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Experimental study of epoxy surface discharge under different frequencies

T. Luo, W. Zhao, M.G. Niasar
DCE&S, TU Delft
Mekelweg 4
2628CD, Delft, The Netherlands

***Abstract-* With widely use of power electronics in medium voltage level, there is increasing concern about behaviour of insulation material under arbitrary voltage stress. Solid-gas insulation is a general choice in medium voltage level. Therefore, it's unavoidable to encounter surface discharge problem. In this paper, the surface discharge on epoxy-air interface is investigated, which is a commonly used insulation material. Point to plate electrode was used to test the surface flashover voltage and partial discharge (PD) behaviour at 50Hz, 500Hz, 1kHz, 2kHz and 5kHz. As the result, with increasing frequency, PDIV keeps roughly constant and flashover voltage first increases and then decrease, and the frequency obtaining highest flashover voltage is related to gap length.**

I. INTRODUCTION

The development of silicon carbide (SiC) semiconductor offers the possibility of handling medium voltage with fewer number of switches, which can have 10-15 kV blocking voltage. In recent years, enormous works about medium voltage level application based on SiC devices were done, which have shown the superior performance comparing to Si IGBT [1]. These converters have the ability to operate higher voltage, higher frequency, and normally non-sinusoidal waveform, so the reliability of its insulation attracts more attention. Gas-solid insulation system is a popular choice for medium voltage application. Many factor that related to this insulation system under new stress were discussed. The effect of frequency on insulation is one of widely studied aspect.

For air under homogeneous field, after a critical frequency, a reduction of the breakdown voltage begins to occur. And it is attributed to that, ions produced during avalanche can't 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 [2]. When frequency is above MHz frequencies, the breakdown voltage reaches its minimum. It is because with further increasing frequency, mobility of electrons also plays a role in breakdown, and electrons stay in the gap [3]. Therefore, dielectric strength increases with increasing frequency.

For solid material, many studies have shown that rising frequency sinusoidal stress causes lower breakdown strength of insulation material. Most researchers attribute this reduction to enhanced dielectric loss or enhanced discharge repetition frequency [2], [4]–[6]. Lifetime also present the same trend as breakdown strength, i.e., becoming shorter with increasing frequency. It is discussed in two different situations, whether or not the PD happens. When there isn't PD happening, according to reference [7], relation between frequency and lifetime may write as (1).

$$L_f = L_1 (f_1 / f)^{\gamma} \quad (1)$$

The presence of PD can greatly reduce the lifetime [8]. When only compare the lifetime with PD, the relationship is similar to the one without PD, but there is some disagreement about the value of the exponential factor. Study [9] observe the lifetime to scale inversely with frequency ($\gamma = 1$), while from the data of other investigations [10], values $\gamma < 1$ are obtained (typically between 0.6 and 0.8).

The surface discharge character is an important property in gas-solid insulation system. Intensive studies related to surface discharge were done in last decades under DC and line frequency AC conditions [11], [12]. Relative fewer studies were done about the effect of frequency, despite the fact that flashover fault is one of the typical faults in SiC module and creepage distance hinder the development of highly compact device. Therefore, it's well worth understanding the phenomena in more detail. In one of earliest studies [13], the effect of frequency on flashover strength of 3/8 inch on many materials in the range of 60 Hz to 100 MHz were studied, result shows that the flashover strength decrease with increasing frequency. Pfeiffer [2] attributed this reduction to the decreasing of breakdown strength of air. In [14], tracking resistance was studied under 50-500 Hz stress according to IEC 587, results show under the same voltage, higher frequency leads to shorter time to tracking breakdown. In [15], the flashover voltages with square waveform of 1cm gap on various material in the range of 50 Hz to 20 kHz were tested, its result shows faster reduction of flashover voltage than what was shown in [13].

PD is an important factor closely related to breakdown and aging, and is helpful in related analysis. Studies of the effect of frequency on the PD performance mainly focus on cavity defect. Reference [16] shows maximal magnitude decreased with frequency and partial discharge inception voltage (PDIV) increased with increase in supply voltage frequency. Wang etc. [17] studied PD in rotation machine, and found PD occurrence time decreases with increasing frequency and that the average magnitude is almost constant until 2 kHz. However, studies about surface discharge are relatively fewer. Zhao etc. [15] show the PDIV of surface discharge under square waveform doesn't vary much at different frequencies. Liu etc. [18] studied the phase resolved PD pattern (PRPDP) for surface discharge under 5-30 kHz sinusoidal voltage. Results shows when frequency is under 10 kHz, average PD amplitude and total PD number per cycle will increase with frequency, and when it is above 10 kHz, two parameters have opposite trend. Compare to the effect of frequency on air and solid breakdown and PD caused by cavity defect, there are relative fewer studies focusing on surface discharge, but it is an important part in power electronic converter design. In this paper, flashover voltage and surface discharge behaviour of epoxy with point-plate method in the range of 50 to 5kHz sinusoidal wave are studied.

II. Experiential Procedure

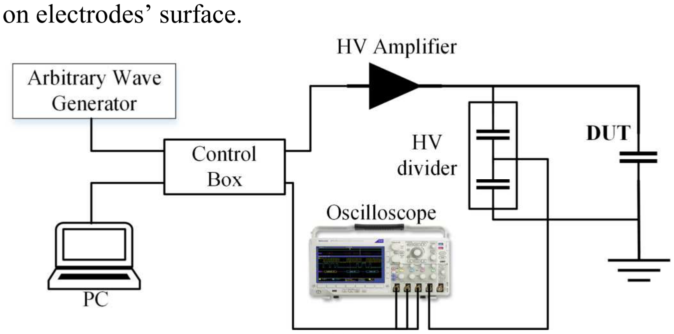
A. Material

The samples were prepared by bisphenol A epoxy resin (CY225) along with hardener (HY925) without filler, supplied by Huntsman. The weight ratio of epoxy resin to hardener is 5:4. Initially, the epoxy resin and the hardener were both degassed at 60°C for one hour to remove air and moisture. Then, the hardener was added to resin and mixed thoroughly. The mixture was evacuated to remove trapped air at 60°C for 1.5 hours. The samples were prepared by hot press method. Mixture was casted in a mould at 60°C, which was composed by aluminium plates covered by silicon rubber and paper spacer. The thickness of samples was controlled by thickness of the spacer. Epoxy resin was cured at 120°C for 4 hours. Samples of around 150μm thickness were used for current study.

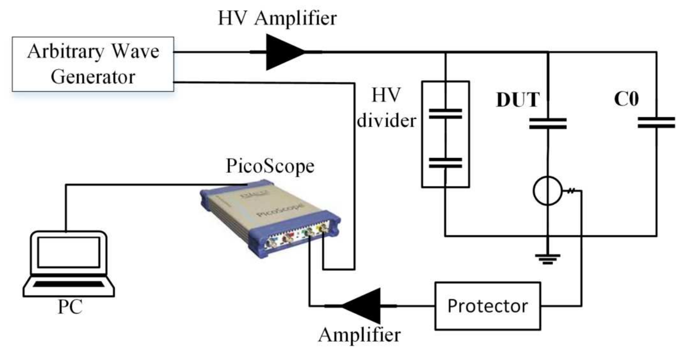
B. Test system

The experimental system used for test flashover voltage and PD are depicted in Fig. 1 (a) and (b), respectively. For both applications, an HV amplifier Trek 30/20A is used to generate high voltage at different frequencies. The Trek amplifier is equipped with an internal voltage divider which is used to measure the output voltage. The input signal is produced by a TENUMA 72-14111 function generator. The point-plate electrodes are shown in Fig. 2. High voltage electrode is made of steel, and ground electrode is made of brass. The support structure is made of plastic.

For flashover voltage test, ramp breakdown test is used, peak value of sinusoidal wave rise with 1kV/s. Oscilloscope DPO 3034 is used to monitor flashover voltage. Although, HV amplifier has intern short circuit protection, an additional short circuit detector is used to minimize the damage of flashover on electrodes' surface.



(a)



(b)

Fig. 1 Experiment setup for (a) flashover test and (b) PD test

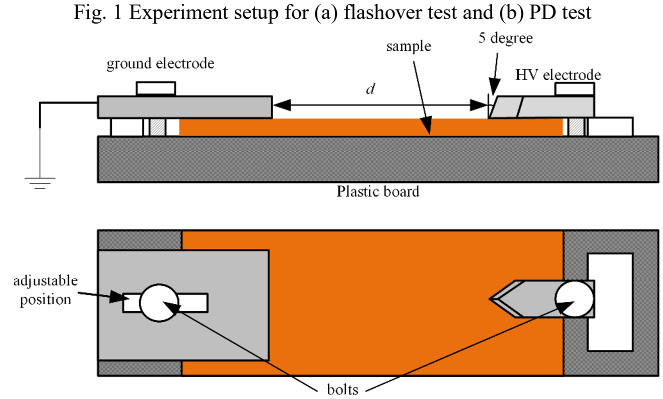


Fig. 2 Schematic diagram of electrode

In many frequent related studies, coupling capacitor is not used to reduce the power demand of source, however, in [19] the importance of coupling capacitor in PDIV measurement is shown. Therefore, in our study, a coupling capacitor with 50pF is used, to ensure it's at least ten times large than that capacitance of sample, which is lower than 2pF according to FEM calculation. To measure High frequency CT [18], [20] and antenna [10] are generally used to measure PD signal. In our case, a high frequency current transformer (HFCT) is adopted, and its bandwidth is 34.4kHz to 60MHz. Signal from HFCT pass through a protector and an amplifier, and the amplifier has 21.7dB gain and bandwidth is 25kHz to 900MHz. PicoScope 6404C is used to collect PD signal. Its bandwidth is 500MHz, maximal sampling rate is 2.5Gs/s with 2 input channels. We acquired 1000 triggered pulses continuously which is used to get PRPDP, then data is transferred to computer to process. PD flex [21] is used to analyse the obtained data.

Flashover voltage is performed under 50Hz, 500Hz, 1kHz, 2kHz and 5kHz with gap length d = 5mm, 10mm and 15mm. Each case was tested more than ten times. PD is tested under the same frequency range with 10mm gap. The whole tests were done in laboratory environment, temperature was control at 20±1°C, relative humidity was in the range from 50% and 60%. The electrodes were cleaned with wipe paper every ten tests, and after finishing a set of tests or in case dark spots were observed on the electrodes, both electrodes were polished by both machine and hand to maintain their surface condition.

III. Result

A. Flashover voltage

For flashover voltage, 2-parameter Weibull distribution as shown in (2) is used to analyse the flashover voltage.

$$\mathrm{F}(E) = 1 - \mathrm{e}^{-\left(\frac{E}{\eta}\right)^{\beta}} \quad (2)$$

In (2), E is breakdown strength, F(E) is cumulative probability of breakdown, β is the shape parameter which is the slope of regression line in the probability plot, and η is the scale parameter. Probability of breakdown for the specimens is 63.2% at an electric field equal to η.

The Weibull plot of flashover tests for d =10mm are shown in the Fig. 3. At 50Hz, the flashover voltage is 12.63kV, and it increases with rising frequency. At 1kHz, the voltage is 13.84kV, which is nearly 10% higher than that of 50Hz. And with further increasing frequency, it decreases. Case with 5kHz has lowest value, 12.14kV. For part from 1kHz to 5kHz, the flashover voltage shows the same changes as [15] reported. However, for the whole range, the changes are not the same as what happened in solid and air, i.e., with higher frequency the breakdown strength decrease in this frequency range. The same trend also happens in other two gap, as shown in **Fig.** 4, which reflects the changes of flashover voltage with error bar. Comparing to d=15 and 10mm, the trend in d=5mm is not obvious, when frequency is 1kHz, flashover voltage only has slightly higher value, 7.76kV compared to 7.65kV at 50Hz. Besides, with bigger gap, the frequency of highest value seems moves towards lower frequency.

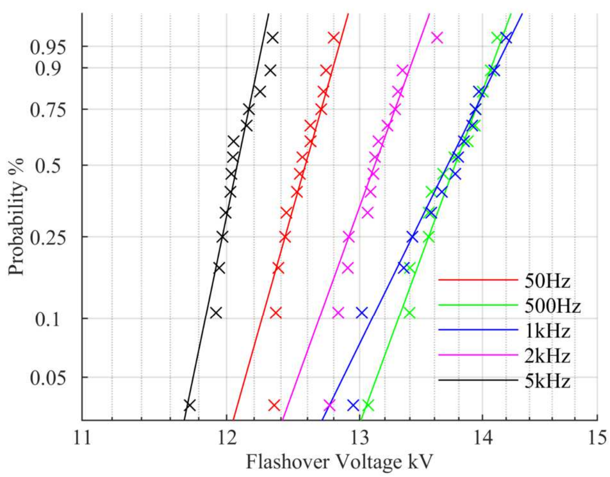


Fig. 3 Flashover voltage (peak value) with d=10mm under different frequency

According to this tendency, this unusual trend could be attributed to the mobility of ions. With inhomogeneous field, electric field along gap would be higher near the point, lower near the plate electrode. For the increasing trend of flashover voltage, although ion stays in the gap and distorts the electric field, it could stay near the plate and lower the field near the plate while not contributing noticeable to the increase of electric field near the point. For the decreasing trend of flashover voltage, it could be that the ions cannot move very far from the point during the negative half cycle and hence they enhanced the electric field near the point considerably during the positive half cycle, while not decreasing the electric field in the rest of gap noticeably.

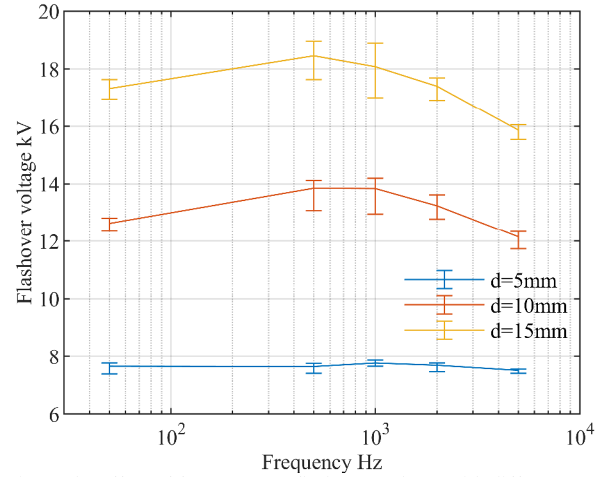


Fig. 4 The effect of frequency on flashover voltage with different gap d.

The Fig. 5 shows the relation between flashover voltage and gap length, which is usually follow the power law [11], as (3).

$$V \propto d^{\alpha} \quad (3)$$

In (3), V is flashover voltage, d is gap length, and α is a coefficient, which is normally 0.5-1. With smaller gap and rougher surface, α is closer to 1, and in our test, α is around 0.75, which is reasonable.

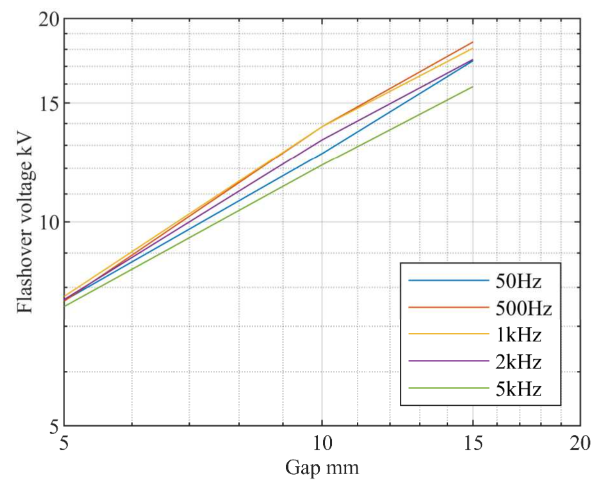


Fig. 5 Relation between flashover voltage and gap length

B. PD measurement

PDIV at different frequency is measured on the same sample. the trigger is set according to the result of 10pC calibration pulse at 100Hz. As shown in Table 1, PDIV seems to stay constant with increasing frequency, which is the same as the result from [15].

Table 1 PDIV at different frequency

Frequency (Hz)	50	500	1000	2000	5000
PDIV (kV peak)	4.2±0.4	4.1±0.3	4.1±0.2	4.3±0.2	4.3±0.1

In order to get higher repetition frequency, PD pulses for phase resolved surface discharge pattern are measure under 7.5kV sine wave, peak value. The results are shown in Fig. 6, in which different colour represents different pulse density. It is obvious that for all frequencies, the most PD pulses congregate in 0-90 degree and 180-270 degree and positive pulse have higher maximal amplitude. Among all studied frequencies, 1kHz has highest maximal value, which may relate to flashover voltage. There is a weakly trend that PD has lower maximal amplitude at higher frequency. Positive pulses distribute in a more narrow phase range and have larger range of amplitude compared to negative pulses. Besides, pulse number in positive and negative polarity are roughly equal, whereas 50 Hz has more negative pulses.

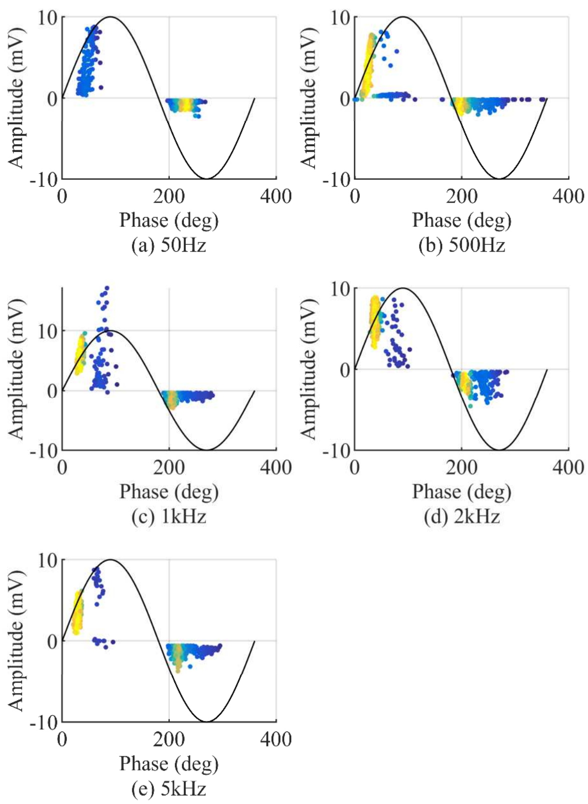


Fig. 6 Phase resolved surface discharge pattern at various frequency.

IV. Conclusion

In this paper, the effect of frequency on flashover voltage and surface discharge on the epoxy-air interface were tested under 50Hz-5kHz with point-plate electrodes. Flashover voltage under different frequencies and different gap lengths, PDIV and phase resolved surface discharge patterns are presented. The result indicates that with increasing frequency, flashover voltage first increases and then decreases, and the frequency obtaining highest flashover voltage is related to gap length. This observation could be attributed to ion mobility. Besides, it was observed that with increasing frequency, PDIV seems stay constant.

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