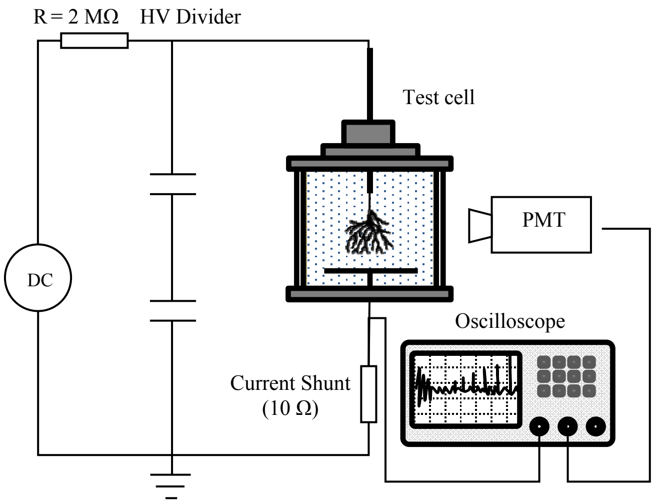



Fig. 2. Sketch of experimental setup

## III. Effect of Tip Radius on Inception Voltage

The probability of the inception voltage was determined by using a rising-voltage method. The initial voltage applied was set at 60% of expected streamer inception voltage. Then, the applied voltage was increased in steps of 1 kV until streamer inception occurred. For each step of applied dc voltage, 60-second duration was applied to allow the capturing of streamer inception, and a minimum of 60-second interval was used between different steps. Finally, 20 streamer inception voltages per sample were obtained to determine the 50 % streamer inception voltage under tip radii of 5 µm, 10 µm, 20 µm and 50 µm. The test cell was filled with clean oil samples and kept still for 30 minutes before the test.

An example of typical current and emitted light signal of streamer inception in the mineral oil and the synthetic ester liquid observed under both positive and negative polarities are shown in Fig. 3. Due to possible noise in the current signal, the emitted light signal corresponding to current signal was used to prove streamer inception. Under positive polarity, the current and emitted light signals were more intensive and consist of continuous current components with large discrete pulses. Under negative polarity, normally one single pulse was detected for both the current and light signals. And the time duration of negative pulses was extremely short, i.e. no more than 100 ns. The maximum pulse peak of current signals remains at about a few mA at inception stages for both Gemini X and MIDEL 7131 under positive and negative polarity. Higher magnitudes of emitted light signals were recorded under positive polarity, which gives an indication that streamer inception under positive polarity, is brighter than under negative polarity.

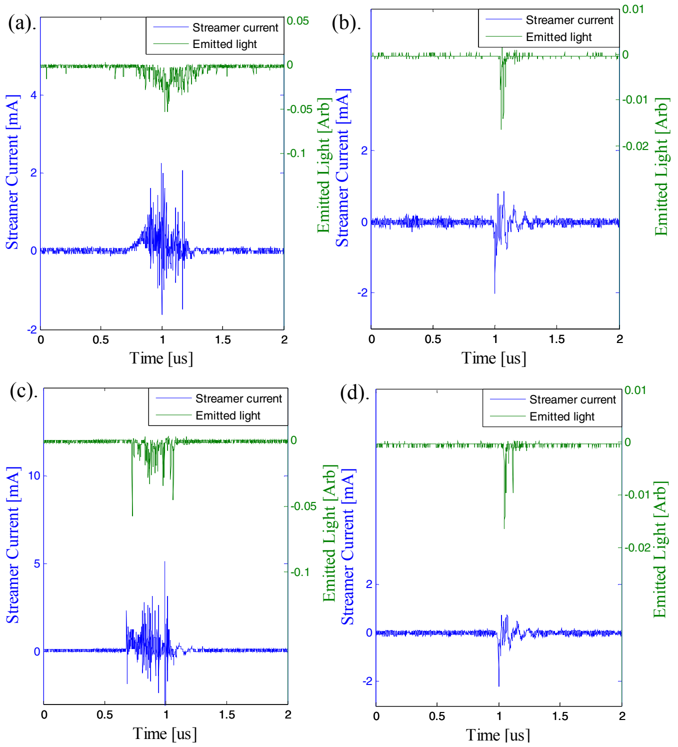
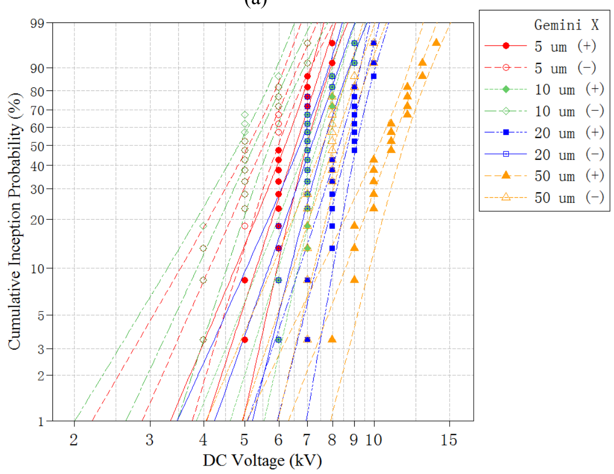



Fig. 3. The current and emitted light signals of streamer inception under DC stress (a). Mineral oil – positive polarity, V = 8 kV (b). Mineral oil – negative polarity, V = 7 kV (c). Synthetic ester – positive polarity, V = 7 kV (d). Synthetic ester – negative polarity, V = 6 kV; d = 10 mm, r = 10 μm.

To statistically analyse the inception voltage, Weibull distribution was used to fit the inception results and to calculate 50% streamer inception voltage. Weibull distribution plots of the streamer inception voltages obtained under various tip radii of the mineral oil and the synthetic ester liquid are shown in Fig. 4, and parameters are summarised in Table I.

(a)




(b)

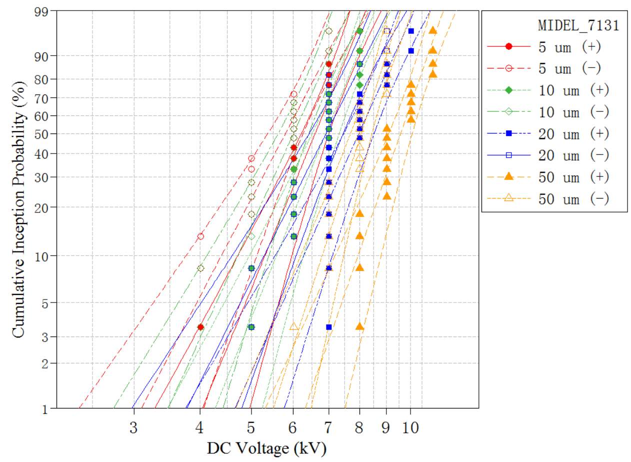



Fig. 4. Weibull distribution plot of inception results with various tip radius under dc stress, (a) Gemini X, (b) MIDEL 7131, $d$ = 10 mm.

TABLE I. WEIBULL PARAMETERS OF INCEPTION VOLTAGES WITH VARIOUS TIP RADII AT POINT-PLANE ELECTRODE, NEGATIVE AND POSITIVE POLARITY

| Oil Type | Polarity | Tip Radius (μm) | Shape | Scale | 50 % Breakdown Voltage |
|---|---|---|---|---|---|
| Gemini X | Positive (+) | 5 | 8.8 | 6.8 | 6.5 |
| | | 10 | 9.1 | 7.6 | 7.4 |
| | | 20 | 11.1 | 8.9 | 8.6 |
| | | 50 | 7.6 | 11.5 | 11.9 |
| | Negative (-) | 5 | 6.5 | 5.8 | 5.5 |
| | | 10 | 6.1 | 5.5 | 5.3 |
| | | 20 | 8.1 | 7.4 | 7.1 |
| | | 50 | 8.5 | 8.4 | 8.0 |
| MIDEL 7131 | Positive (+) | 5 | 8.6 | 6.8 | 6.5 |
| | | 10 | 8.7 | 7.1 | 6.9 |
| | | 20 | 7.8 | 8.3 | 7.9 |
| | | 50 | 10.1 | 9.9 | 9.5 |
| | Negative (-) | 5 | 6.7 | 6.1 | 5.7 |
| | | 10 | 7.7 | 6.2 | 6.0 |
| | | 20 | 6.9 | 7.2 | 6.9 |
| | | 50 | 11.0 | 8.3 | 8.0 |

The Fig. 5 shows the effect of tip radius on streamer inception voltage of the mineral oil and the synthetic ester liquid under dc stress. With the increase of tip radius, streamer inception voltages of both positive and negative streamers increase with tip radius. Polarity effect was observed that inception voltage under negative polarity is slightly lower than that of positive polarity. It is because, positive space charges accumulated ahead of the positive point weaken the near tip field and suppress streamer inception under positive polarity, while positive space charges accumulated ahead of the negative tip enhance the near tip field and then decrease the inception voltage under negative polarity. Under positive polarity, when tip radius $r$ = 5 μm, the inception voltages of the mineral oil are the same as that of the synthetic ester liquid; when r > 5 μm, inception voltage of the mineral oil becomes noticeably higher than that of the synthetic ester liquid. However, under negative polarity, the inception voltages of the mineral oil are almost the same as those of the synthetic ester liquid for all tested tip radii.

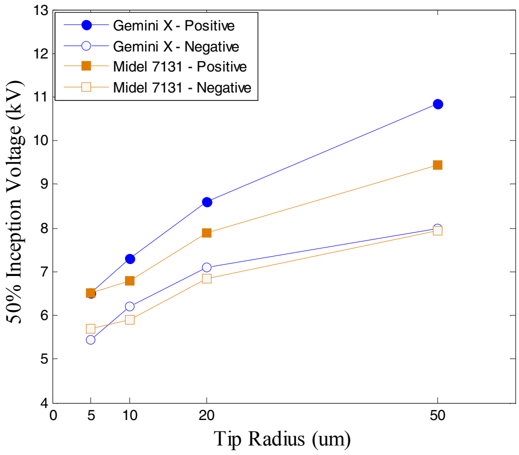



Fig. 5. Effect of tip radius on inception voltage under DC stress, d = 10 mm; based on 50% inception voltage.

## IV. Effect of Gap Distance on Breakdown Voltage

The breakdown voltage was measured by using rising voltage method. The initial voltage applied was set at 70% of expected breakdown voltage. Voltage level was increased step by step with an increase of 2 kV. For each step of applied dc voltage, 60-second duration was applied to allow the capturing of breakdown, and a minimum of 120-second interval was used between different steps. 20 breakdowns per sample were obtained to determine the 50 % breakdown voltage under gap distances of 2 mm, 5 mm, 10 mm, 20 mm and 30 mm.

Breakdown results of the mineral oil and the synthetic ester liquid under positive and negative polarities are shown in Fig. 3. Weibull distribution parameters and the 50% breakdown voltages are summarised in Table II. Strong polarity effect was observed, breakdown voltages under negative polarity are nearly 2.5 times of that of positive polarity. This conclusion is valid for both the mineral oil and the synthetic ester. The reason is, under positive polarity, the concentration of positive charges enhanced the boundary field at the head of the charge cloud, which promotes streamer propagation and then weakens breakdown voltages. However, the diluted negative space charges, like a shielding of the negative tip, weaken the boundary field, which slows down the streamer propagation and then increases the negative breakdown voltage.

(b)

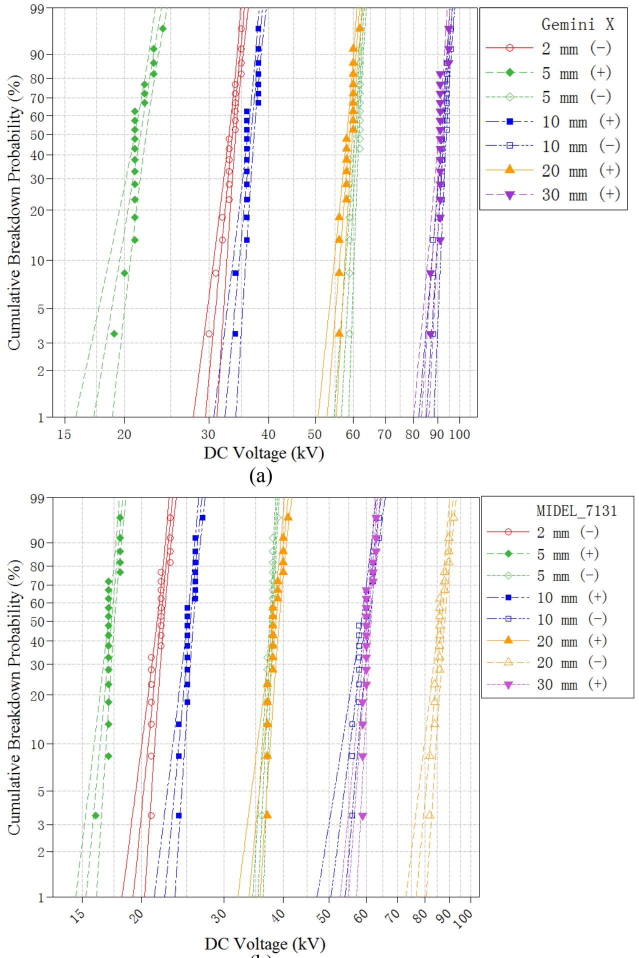



Fig. 6. Weibull distribution plot of breakdown results with various gap distances under dc stress, (a) Gemini X, (b) MIDEL 7131, $r = 10$ µm

TABLE II. WEIBULL PARAMETERS OF BREAKDOWN RESULTS WITH VARIOUS GAP DISTANCE AT POINT-PLANE ELECTRODE.

| Oil Type | Polarity | Gap distance (mm) | Shape | Scale | 50 % Breakdown Voltage |
|---|---|---|---|---|---|
| Gemini X | Positive (+) | 5 | 22 | 18.9 | 21.5 |
| | | 10 | 33.9 | 37.0 | 36.9 |
| | | 20 | 39.1 | 59.5 | 58.9 |
| | | 30 | 44.7 | 92.1 | 91.4 |
| | Negative (-) | 2 | 32.3 | 33.9 | 33.5 |
| | | 5 | 61.4 | 55.9 | 61.0 |
| | | 10 | 49.3 | 93.5 | 92.8 |
| MIDEL 7131 | Positive (+) | 5 | 17.4 | 34.0 | 17.2 |
| | | 10 | 33.7 | 35.6 | 25.4 |
| | | 20 | 37.9 | 39.0 | 38.6 |
| | | 30 | 44.0 | 61.3 | 60.8 |
| | Negative (-) | 2 | 31.6 | 22.2 | 21.9 |
| | | 5 | 37.9 | 59.9 | 37.7 |
| | | 10 | 32.1 | 60.7 | 59.8 |
| | | 20 | 33.8 | 87.7 | 86.8 |

The effect of gap distance on breakdown voltages under both positive and negative dc voltages are shown in Fig. 7. With the increase of gap distance, breakdown voltages under both positive and negative polarities increase with gap distance. The breakdown voltages of the synthetic ester are lower than those of the mineral oil. The difference of breakdown voltage between the mineral oil and the ester liquid increases with the increase of gap distance. This is probably due to that streamer propagates easier and faster in the synthetic ester liquid than in the mineral oil [9].

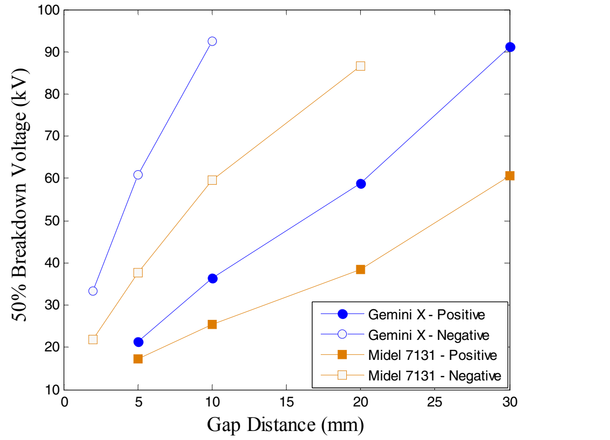



Fig. 7. Effect of gap distance on breakdown voltage under dc stress, $r = 10$ µm; based on 50% breakdown voltages

## V. Conclusion

In this paper, the effect of tip radius on streamer inception and effect of gap distance on breakdown voltages of a mineral oil and a synthetic ester liquid under dc stress in a divergent field were studied. It was found that increase of tip radius results in the increase of inception voltage, and the increase of gap distance leads to increased breakdown voltages under both polarities.

Although inception voltages of the synthetic ester liquid are comparable to those of the mineral oil, breakdown voltages of synthetic ester liquid are nearly 40% lower than that of mineral oil for the investigated divergent needle-plane gaps.

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