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Assessment of Partial Discharge Phenomenon in AC and Fast-rising Square Voltage Using Optical Detection Technique in Needle-Plane Configuration With Pressboard in Mineral Oil

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***Abstract*—The benefits offered by silicon carbide (SiC) switches in terms of repetition rate (> 100 kHz) and switching speed (up to 100 kV/µs) make them a popular choice for the converters of future grid projects. However, the impact of the fast repetitive pulses generated by these devices on the insulator discharge mechanism is yet unknown. This could be a significant obstacle in the future development of power system applications. This paper investigates the partial discharge (PD) phenomenon for pressboard/mineral oil insulation system under unipolar square voltage (USV) waveforms (dV/dt > 50 kV/µs), using a photomultiplier tube (PMT), with a high divergent field. As compared to AC, the partial discharge inception voltage (PDIV) is found to be lower under USV for tested specimens. The phase resolved partial discharge (PRPD) pattern highlights the difference in PD mechanism between AC and USV waveforms. Also, the number of PDs (NPDs) and average charge amplitude (Qavg) obtained under AC and USV waveforms are compared and discussed.**

Keywords— Unipolar square voltage, AC, partial discharge, mineral oil, pressboard, optical method

I. Introduction

Wide band gap (WBG) semiconductor devices such as SiC-MOSFETs offer several advantages over Si-devices in terms of breakdown voltage (as high as 15 kV), operating frequency (> 100 kHz), and fast switching speed (up to 100 kV/µs) [1]. On the one hand, the high frequency operation can reduce the weight and volume of the passive components such as capacitor and medium frequency transformers (MFTs); furthermore, higher dV/dt can considerably decrease the switching losses. On the other hand, the high dV/dt and high frequency operation can lead to accelerated degradation of the insulation system [2]. So far, the impact of repetitive pulses on insulation system has been mainly investigated for slew rates of up to 20 kV/µs and repetition frequency of 10 kHz [3], [4]. The lack of experimental data about the effect of fast repetitive pulses generated by WBG devices on insulation systems makes it important to assess the reliability of insulators under these waveforms for future power conversion equipment.

Partial discharge measurement is widely used to examine the quality of insulation systems. For high voltage applications, the insulation system of MFTs is likely to involve both dielectric liquids and solid barriers [5], [6]. Therefore, this paper investigates PD phenomenon for such composite insulation system (here pressboard/mineral oil) under repetitive fast rising pulses and AC. In the first step, a test bench generating unipolar square voltage (USV) waveform is developed. Unlike in AC, electrical detection of PD is difficult under high dV/dt, as high displacement currents appear during the switching events, masking the PD signal. Here, PD detection is also performed optically, which offers high immunity against displacement currents and electromagnetic interferences [7], [8], but requires calibration against the standard electrical detection. For sake of the demonstration, a needle-plane configuration is used to achieve the high electric field necessary for PD generation with the voltage available in the testing system. The PDIV, PRPD pattern, NPDs and Qavg data thus obtained under AC and USV are compared and analyzed.

II. Device Under Test

The device under test (DUT) comprises of needle-pressboard-plane configuration immersed in mineral oil, as shown in Fig 1. The pressboard is placed vertically against a 20 mm diameter plane electrode fabricated with stainless steel and electrically grounded. At high voltage, a tungsten needle with 1 µm tip radius is clamped by a mandrel. The gap between tip and pressboard, controlled by a spacer, is 0.7 mm.

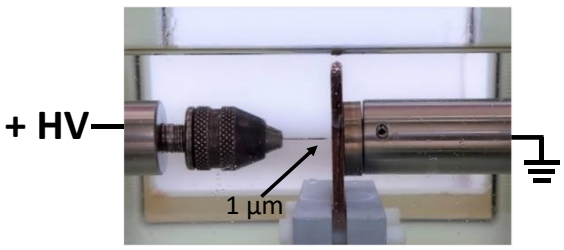

Fig. 1. DUT with needle-pressboard plane configuration in mineral oil

The mineral oil used is Nytro4000X from Nynas. Before PD tests, the mineral oil is filtered using a porosity grade 4 (or P4) sintered-glass filter, while maintaining a pressure of less than 1 mbar. Following the treatment, the quality of the oil is monitored by performing breakdown voltage (BDV) tests in compliance with IEC60156 standard and water content (WC) measurements using coulometric Karl Fischer titration. The results thus obtained are provided in Table 1, which shows the mean of 30 BDV tests and 2 WC measurements. As shown in the table, the measured values meet the Nytro4000X datasheet criteria using the same standards.

TABLE 1 : MEASURED VALUES OF MINERAL OIL AFTER TREATMENT

Properties	*Nytro 4000X datasheet*	*Measured value after treatment*
Breakdown voltage (kV) (as per IEC60156)	> 70	90 (mean of 30 BDV tests)
Water content (ppm)	< 20	7.8 (mean of 2 WC tests)

Pressboard (PB) samples with two thicknesses (2 and 3 mm) are used for PD tests. PB samples are cut into 40 mm × 40 mm size, which covers the plane electrode completely to avoid any flashover during the PD tests.

Prior to testing, PB samples are impregnated in Nytro 4000X as follows: the PB samples are dried for one day at 105°C, then for two days under vacuum (≈1 mbar) at 85°C. The moisture contents of PB samples is found to be 1.1 % which is close to its nominal value. In the next step, the PB samples are immersed in Nytro 4000X at 85°C under vacuum. To ensure the complete impregnation of PB samples, their weights are checked every day, until they reach a constant value (here, the weight of the sample was found not to change on the fourth, fifth and sixth day, at which point complete impregnation was assumed).

III. EXPERIMENTAL SET-UP

For PD comparison between AC and square voltage waveforms, two test setups are developed inside the same Faraday cage. The AC test setup has a maximum voltage rating of 25 kV. The PD measurement circuit in AC consists of a coupling capacitor (Ck) and measuring impedance (Zmi) as shown in Fig 2, in compliance with IEC60270 standard. Additionally, a photomultiplier tube (PMT : R943-02 from Hamamatsu) is used for optical detection of PDs. Both the PMT and Zmi are coupled with commercially available acquisition systems from Omicron, thus allowing detection of PD events using electrical and optical sensors simultaneously, as discussed in our previous paper [9]. The PMT detects photons emitted from discharge events and the readings are reported using arbitrary unit (a.u.).

The second test setup is developed with a high voltage switch from Behlke (HTS 1401-10-LC2) which generates unipolar square voltage (USV) waveform with maximum output of 30 kV (Fig. 2). R1 and R3 are current-limiting resistors. The purpose of R2 is to allow complete discharging of the DUT when the HV switch opens; its large value (2 MΩ) ensures most of the source voltage is applied across the DUT when the HV switch closes (as R1 and R2 form a voltage divider with a ratio close to 1). With the parameters provided in Fig. 2, the rise time measured across the DUT is around

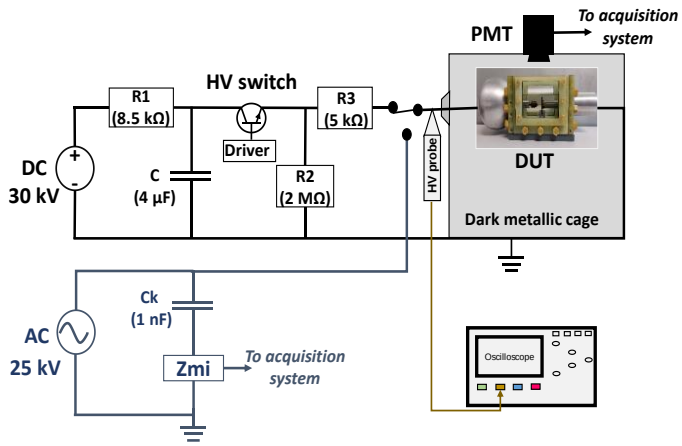

Fig. 2. Schematics of experimental set-up with square voltage (top) and AC voltage waveform (bottom)

256 ns which corresponds to a dV/dt of about 78 kV/µs at 20 kV. Due to the discharging time of the DUT when the switch opens, the frequency cannot exceed 500 Hz. The DUT is placed inside a dark metallic cage to improve the capturing capability of the PMT. The voltage across the DUT is measured with an HV probe (Tektronix P6015A) coupled to an oscilloscope (Tektronix: MDO34). This voltage cannot be acquired using the Omicron acquisition system due to impedance mismatch with the HV probe. To get the phase data (e.g. for the PRPD patterns), the acquisition system is synchronized to the control signal sent to the driver of the HV switch.

IV. METHODOLOGY

The tests are performed under AC 50 Hz and USV 50 Hz with 50 % duty cycle. In AC, the PD measurements are carried out using both electrical and optical detection methods. This allows a coarse calibration of the optically acquired PDs by comparing them with those obtained electrically. In USV, only the optical detection method is used. The PD comparison between AC and USV presented in this paper are obtained from optical measurements, with a threshold set at 0.5 pa.u. (pico arbitrary unit).

Five DUT specimens are tested with each thickness of pressboard (2 mm and 3 mm). Every DUT specimen undergoes ten PD tests (5 under AC and 5 under USV). At the end of ten tests, the needle, dielectric liquid and pressboard sample are replaced to ensure the reproducibility of tests and avoid the impact of deformation of the needle tip on the results. Also, the order of tests is reversed from one DUT specimen to the next, which means that if PD tests start under USV for the first DUT specimen, then they start with AC for the second one.

The test method shown in Fig. 3 is adopted for AC and USV waveforms: firstly, the voltage is increased by ramp to find the first PDIV; after 30 s at 0 V, the voltage is increased to 60 % of the 1st PDIV value; then, the voltage is increased in steps of 1 kV with a waiting time of 30 s until PDIV is reached again. This step is repeated five times. Between each voltage application an interval of 30 s at 0 V is enforced.

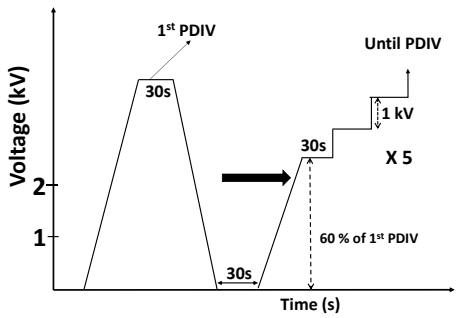

Fig. 3. Voltage application method used for comparing PD parameters in AC and USV

Unlike the ramp voltage profile, the selected test method allows the acquisition of PD parameters for 30 seconds at PDIV, which is then used for extracting NPD (number of partial discharges) and Qavg (average charge of the partial discharges) as discussed further in this paper. The PD data thus obtained in AC and USV are compared using peak-to-peak (pp) voltage values.

V. Results

A. Electrical and Optical Detection of PDs in AC 50 Hz

Fig. 4 presents the mean and standard deviation of PDIVs obtained from 25 PD tests using five DUT specimens, for both pressboard thicknesses. Using the correlation strategy discussed in our previous paper [9], the optically acquired PDs (blue bars) are compared to those obtained electrically during AC tests (green bars). For a threshold of 0.5 pa.u. in optical method and 2 pC in electrical method, the mean PDIVs obtained in AC 50 Hz are almost identical. This means that the optically acquired charges of 0.5 pa.u. broadly corresponds to 2 pC of charges in our experimental conditions (sample-to-PMT distance, thickness and composition of the oil layer between the needle and the PMT, DC supply of the PMT: here set at -1.3 kV for all tests).

Furthermore, it can be observed that the mean PDIV is slightly higher for 3 mm PB than for 2 mm PB. Because a constant distance is kept between the needle tip and the surface of the PB, the tip field gets slightly reduced with increasing barrier thickness, resulting in a larger PDIV for thicker barrier.

B. PDIV in AC and USV

From Fig. 4, it is found that the optically acquired mean PDIV is lower in USV (red bars) than in bipolar AC (blue bar). This is true for both thicknesses of pressboard as shown in Fig. 4. Also, with USV waveforms, a larger standard deviation can be observed in PDIV values, corresponding to a larger scattering in the measurements. Because the standard deviation intervals overlap considerably for both PB thicknesses, showing no significant difference in their mean PDIVs.

The generated square voltage is unipolar in nature, has a long DC plateau duration and higher dV/dt than bipolar AC voltage. These differences from AC waveform could influence the PD mechanism for the composite insulation system. To further investigate this, the PRPD patterns, NPDs and Qavg are compared between two waveforms.

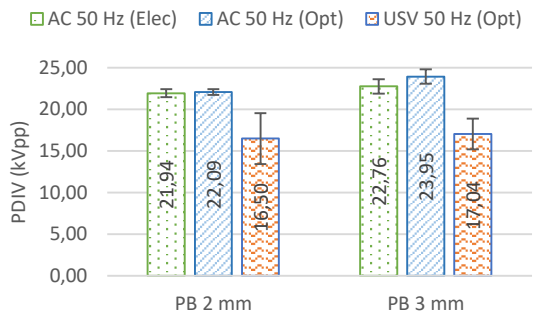

Fig. 4. PDIV comparison between AC and USV waveforms

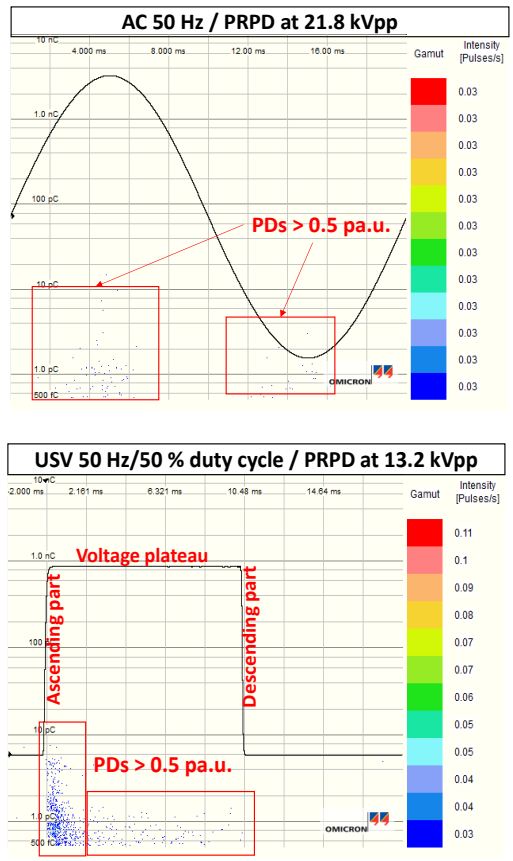

Fig. 5. Optically acquired PRPD patterns in AC and USV for needle-pressboard plane configuration in mineral oil at PDIV; after a recording time of 30 seconds. Note that the square signal (black line) corresponds to the control signal sent to the HV swich, and is only used for synchronization (the actual HV signal has a much steeper rising slope)

C. PRPD patterns in AC and USV

Fig. 5 shows the optically acquired PRPD pattern under AC and USV waveforms, at the PDIV, for the same DUT specimen with 2 mm thick PB. In the figure, the threshold is set at 0.5 pa.u. (reported as 0.5 pC in the chart scale). As can be observed in AC 50 Hz, the PDs are found to be mainly occurring in the first and third quadrants as well as under the peak of the sinusoidal waveform. These PDs represent surface discharges and corona-like discharges occurring in composite insulation system [9], [10].

However, with the USV waveform, a high intensity of PDs can be observed during the ascending part and few under the DC plateau. The dV/dt and longer DC plateau seems to be influencing the PD mechanism under USV, which makes the

PD distribution different from that in AC. Additional investigation will be necessary to identify the influence of each USV parameter such as the duration of the DC plateau or the unipolar nature of USV waveform on the PD mechanism.

D. Comparison of NPDs and Qavg between AC and USV

NPD is the rate of PD occurrence over a given period of time (Δt) at a constant test voltage. Qavg is also evaluated for the same Δt and test voltage; it is calculated as the total PD charge divided by NPD over Δt. For the results presented hereafter, Δt is 30 seconds.

Fig. 6 and Fig. 7 present the NPDs and Qavg for each of the 25 PD tests under AC and USV for 2 mm thick pressboard. From the NPDs plot in Fig. 6, it can be seen that with the exception of DUT n°1 (tests 1 to 5), the NPDs in USV and AC are similar. Regarding Qavg (Fig. 7), scattering is larger for USV than for AC. Considering that Qavg is a measure of the PD activity, the higher Qavg found for many tests under USV points to higher PD activity than in AC. This may accelerate the degradation of insulator under USV waveform than in AC.

During the tests, it is observed that PDs occur intermittently when voltage reaches the PDIV for the tested composite insulation system. On many occasions, the PDs extinguish when voltage is maintained at PDIV level. This behavior is more noticeable in AC than in USV. The intermittent behavior of PD occurrence at inception voltage is known and also reported in IEC60270. As a result, the values of NPD and Qavg calculated for 30 seconds at PDIV are low for many cases .

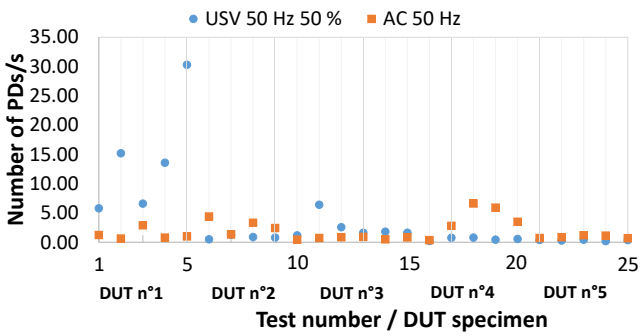

Fig. 6. Comparison of optically acquired NPDs between AC and USV waveforms for the DUT with 2 mm thick pressboard

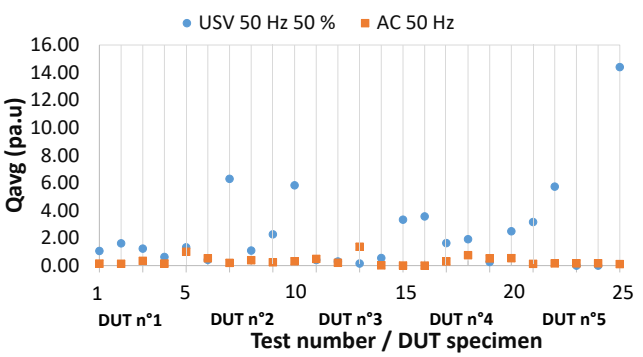

Fig. 7. Comparison of optically acquired Qavg between AC and USV waveforms for the DUT with 2 mm thick pressboard

VI. Conclusion and Future Works

In this work, the PD parameters are examined under AC and fast rising USV waveforms using a photomultiplier tube. The DUT has a needle-plane configuration with pressboard and mineral oil as insulation system, to foster the generation of PDs at a moderate voltage. The result thus obtained indicate that the PD activity starts at lower voltage under USV as compared to AC for tested DUT specimen.

The high concentration of PDs around the ascending part of the USV waveform differentiates the PD phenomenon from AC. The Qavg and NPDs plot suggest large variations, sometimes from one test to another and for some cases from one DUT specimen to another.

For more understandings on PD activity with high dV/dt, the test should be extended to other combination of solid/liquid insulators such as pressboard in ester. Moreover, changing the USV parameters such as dV/dt, duration of DC plateau, or USV frequency will provide necessary insights.

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