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EXPERIMENTAL STUDY OF AIR DISCHARGE UNDER VARIOUS FREQUENCY STRESS WITH INHOMOGENEOUS FIELD

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Abstract

In this paper, air discharges for different frequencies are tested in a point-plane geometry with different air gaps. The stress frequencies vary between 50 Hz to 5 kHz, and air gaps vary from 2.5mm to 10mm. It is observed that the partial discharge inception voltage of the positive corona increases with the increase of frequency, while the inception voltage of the negative corona stays nearly the same. The breakdown voltage increases with the increase of frequency in our test set, and breakdowns happen during negative half-cycle, especially at 5kHz, which is supposed to be caused by the space charges.

1 Introduction

In recent years, power electronics have become more common in power grids due to the development of distributed energy and transportation electrification. In order to achieve high power, the operating voltage gradually rises to the medium voltage level. This, in combination with medium frequency waveforms in these applications, causes the insulation to face a reliability problem. The gas-solid insulation system is a popular choice for the medium-voltage application. Many factors related to this insulation system under new stress were discussed. The effect of frequency on insulation breakdown is one of the widely studied aspects.

In gas-solid insulation, the breakdown faults generally have three types, i.e., solid breakdown, gap breakdown and surface flashover. For solid breakdown, numerous research has shown that higher frequency sinusoidal stress leads to lower breakdown strength [1]–[3] and lifetime [4]–[7]. The reduction of breakdown is attributed to enhanced dielectric loss or increased discharge repetition frequency.

The surface discharge also shows a similar trend as solid insulation. Frisco [8] measured the flashover voltage of a 3/8 inch gap on several materials in the range of 60Hz to 100MHz. It shows that the flashover strength decreases with increasing frequency. The reduction is also observed by [9] Pfeiffer [1] attributed this reduction to the decreasing breakdown strength of air. In [10], tracking resistance was studied under 50-500 Hz stress according to IEC 587. Results show that higher frequency leads to a shorter time to tracking breakdown at the same voltage.

The last one is the gas breakdown. Many gases are studied for different applications. In this work, the focus is on the atmospheric air. The homogeneous field air breakdown has been measured for a wide frequency range. Based on their results, there is a critical frequency where a reduction of the breakdown voltage begins to occur. It is attributed to the fact that ions produced during an avalanche cannot sweep out of the gap within a half cycle. The ions stay in the gap, distort the electric field and eventually reduce the breakdown voltage. When the frequency is above MHz frequencies, the breakdown voltage reaches its minimum. It is because with further increasing frequency, the mobility of electrons also plays a role in the breakdown, and electrons stay in the gap [11], [12]. Therefore, the dielectric strength increases with increasing frequency.

For inhomogeneous field air breakdown, this is also measured by several research contributions. Pfeiffer [1] has shown that the breakdown voltage drops about 50% at 75kHz compared to at 50Hz. Besides, Misere [13] measured the breakdown voltage at atmospheric pressure for 0.5 and 1.0 MHz for a gap greater than 1 cm. The results also showed that a significant breakdown voltage reduction occurs at higher frequencies. Seifert [14] measured the breakdown voltage from 50 Hz up to 30 kHz with the tip having different curvatures. They concluded that the accumulation of positive ions influences the field distribution in gaps, which causes the reduction of breakdown voltage at higher frequencies. Also, the partial discharge (PD) inception voltage for inhomogeneous fields also decreases under high frequency [15].

There are relatively few data points about the air breakdown voltage for an inhomogeneous field under several kilohertz, a common frequency range for power electronic converters. In this paper, air breakdown voltage and partial discharge behaviour with a point-plate electrode in the range of 50 to 5kHz sinusoidal wave are measured and analysed.

2 Test system

The experimental system used for testing breakdown voltage and PD are depicted in

Fig. 1 (a) and (b), respectively. For both applications, an HV amplifier Trek 30/20A is used to amplify the input signal to high voltage. A high voltage probe GE.3830 is used to measures the output voltage. The input signal is produced by a TENUMA 72-14111 function generator. The adjustable point-plate electrodes are shown in Fig. 2. The high voltage electrode is a conical rod made of tungsten, and the ground electrode is made of brass. The support structure is made of plastic. The gap distance can be adjusted in a range.

For the breakdown voltage measurement, a ramping voltage is used, and the peak value of the sinusoidal wave rises at 1kV/s. A DPO 3034 oscilloscope is used to monitor the breakdown voltage and waveform. Although the HV amplifier has internal short circuit protection, an additional short circuit current detector is used to minimise the potential damage of breakdown.

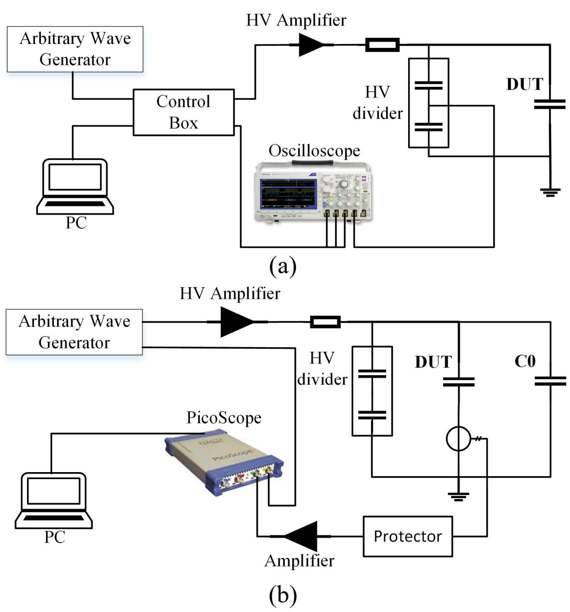

Fig. 1 Experiment setup for (a) flashover test and (b) PD test [16]. This figure has been reproduced with permission from IEEE, 2023.

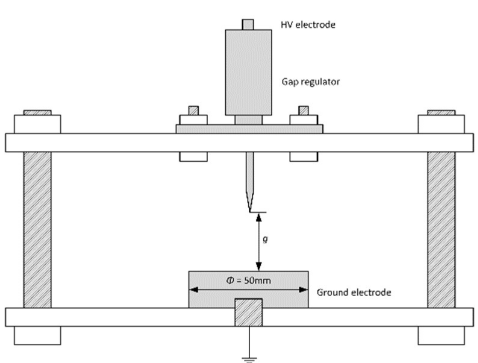

Fig. 2 Schematic diagram of the electrode

For PD measurements, a high-frequency current transformer (HFCT) is used, whose bandwidth is 34.4kHz to 60MHz and gain of 9.1mV/mA. A signal from the HFCT passes through a protection circuitary and an amplifier. The amplifier has 22.2dB gain and bandwidth 25kHz to 900MHz. Due to the limitation of the power amplifier, a coupling capacitor with 50pF is used, which can still guarantee much larger than the capacitance of the gap. PicoScope 6404C is used to collect PD signals. Its bandwidth is 500MHz, and the maximal sampling rate is 2.5Gs/s with two input channels. We acquired 1000 triggered pulses continuously, which are used to get phase resolved partial discharge pattern (PRPDP), and then data is transferred to a computer to process. PD flex [17] is used to analyse the obtained data.

Breakdown voltage and PD measurements are performed from 50Hz-5kHz with different gap lengths g. Each situation was tested more than thirty times. The whole test was done in a laboratory environment. The temperature was controlled at 20 ± 1℃, and relative humidity was in the range of 20% to 30%.

3 Results

3.1 Breakdown Voltage

Mean air breakdown voltages and 99 percent confidence intervals for different combinations of gap and frequency are shown in Fig. 3. The results surprisingly contradict the trend mentioned in the introduction. In all four measured gaps, as frequency increases, the breakdown voltages rise to different degrees compared to the results at 50Hz. The rising under 5kHz is about 10%, 29%, 54% and 45% for 2.5mm, 5mm, 7.5mm and 10mm, respectively. The highest rising occurs at 7.5mm, and the breakdown voltages of 2kHz and 5kHz are close to each other for the 10mm gap, which suggests that there might be a critical frequency where the breakdown voltage starts to decrease for a certain gap.

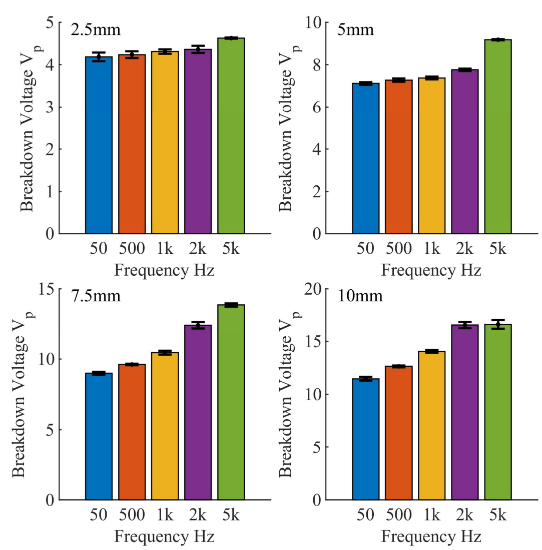

Fig. 3 Mean air breakdown voltage at different frequencies with different gaps. Error bars show a 99% confidence interval.

Of course, the breakdown voltage rising relates to the ion movement in the inhomogeneous field. For the positive point-plane, the electrons produced by ionisation are rapidly absorbed by the anode. The positive space charges move further into the gap, causing field distortion. When the field strength at the tip of positive space charges is high enough, a streamer may be incepted and lead to a breakdown. Therefore, rising breakdown voltage for higher frequencies implies that higher voltage is needed to reach the streamer criterion. In our test range, the frequency might just rise to a high enough level to keep the ions staying in the gap. The negative ions produced in the negative half-cycle left and move back in the positive half-cycle. They could recombine with the generated positive ions during moving and reduce the strength of positive ions. Therefore, a higher voltage is required to achieve the streamer criterion. It might explain why the breakdown voltage increases in our test. Under higher frequency than used in this paper, due to short recombination time and travel distance, positive ions have higher density and are closer to the tip, which leads to breakdown voltage decrease under high frequency [14].

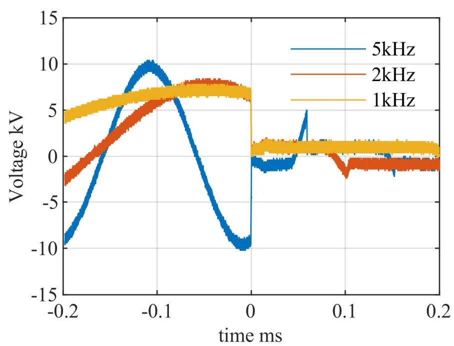

Fig. 4 Breakdown voltage waveform with 5mm gap for 1kHz, 2kHz and 5kHz.

Table 1 Probability of breakdown occurring at negative polarity

Freq Hz \ Gap mm	2.5	5	7.5	10
50	40%	0%	0%	0%
500	36.7%	0%	0%	0%
1k	30%	0%	0%	0%
2k	13.3%	0%	0%	0%
5k	90%	100%	83.3%	0%

Furthermore, the polarity of breakdown was also observed. Fig. 4 shows the voltage waveforms under 1kHz, 2kHz and 5kHz stress for a 5mm gap. The breakdown happens roughly at the peak of the voltage. Unlike 1kHz and 2kHz, the breakdown under 5kHz happens in negative half-cycles. The probability of breakdown occurring at negative polarity is listed in Table 1. When the gap is 2.5mm, the breakdown happens with both polarities for each frequency. It may be attributed to the fact that the breakdown voltage of both polarities is similar for small gaps. When the gap is 5mm or 7.5mm, the breakdown always happens during positive half-cycles except for 5kHz. When the gap is 10mm, the breakdown happens during positive polarity. According to classic inhomogeneous breakdown analysis, the positive point-plane breakdown voltage is lower than the negative point-plane. But, the increasing frequency might suppress the expansion of ionisation, leading to a higher voltage requirement. Once the voltage is enough to allow secondary emission at the cathode, a self-sustained discharge is achieved. However, the same voltage cannot have enough space charges to incept a streamer during the positive half-cycle. Then the breakdown could happen during negative half-cycles.

3.2 Partial Discharges

The partial discharge inception voltage (PDIV) and PRPDP are measured under different frequency and gap. Based on the breakdown voltage measurement, the frequency might impact the positive corona. Therefore, the PDIV was measured based on their polarity. The negative corona inception voltage is shown in Fig. 5. When the frequency increases from 50Hz to 5kHz, the inception voltage has a slight reduction. The reduction of negative corona inception voltage is also observed in [18].

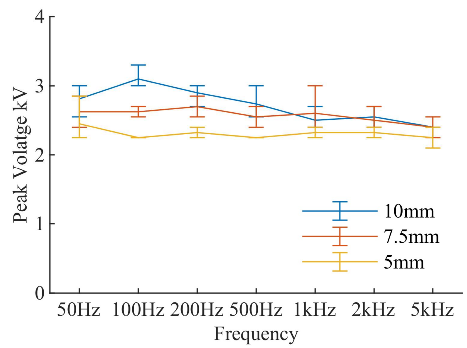

Fig. 5 Mean PDIV at different frequencies with different gaps, error bars show results' range.

Compared to the negative corona inception voltage, the positive corona has significant changes. The results are listed in Table 2. In all gaps, the inception voltage at 5kHz is at least double the value at 50Hz. For the 10mm and 7.5mm gap, the inception voltage shows an obvious increase at 500Hz, while it happened at 2kHz for the 5mm gap. It is obvious the higher frequency stress suppresses the inception of positive corona in the tested range.

Table 2 Positive corona inception voltage under different situations, peak value.

Freq Hz \ Gap mm	5	7.5	10
50	3kV	3.15kV	3.6kV
500	3kV	6kV	7.5kV
1k	3.3kV	7.5kV	11.1kV
2k	4.5kV	>8.4kV	>12kV
5k	>6kV	>8.4kV	>12kV

In order to show the impact of frequency on the partial discharge more clearly, the PRPDPs are plotted. The brightness represents the density of discharge. The more bright, the higher the density is. First, the discharges are collected by

PicoScope with the window trigger having the same threshold for both polarities.

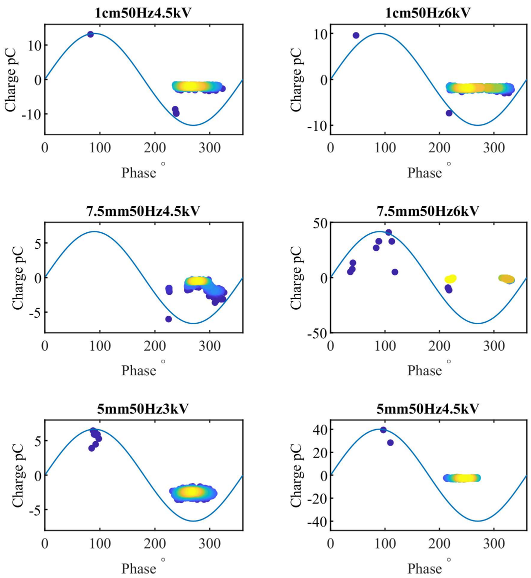

Fig. 6 PRPDP with different voltage and gap under 50Hz.

Fig. 6 shows the PRPDP with different voltages and gaps under 50Hz. PD mostly happened during the negative half-cycle. There are only several points located in the positive half-cycle among 1000 triggers. Compared to negative corona, the occurrence frequency of positive discharge is quite small. The charges per positive corona are larger than per negative corona. The charges per negative corona are quite constant and are insensitive to the voltage and gap.

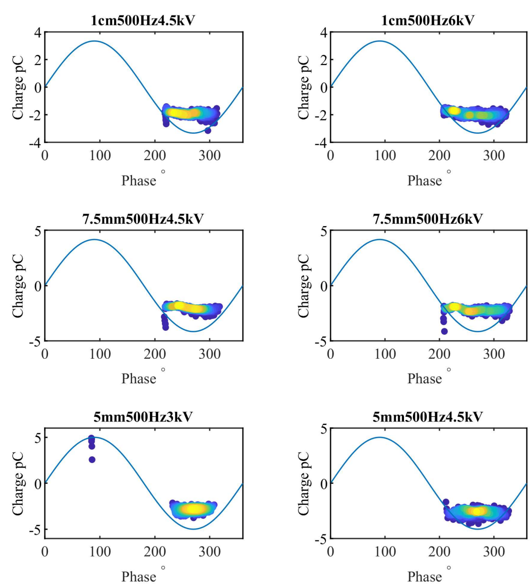

Fig. 7 PRPDP with different voltage and gap under 500Hz.

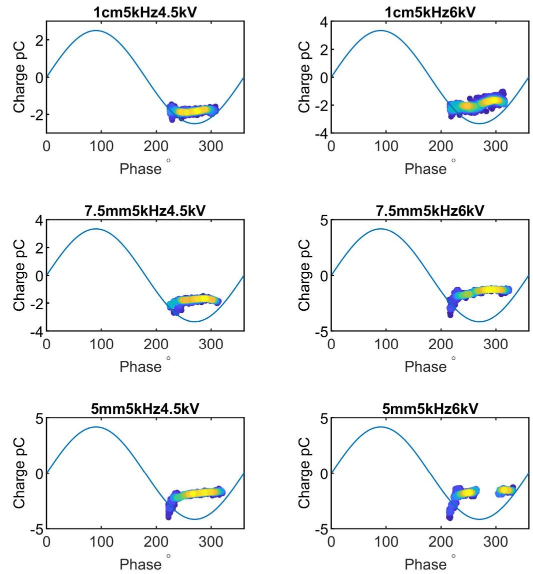

Fig. 8 PRPDP with different voltage and gap under 5kHz.

Fig. 7 and Fig. 8 show the PRPDPs under 500Hz and 5kHz. In the majority of situations, only negative corona discharges are captured. The charges per negative corona are at the same level as 50Hz. Therefore, the frequency of up to 5kHz does not have much impact on the charge per negative discharge.

Then, the discharges are collected with the normal trigger having a positive threshold, as shown in Fig. 9. The threshold was selected based on the observed minimum amplitude of the positive corona. Therefore, some negative coronas with high amplitude were also captured. The applied voltage is based on the inception voltage in Table 2. The charges per positive corona have a wider range of values compared to those per negative corona. For the situation with 50Hz 4.5kV, the charges vary between 7pC to 30pC. The charge value is quite different between frequencies. It means that with higher frequency, more energy is needed to cause a positive corona.

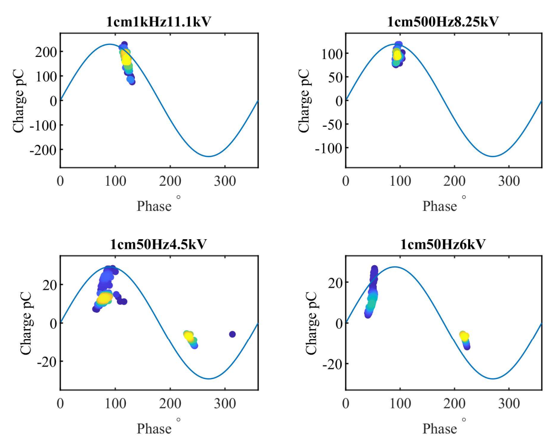

Fig. 9 PRPDP with 1cm gap under different.

The changes in positive corona can be explained by the ion movement. For higher frequencies, the positive ions move shorter distance, and there is less time for occurance of recombination. Therefore, positive ions have higher density and accumulate closer to the tip, which further decreases the field strength between space charges and the tip. Consequently a higher voltage is needed to incept a positive corona discharge, and the charge per discharge also would be higher.

4 Conclusion

In this paper, the breakdown voltage and corona discharge in atmospheric air was tested under 50Hz-5kHz with point-plate electrodes. The breakdown voltage increases with increasing frequency which contradicts other references. Based on the result, there might be a critical frequency that the breakdown voltage starts to decrease with a certain gap. The polarity when the breakdown happened was observed. Under certain conditions, especially at 5kHz, the breakdown happened during the negative half-cycle. PDIV and PRPDP were measured. The negative corona discharges seem to stay constant, whereas the positive corona's inception voltage increases significantly with increasing frequency. This observation could be attributed to ion movement, and a possible process is given to explain this phenomenon.

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