Glass Fibre Insulated Wire Assessment Under Partial Discharges Activity via Dielectric Dissipation Factor Measurements

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***Abstract* – This experimental study evaluates the ageing rate associated with partial discharges (PD) activity for a Type-II insulated wire (i.e., Glass fibre), relying on the dielectric dissipation factor (DDF) and capacitance tip-up measurements. The employed specimens model the turn-to-turn insulation for low-voltage electrical machines. The turn-to-turn insulation was investigated because is the weakest point of the whole insulation system. The repetitive partial discharge inception voltage (RPDIV) is determined for unipolar and bipolar square waveform excitations with different rise times and frequencies. Then, the samples are stressed constantly under RPDIV at several exposure times for ageing purposes. The DDF and capacitance tip-up measurements are performed at the end of each ageing cycle. The reported findings enable the definition of indicators for the PD activity through the selected diagnostic markers (i.e., DDF and insulation capacitance). In addition, the proposed approach can provide reliable information on the Glass fibre ageing level associated with PD activity, comparing the harmfulness of different steep-fronted square waveforms.**

Keywords: electric machines, insulation, partial discharges, condition monitoring, accelerated aging, pulse width modulation, variable speed drives, predictive maintenance

I. INTRODUCTION

The technology of converter-fed electrical machines is moving toward using modern inverters (e.g., silicon carbide-based inverters) to increase the power density besides reducing losses [1]. Modern inverters are featured by faster rise times, enabling higher switching frequencies, voltages, and temperatures than those typical of standard silicon MOSFETs [2, 3]. A shorter voltage rise time enhances the risk of partial discharges (PD) inception for the turn-to-turn winding insulation. Generally, the used winding insulation for low voltage electrical machines is Type I insulation (i.e., organic insulating materials). Unfortunately, PD is the end-of-life criterion for the organic turn-to-turn insulations, reducing the reliability [4]. Indeed, consecutive PD activity can lead to a premature failure of the winding insulation, resulting in electrical machines being out of service [5]. One of the possible solutions is using Type II insulations (i.e., mixed organic-inorganic insulating materials, so-called corona-resistant materials) which can deliver a better endurance against PD activity, introducing a paradigm shift. Therefore, Glass fibre insulated wire as a Type II insulation is considered for this study.

The reliability of the insulation system can be enhanced more by developing some PD indicators, as introduced by this paper, through non-destructive condition monitoring and diagnosis techniques (e.g., dielectric dissipation factor (DDF) and capacitance tip-up), providing a predictive maintenance approach. The proposed method in this paper can help the maintenance manager plan proper actions to decrease the maintenance costs in critical assets such as electrical machines applications for more-electric aircraft, stressing the importance of analyzing non-destructive diagnostics markers. In addition, it is interesting to understand which steep-fronted square waveform characteristics (e.g., rise times and frequencies) can impose higher harmfulness/damage associated with PD activity. It can be determined by these non-destructive approaches, which are faster and easier than custom accelerated life tests. In other words, when the purpose is only to understand which voltage waveform is more harmful under the PD regime, the proposed method can be less time-consuming. Indeed, at least 15 accelerated life tests should be done to derive a lifeline for each voltage waveform (i.e., at least three points (three voltage levels), each obtained from at least five tests) [6]. However, each DDF and capacitance tip-up measurement is performed much faster (e.g., less than five minutes).

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II. METHODOLOGY

A. PD Measurement Setup

The schematic diagram of the PD measurement setup is shown in Fig. 1. The PD sensor is an ultra-high-frequency (UHF) antenna having a bandwidth of 100 MHz–3 GHz. The detection bandwidth is 16 kHz up to 48 MHz. The frequency content of the acquired UHF signals is reduced to the required range for both the impulsive test synchronization module (ITSM) and the PD detection unit using a frequency shifter.

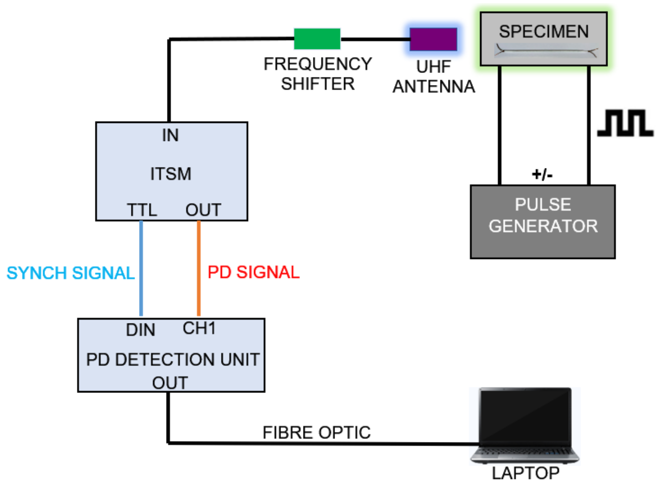

Figure 1. Circuit and connections layout for PD measurements setup.

The role of ITSM is the production of a digital synchronization signal synchronized to the pulse generator fundamental frequency by low pass filtering. Thus, the PD detection unit can acquire the PD signals free from switching disturbances under impulsive voltage excitations [7]. The sampling rate of the PD detection unit is 200 MSa/s. An oscilloscope (350 MHz bandwidth, 2 GS/s sampling rate) is employed to monitor the voltage across the specimen under test which is measured by a differential probe (50 MHz bandwidth, 2000:1 voltage ratio, 50 Ω impendence).

B. Test Samples

The test samples are polytetrafluoroethylene (PTFE)-wrapped pairs of Glass fibre insulated wires (2 Silix VSI manufactured by Von Roll), mirroring the turn-to-turn insulation system (Fig. 2). The insulation thickness and bare wire radius are 100 μm and 0.45 mm, respectively. The thermal class of insulation is 200°C impregnated with silicone-based varnish.

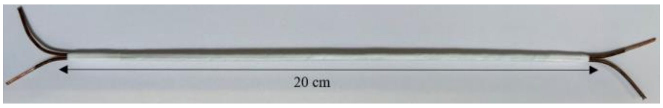

Figure 2. A typical PTFE-wrapped pair of Glass fibre insulated wires.

The two individual cylindrical insulated wires which compose each sample are not twisted to avoid/prevent the cracking of the Glass fibre coating during the twisting process. Therefore, PTFE-wrapped pairs of Glass fibre insulated wires are used to model the turn-to-turn insulation system instead of twisted pairs. Indeed, the two insulated wires are held next to each other using a binding tape (i.e., PTFE tapes) to deliver a perfect contact between their insulation surfaces [3]. Hence, the PTFE tapes are employed for a purely mechanical purpose in the specimen assembly and do not play any electrical insulation role.

C. Measurement Procedure

The negative square unipolar and bipolar excitations are generated using a commercial pulse generator (RUP6-18bip). Two rise times: 80 ns and 800 ns, and two impulse voltage repetition frequencies: 50 Hz and 2.5 kHz, are considered to stress the test samples. The positive and negative impulse width durations are 100 μs for the bipolar and negative unipolar excitations. The measurements are performed at room temperature (21°C), atmospheric pressure (1013 mbar) and relative humidity (28±5%). First, the repetitive partial discharge inception voltage (RPDIV) is measured according to the approach described in [3]. Then, the voltage is kept constant to age the specimens electrically for different cycles: 15, 30, 45 and 60 minutes (Fig. 3). Thus, since ageing is a cumulative phenomenon the exposure times are 15, 45, 90 and 150 minutes. At the end of each stress period, the DDF and capacitance tip-up are measured by adopting a Megger Delta4000 [8]. After finishing the final exposure duration (i.e., 150 minutes), the stressed specimens are wrapped in an Aluminum foil and placed in the oven with a temperature of 150°C (i.e., 50°C lower than the thermal class) for 48 hours to discharge the specimens and remove the free charge carriers caused by PD. Indeed, this new approach can help eliminate the possible impact of the deposited charges due to PD activity on the DDF and capacitance values. Therefore, the focus can be made only on the damages owing to PD activity. Thus, the DDF and capacitance tip-up are measured again for the "Discharged" samples.

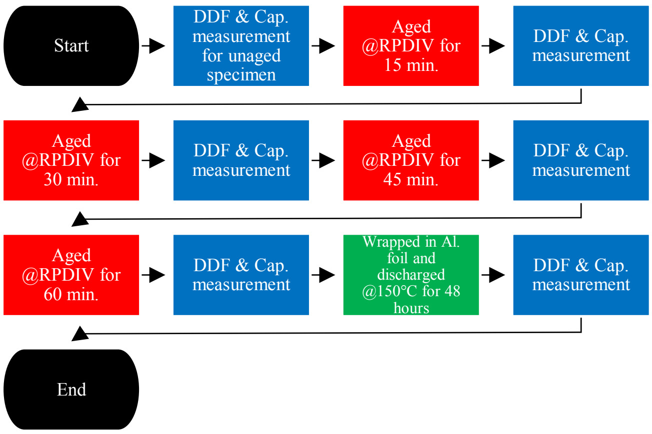

Figure 3. A flowchart to visualize the measurement procedure.

This process is repeated five times each run using a pristine specimen for each test waveform. Finally, the average results of five measurements for each case study (i.e., each specified test waveform and exposure duration) are post-processed and analyzed. Fig. 3 illustrates the measurement procedure.

III. Experimental Results and Discussions

A. RPDIV

Fig. 4 reports the RPDIV (mean peak-to-ground value) for different square unipolar and bipolar test waveforms. These voltage levels were employed to age the specimens under PD activity for different exposure times.

The peak value of RPDIV is higher for the unipolar excitations than the bipolar ones at the same rise time and frequency as expected [9]. The maximum RPDIV is ascribed to the unipolar excitation with a faster rise time and a lower frequency (i.e., 80ns-50Hz). However, the minimum RPDIV is attributed to the bipolar waveform with a longer rise time and a higher frequency (i.e., 800ns-2.5kHz). Regarding the impact of rise time under bipolar excitation at a constant frequency, a higher RPDIV is associated with a faster rise time for both switching frequencies.

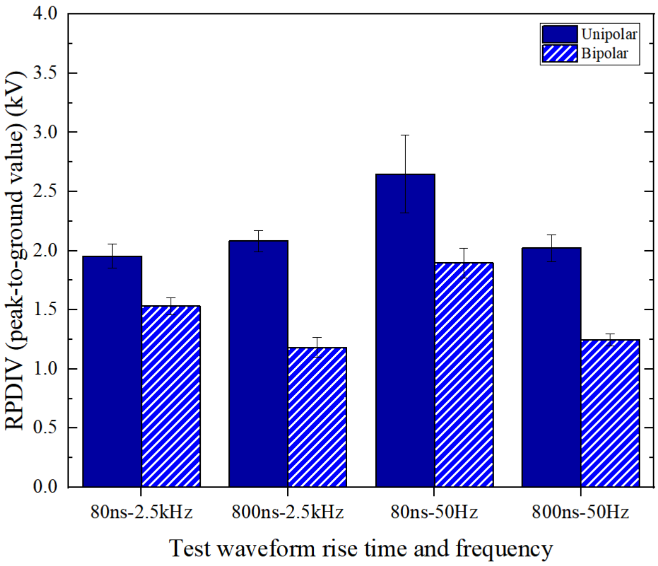

Figure 4. RPDIV (mean peak-to-ground value) for various test waveforms (square unipolar and square bipolar) with different rise times and frequencies. Confidence intervals with a probability of 95% are also indicated.

However, the effect of rise time under unipolar excitation seems to be frequency-dependent [3]. Indeed, while a faster rise time gives a higher RPDIV at a lower frequency (i.e., 50 Hz), the opposite holds at a higher switching frequency (i.e., 2.5 kHz).

Regarding the influence of switching frequency at a constant rise time, the same trend is observed for the unipolar and bipolar excitations. Indeed, when the rise time is faster (i.e., 80 ns), a higher switching frequency delivers a lower RPDIV. However, the frequency impact on RPDIV is almost negligible when the rise time is longer.

B. Dielectric Dissipation Factor (DDF) Tip-Up

Fig. 5 presents the measuring results of tanδ tip-up using a sinusoidal waveform at 50 Hz, comparing the pristine specimen vs the PD-affected ones stressed under different square waveforms excitations for 150 minutes. Fig. 5 shows that all the PD exposure samples give higher tanδ than the new insulation for the test voltage ≤ 900 V. The DDF of the unaged insulation remains independent of the test voltage over a wide range (i.e., ≤ 750 V). However, it starts to rise (due to ionization losses) at a lower voltage level for the PD-affected specimens. The lowest voltage level is associated with the PD-affected samples under bipolar excitation with a longer rise time and a higher frequency. Additionally, the increasing rate of tanδ is steeper for the new insulation. The comparison between the PD-affected specimens substantiates that higher tanδ can be ascribed to the samples affected by PD at a higher frequency of the impulsive voltage (i.e., 2.5 kHz). The comparison between the PD stressed specimens at 2.5 kHz (for all voltages) and at 50 Hz (when test voltage ≥ 650 V) demonstrates that higher tanδ can be attributed to the bipolar excitation with a longer rise time. When rise time is faster, the comparison of unipolar vs bipolar is frequency dependent. For instance, the tanδ is higher for unipolar than bipolar excitation when the square waveform has a higher frequency (e.g., 2.5 kHz). However, the opposite holds for a lower frequency. Interestingly, the test waveforms associated with the highest and lowest measured tanδ (shown in Fig. 5) can be ascribed to the test waveforms with the lowest and highest RPDIV, respectively (Fig. 4).

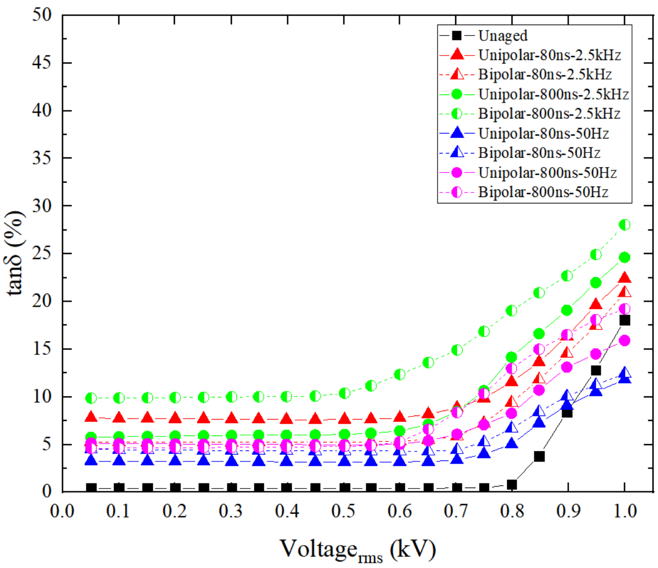

Figure 5. Change of DDF as a function of test voltage measured at 50 Hz for the PD-affected specimens stressed under square unipolar and bipolar excitations with different rise times and frequencies for 150 minutes.

As illustrated in Fig. 5, the voltage level at which tanδ starts to rise steeply (due to ionization losses) is 850 V for the unaged insulation. Interestingly, sorting the measured tanδ from the maximum to minimum value at this voltage level can reflect the sequence of the bipolar test waveforms associated with the minimum to maximum RPDIV values (Fig. 4).

Fig. 6 depicts the variation of starting value or absolute DDF value, $\tan\delta_0$, at a low voltage (50 V) as a function of exposure time to RPDIV, normalized to unaged mean. The $\tan\delta_0$ delivers the sum of the polarization and conducting losses [10]. Fig. 6 shows that $\tan\delta_0$ rises vs RPDIV exposure time introducing an indicator for PD activity. This increment trend is likely due to the increase of both the polarization and conducting losses vs exposure time to PD activity. However, this trend is not monotone for a faster rise time and a lower frequency (i.e., 80ns-50Hz, both unipolar and bipolar excitations). It can be ascribed to the different polarization mechanisms since the applied voltage (i.e., RPDIV) is higher for this case than other test waveforms (Fig. 4). Moreover, an almost monotone increasing trend for 800ns-50Hz emphasizes the different polarization mechanisms when the rise time is faster (i.e., 80ns-50Hz).

Fig. 6 shows that $\tan\delta_0$ reduces to its initial value (same as unaged sample) after discharging the specimens. It confirms that $\tan\delta_0$ is most affected by the conducting losses resulting from the deposited charges by subsequent PD. As a result, $\tan\delta_0$ does not reflect the damage/harmfulness associated with the PD activity. After 150 minutes of exposure to PD activity, the highest conducting losses (i.e., $\tan\delta_0$) are related to the PD-affected specimens by bipolar excitation with a longer rise time and a higher frequency. However, its lowest value is associated with unipolar excitation having a faster rise time and a lower frequency. The same description stands for tanδ at the highest voltage (i.e., 1 kV_{rms}), as illustrated in Fig. 5. Interestingly, the comparison of unipolar excitations vs RPDIV exposure time shows that the most increasing rate of $\tan\delta_0$ (conducting losses) can be associated with the fastest rise time and highest frequency (i.e., 80ns-2.5kHz). It confirms a higher level of surface charge density than other unipolar excitations [3].

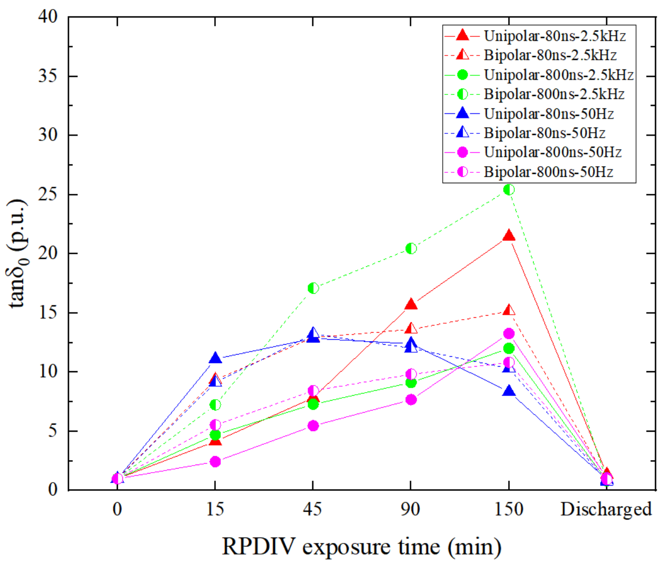

Figure 6. Change of $\tan\delta_0$ measured at 50 Hz for the PD-affected specimens as a function of exposure time to RPDIV stressed under unipolar and bipolar excitations with different rise times and frequencies. (Normalized to unaged mean).

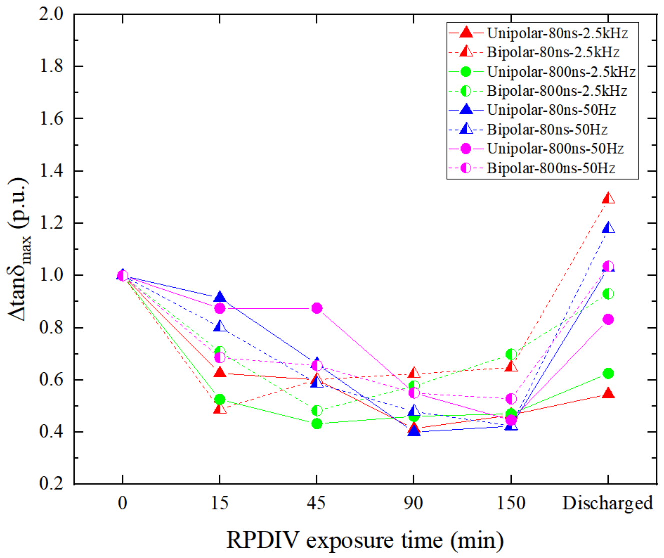

Figure 7. Change of $\Delta\tan\delta_{max}$ measured at 50 Hz for the PD-affected specimens as a function of exposure time to RPDIV stressed under unipolar and bipolar excitations with different rise times and frequencies. (Normalized to unaged mean).

Fig. 7 displays the trend of maximum DDF increment per 50 V incremental step up to 1 kV_{rms}, $\Delta\tan\delta_{max}$, measured at 50 Hz vs RPDIV exposure time, normalized to unaged mean. The $\Delta\tan\delta_{max}$ decreases for all the PD-affected specimens stressed by different test waveforms to a lower value than the new insulation. The free charge carriers (conducting losses) caused by PD activity before discharging the specimens, might result in a reduction of $\Delta\tan\delta_{max}$. Hence, $\Delta\tan\delta_{max}$ is an indicator of PD activity through the tanδ tip-up measurement. Higher $\Delta\tan\delta_{max}$ can be a marker for increasing the number and size of voids or the formation of delamination in the insulating system [10]. $\Delta\tan\delta_{max}$ increases after discharging the samples (i.e., after eliminating the deposited charges caused by PD), being able to reflect the damage/harmfulness of PD activity. The discharged specimens aged by PD under different test waveforms can be compared. It substantiates that always PD activity under bipolar excitation leads to a higher $\Delta\tan\delta_{max}$ than the unipolar ones with the same rise time and frequency. Therefore, bipolar excitations are more damaging than the unipolar ones in the PD regime, as demonstrated through the accelerated life tests [11]. The most significant difference between bipolar and unipolar test waveforms is observed for the fastest rise time and highest frequency. Hence, the harmfulness of the PD activity is likely higher under bipolar excitation with a shorter rise time and a higher frequency. The comparison of the PD-affected specimens by unipolar excitation after discharging demonstrates that the lowest value of $\Delta\tan\delta_{max}$ is associated with the test waveform with a higher frequency (i.e., 2.5 kHz). Thus, lower damage can likely be ascribed to the PD activity under unipolar excitation with a higher frequency.

Fig. 8 indicates the tanδ as a function of frequency comparing the new specimen vs PD-affected ones stressed under different square waveforms for 150 minutes measured at a constant voltage of 500 V_{rms}. As illustrated in Fig. 8, tanδ is independent of frequency for the new insulation. However, it is frequency-dependent for the PD-affected specimens, decreasing as a function of frequency. It can be another indicator of PD activity through tanδ frequency sweep measurement.

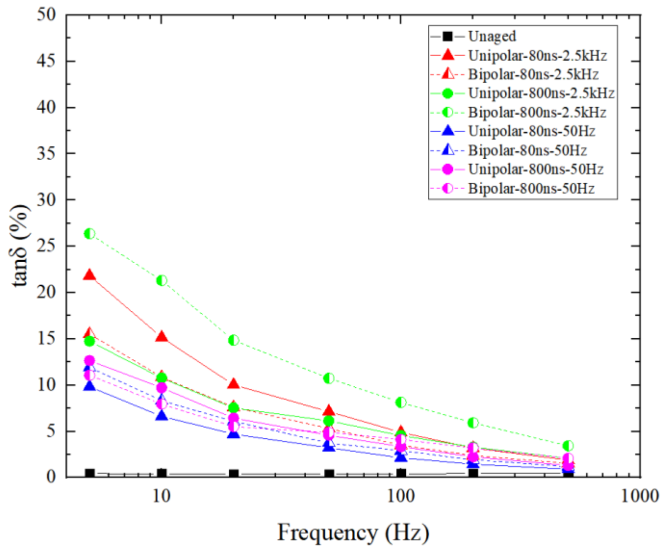

Figure 8. Change of DDF as a function of frequency measured at 500 V_{rms} for the PD-affected specimens stressed under unipolar and bipolar excitations with different rise times and frequencies for 150 minutes.

Although the measured tanδ in all frequency values is lower for the unaged insulation, this superiority is more evident if the tanδ measurement is performed at a lower frequency level. The highest tanδ is associated with the PD-affected specimens under bipolar excitation with a longer rise time and a higher impulse voltage repetition frequency. However, this inferiority is less evident if the tanδ measurement is carried out at a higher frequency level.

C. Capacitance Tip-Up

Fig. 9 displays the capacitance tip-up results measured at 50 Hz, comparing the fresh specimen vs the PD-affected ones stressed under different square waveforms for 150 minutes. As indicated in Fig. 9, the increase rate of the capacitance from 800 V onwards is the highest for the new insulation. The same as tanδ tip-up, the maximum and minimum measured capacitances belong to the bipolar-800ns-2.5kHz and unipolar-80ns-50Hz, respectively, reflecting the minimum and maximum RPDIV (Fig. 4).

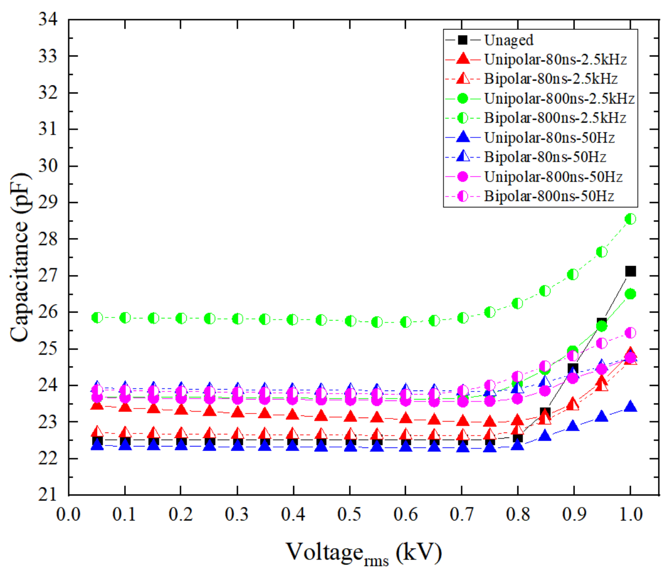

Figure 9. Change of capacitance as a function of test voltage measured at 50 Hz for the PD-affected specimens stressed under unipolar and bipolar excitations with different rise times and frequencies for 150 minutes.

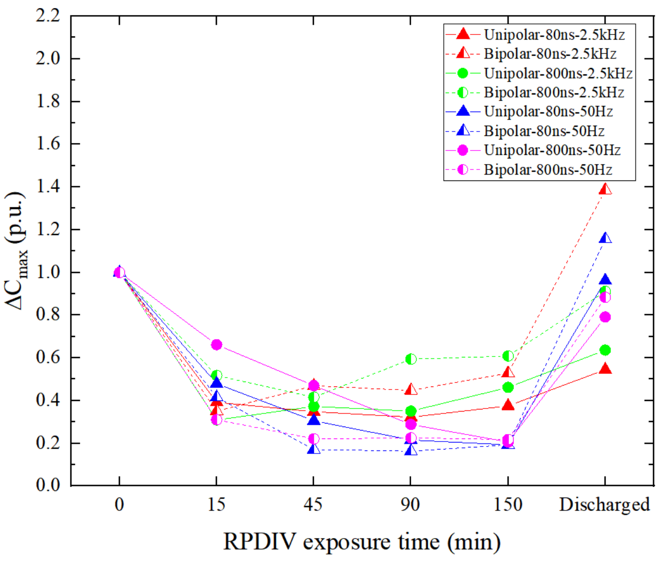

Figure 10. Change of ΔC_{max} measured at 50 Hz for the PD-affected specimens as a function of exposure time to RPDIV stressed under unipolar and bipolar excitations with different rise times and frequencies. (Normalized to unaged mean).

Indeed, the highest capacitance can be ascribed to the highest surface charge density, increasing the effective permittivity [3]. Consequently, the field amplification factor in the air gap would be the highest. Thus, RPDIV would be the lowest under bipolar excitation with a longer rise time and a higher frequency. The DDF and capacitance tip-up results (Figs. 3 and 7) demonstrate that higher values can be ascribed to the bipolar excitations than the unipolar ones, except for the fastest rise time and highest frequency. It is likely due to the significant interface space charge accumulation at the unipolar excitation at 80 ns and 2.5 kHz [3].

Fig. 10 shows the trend of the highest capacitance increment per 50 V incremental step up to 1 kV_{rms} measured at 50 Hz vs RPDIV exposure time, normalized to unaged mean. Fig. 10 demonstrates that ΔC_{max} is lower than the new insulation for the PD-affected specimens, introducing another indicator for PD activity. After 150 minutes of exposure to PD activity, ΔC_{max} for the PD exposure samples at a lower frequency (i.e., 50 Hz) shows the same ΔC_{max} independent of the rise time and polarity of the test waveform. In addition, the ΔC_{max} of the PD-affected specimens under the impulsive voltage with the frequency of 50 Hz is lower than that of 2.5 kHz. Considering the PD-affected samples under 2.5 kHz, the ΔC_{max} of the bipolar test waveforms are higher than those of unipolar waveforms. Considering the capacitance tip-up measurement, the maximum rise of the capacitance curve increases with enhancing the quantity of the air-filled voids [10]. As shown in Fig. 10, there is almost the same sequence for ΔC_{max} as $\Delta\tan\delta_{max}$ after discharging the specimens. Indeed, it emphasizes that bipolar excitations are more harmful than the unipolar ones with the same rise time and frequency in the PD regime, as already proved through the accelerated life tests [11]. Both ΔC_{max} and $\Delta\tan\delta_{max}$ are the highest for the PD-affected samples by bipolar excitation with a faster rise time and a higher frequency. Consequently, the highest void content within the insulation is estimated for the PD activity under this test voltage waveform.

IV. Conclusions

The reported results confirm that dissipation parameters derived through DDF and capacitance tip-up measurements at 50 Hz, such as $\tan\delta_0$, $\Delta\tan\delta_{max}$ and ΔC_{max}, can be considered as PD indicators for the affected turn-to-turn insulation by the PD activity under steep-fronted square waveform excitations. Moreover, it is shown that tanδ of the PD-affected specimens is frequency-dependent, unlike fresh samples, introducing a new diagnosis marker. The comparison of the discharged test samples reveals that while the most harmful test waveform can be bipolar excitation with the fastest rise time and highest frequency, the lowest damage level can be associated with the unipolar excitation with the same rise time and frequency.

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